DISSERTATION

METHODOLOGY FOR INCLUSION OF RISK IN MULTIRESERVOIR OPERATIONS

Submitted by
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ABSTRACT OF DISSERTATION

METHODOLOGY FOR INCLUSION OF RISK IN MULTIRESERVOIR OPERATIONS

To provide a reservoir operator and a decision maker the information about the chance of failure (risk) associated with the decision in the operation of a reservoir system explicitly, the concept called " Anticipated Decision Influence Period or ADIP " which was originally introduced by Anderberg(1979) is extended in this study such that it is applicable to a series of large reservoirs. According to the ADIP concept the time frame for reservoir operation decision making called ADIP is first identified. The conditional probability of storage at the end of ADIP and consequently the exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II as a function of a reservoir initial storage and initial month are generated. The generated exceedance probabilities of spill and deficit will help the decision makers evaluate the effect of their release decisions on the future state of the reservoirs in term of the probability of failure (spill and deficit) at the end of ADIP.

Lakes Powell and Mead of the Colorado River were chosen as the case study to demonstrate the applicability of ADIP

concept to a series of large reservoirs. The ADIP of Lakes Powell and Mead were identified using the concept of an equivalent reservoir. The exceedance probabilities of Powell spill and deficit as a function of Powell initial storage and initial month and those of Mead spill and deficit as a function of Powell and Mead initial storages and initial month were generated by Monte Carlo techniques. A methodology was developed to use the apriori generated exceedance probabilities for evaluating the release decision in operation of large reservoirs in series when the initial storages are known.

To demonstrate how the ADIP concept can be applicable to a series of large reservoirs, three illustrations were presented. Illustration No. 1 shows how the exceedance probabilities of future spill and deficit effect the release decision and how the release decision can be made by trading off the benefits against the risks associated with the release decisions. Illustration No. 2 shows how to use the future failure probability criteria derived from the operational history to make a risk-based operating plan. The last illustration shows how to incorporate the forecasts of inflow into the ADIP concept.

The study showed that for a system of tremendous capacity such as Lakes Powell and Mead where the combined capacity is about 4 times the mean annual flow and the mean annual flow is greater than the target demand, the deficit is almost out of concern except when the reservoirs are almost empty. The spill will be a prime concern when the storages are above a certain level. There is a wide range in storages of Lakes Powell and Mead where failures (spill and deficit) will never take place when the storages are in that zone.

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DEDICATION

To My Parent

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CHAPTER I

INTRODUCTION

A reservoir is a man-made mechanism to transfer an unreliable source of water to dependable water so that it can be used when and where it is needed. How well the reservoir performs its function depends on how well it was designed and how well it is operated. No matter how well the reservoir was designed, a good operation plan will insure benefit from the reservoir.

Types of questions in reservoir operations include how much water should be released today, tommorrow, next week or next month. Although the question appears simple, it is not simple to answer. There are many factors involved, such as the current state of the reservoir, random inflows, variation of demands, primary and secondary objectives of the operations and socio-economic-political-legal constraints. A lot of analysis must be done before the reservoir operator can answer this simple question.

In operation of reservoir systems, there are some factors which cannot totally predicted such as inflows. Over estimating the future inflows may cause a deficit. Under estimating the future inflows may cause a spill and flooding. There are risks of operational failures (spill and deficit) involved in predicting inflows and making a release decision. The risks in this study are defined as the probability and magnitude of spill and deficit. Knowing the risks associated with the release decision will help a reservoir operator and a decision maker assess their release decisions whether the benefits to be obtained is worth the risks. Therefore this study is proposed to develop a methodology for multireservoir operations, particularly for large reservoir systems. The methodology will contain a criteria for evaluating the risks of operational failures associated with the relesase decision explicitly.

1.1 Current Practice in Reservoir Operations

A common current practice for reservoir operations employs the use of rule curves. Rule curves also called guide curves are the set of predetermined rules for determining releases based upon current reservoir storage levels. The rule curves are usually developed by using the most critical period of the record. On this basis, the rule curve implicitly provides assurance for the reservoir to meet the future demands, as long as the future inflows are not more critical than the past recorded inflows. Knowing the current state of the reservoir, the operator will base his release decision on the rule curves and his judgement according to his own experiences.

One of the disadvantages of rule curves is that the risk (for example , the probability of not meeting the future demands) and the benefits assiociated with the release decision are not considered and evaluated explicitly. The benefits and risk in reservoir operations are not independent. Any decision to release more water to generate benefits (for example, water supply and hydropower benefits) will increase the risk of not having enough water to meet the future demands (increase the foregone future benefits). Any decision to maintain high storage volume in a reservoir for future hydropower production benefits will increase the risk of flooding in the future. Therefore the risk and benefits should be explicitly considered in reservoir operations.

Another disadvantage of rule curves is their lack of flexibility. They do not have the flexibility to be updated upon new information such as forecasts of inflows and demands. This information can only be used through the subjective judgement of the operator in making the release decision. Moreover many rule curves are developed during the pre-operational period and are not based on the actual experience in operation. Once the reservoir has actually been operated, experience is gained and new information on inflows and demands is available. This is the more useful information to utilize in order to operate the reservoir more efficiently. Often rule curves do not have the flexibility to update this information, and an entire new analysis has to be repeated to develop new sets of rule curves.

1.2 Uncertainties and Risk in Reservoir Operations

It is recognized, in general, that uncertainties are in existence in water resources system. Uncertainties can be defined in many ways. Chow(1979) defined uncertainties as the occurrence of events that are indeterministic and beyond rigid control. Yevjevich(1972) defined uncertainties by the following statement:

> Because inaccurate, deficient, and biased data are usually always available, and because population properties must be estimated from these data by some technique, various errors and information losses are represented as uncertainties. Differences between the population properties and properties derived from sample data, available for drawing inferences about the population, constitute the concept of uncertainties.

Uncertainties can be changed only by changing the ways in which they are produced. These two definitions are more or less the same. By definition, uncertainties are outside domain of quantitative analysis.

In reservoir operations, there are four basic sources of uncertainties (Croley,1979) which can be identified as follows: (1) basic uncertainty inherent in the nature of stochastic processes, consisting of hydrologic inputs such as precipitation, evaporation, infiltration, etc., (2) uncertainty introduced by the model representing the stochastic process, (3) uncertainty introduced in the models through estimation errors of model parameters, and (4) uncertainty resulting from unforeseen demands, benefits, costs and other parameters likely to change after the reservoir is operated . This is similar to the types of uncertainties identified by Duckstein and Bogardi(1979), Roots(1979) and Chow(1979); natural, model and informational uncertainties. The last type of uncertainty is composed of two aspects: sample or parameter uncertainty and economic uncertainty. It is necessary to address all types of uncertainties because all of these uncertainties bear on consideration of risk and reliability.

Unlike uncertainties, risk can be stated quantitatively if the probability distribution of some future occurrence of an events is known or can be estimated. Risk is defined by Yevjevich(1976) as the probability of failure of an event. Simply risk is the quantitative estimates of probability that the event will deviate from the prediction by a given amount. Theoretically, any physically possible event may take place at any time in the future. However some events are less probable than others and the operator can utilize this knowledge if it is interpreted correctly (there are uncertainties involved in the interpretation). He can decide what possible events should be considered and what possible events should be excluded in the decision. The level of exclusion is the decided risk level. If, for example, events with ten percent or less probability are decided to be excluded in a decision, then the risk that these events will happen is ten percent. It is noted that if the excluded events are realized, the impact can be tremendous.

Risk of an operational failure refers to many aspects of reservoir operation including failing to meet the target demands, operational constraints on outflows, reservoir storage and freeboard requirements, etc. Often times, several different risks need to be considered in reservoir operations. The risks involved in reservoir operations must be identified and measured in some way before they can be assessed. The risks usually have been measured as; the probability of occurrence of a specified undesirable outcome, the number of occurrences in a specified time period, the expected number of occurrences, and the economic cost foregone to prevent these occurrences, Croley(1979).

Although risks can be defined quantitatively in term of the probability of failure, the real value of risk becomes a matter of judgement. For example, in hydropower, a ten percent risk level of operational failure may be accepted if a thermal power plant is ready to take up the shortage, while one percent risk level could be unacceptable for an exclusive hydropower plant with no interconnecting transmission system. It is noted that to decide whether to accept that level of risk or not, the decision maker needs to know not only the probability of operational failure but the magnitude and cost of failure also. This study will be concerned only with matters of risk.

1.3 Justification of Risk Inclusion in Reservoir Operations

As mentioned earlier, risk exists in the reservoir operation decision making process and risk need to be evaluated explicitly. The risk in reservoir operations is induced by the random nature of inflows. There is no way to know how much inflow will come into a reservoir this week or this month. One can only predict with some probability the magnitude of inflows for this week or this month. Therefore there is a certain probability that the inflows will be higher or lower than the predicted amount.

Supposing a reservoir is being operated to avoid flooding based on the 90 percent nonexceedance probability of inflow . This allows 10 percent probability that the inflow will be larger than the designed flow and flooding will occur. This 10 percent probability is called the risk of flooding. Again suppose the reservoir is being operated to avoid shortage in a given month by using 95 percent exceedance probability of inflow. There is 5 percent probability that the actual inflow will be less than the predicted inflow and a shortage will occur. In this case the risk of shortage (not having enough water to deliver as planned) is 5 percent.

However if the reservoir operator has knowledge of risk only as the probability of undesirable outcomes (flooding or shortage, for example), it does not help much in evaluating his operational decisions. In addition to probabilities of spill and shortage, the operator needs to know more about how much (probabilistically) water will spill and costs of flooding or what the magnitude and cost of shortage is. For example if the operator knows that there is 10 percent probability that at least 1.0 million acre-feet of water will be spilled at the end of the planning period, he may estimate the cost of the flood damage that will occur. Then he can make a decision based on the benefits he expects to get from making an additional release and the losses (in term of the risk of deficit in the future which is the result of the additional release) that may happen. As can be seen from this example, if information relating to risk both in terms of probability and magnitude is available, it will be very helpful for the reservoir operator (or decision maker) in deciding how much release to make in each period so as to utilize the reservoir more efficiently while the risk is controlled to an acceptable level.

Generally, an optimum operation policy analyzed from benefits and/or costs of operation will not be an absolutely safe. In fact there exists some non-zero probability (risk) that an undesirable outcome will occur when the policy is implemented. This is due to random effect of inflow. If the policy is modified to lower the risk, the minimum costs or maximum expected net benefits will not be obtained. Thus any alteration to a policy to reduce risk may result in a lowering of the benefits to be obtained. This becomes a question of benefit - risk trade offs. If the trade off function between benefits and risk can be derived, the decision maker can use the trade off function to assess the additional benefits to be obtained according to the action to increase the risk or the benfits to be reduced due to the action to decrease the risk. The decision can finally be made based on the decision makers' benefit - risk preference.

Although an evaluation of risk is rather subjective, it needs to be considered and included in reservoir operation analysis. Croley(1979) correctly pointed out important aspects about risk when he stated that:

> Two aspects are therefore important. First, risk benefit relations must be understood when defining an operation policy. Second, a suitable level of risk and benefit must be selected as satisfactory by the management agency. Consequences of failure will of course govern the selection of the appropriate risk level as well as the lost benefits.

1.4 Time Frame for Decision Making in Reservoir Operations

One thing relating to risk which has not been mentioned so far is the time frame over which the risk (probability and magnitude of future failures) needs to be evaluated. It is obvious that the decision to increase the release from the reservoir today will increase the chance of deficit in the future, if all other conditions are the same. Also the decision to hold the reservoir full will increase the chance of spill in the future. The question at this point is how long will today's decision have an effect on the future state of the system. This time frame should not be arbitrarily assumed but rather it should be systematically analyzed. The concept of a critical time frame was introduced to reservoir operations by Anderberg(1979) and was extended by Ballestero(1981) and Scott(1983).

According to Anderberg's concept, the time frame in reservoir operations depends on many factors including inflows, demands, current storage volume, size of the reservoir and operating policy. Since the inflows are random, the time frame in reservoir operations can only be identified probabilistically. Anderberg(1979) called this time frame Anticipated Decision Influence Period (ADIP) and classified it into 3 types. ADIP Type I is defined as the time period from the present to the end of a spill period which is followed by a deficit period. ADIP Type II is the time period from the present to the end of a deficit period which is followed by a spill period. ADIP Type III is the time period from the present to the end of the influence period if periods of spill and deficit do not exist.

Once the time frame is identified (probabilistically), the benefits and risks associated with the decision (for example the decision to make additional release or cutback release) over that time frame can be identified. This is a very useful information which tells the decision maker that with the selected operating plan how much present benefits (for example, the benefits from the release for water supply and hydropower) can be obtained and what is the level of future risk (for example, the risk of not having enough water for future use) to take and also the additional benefits and risks associated with the additional or cutback release decisions. The decision maker can use this information to make the release decision based on trading off between the benefits to be obtained and the risks to take. By doing so, both the present and future benefits over the specified time frame (ADIP) are considered explicitly in making the release decision.

1.5 Why It Has to Be Multireservoir Operations

A problem in reservoir operations that needs to be addressed is that usually reservoirs are connected in series or parallel or some combination of series and parallel in most of the major river basin. Each reservoir in the system is not independent from the others. For example, in a series of reservoirs, the release from the upper reservoir can be stored and used in the lower reservoir . The deficit in the lower reservoir can be reduced or prevented by the additional release from the upper reservoir if there are no institutional constraints on the release. Spill from the upper resrvoir may cause spill from the lower reservoir. Similarly, for reservoirs in parallel, each reservoir should not release independently otherwise the downstream demands may not be satisfied or they may over release and cause flooding downstream. In order to make proper (optimum) decisions, the entire reservoir system must be considered simultaneously as an integrated system, noting that the sum of the optimum benefits obtained from each single reservoir is not necessary equal to the optimum benefits from the entire integrated system.

1.6 Past Research Efforts

Ideally all of the characteristics of real time reservoir operations including the stochasticity of inflows, multiobjective and multireservoir should be systematically considered and analyzed in developing reservoir operating rules. Although much research effort has been done in this area (reservoir operations), and all recent efforts have recognized the major problems relating to the real time reservoir operations, none of them has entirely overcome all of these problems. Anderberg(1979), Ballestero(1981) and Scott(1983) attempted to prove that Anticipated Decision Influence Period (ADIP) concept is an alternative approach for real time reservoir operations. ADIP concept considers risks (both the probability and magnitude of failures) explicitly. The release decision is based on the trade offs between the benefits and risks associated with the decision within the predetermined time frame. However only the single reservoir problem has been considered in their studies. Scott(1983) recommended that the extension of this concept to multireservoir operations be done.

Colorni and Fronza(1976) introduced the concept of reliability programming which can trade off between benefits and risks explicitly. The risk of violating storage and release targets was converted into losses (in dollars) via a risk-loss function. This approach was extended by Simonovic and Marino(1980,1981,1982), Marino and Mohammadi(1983) and Simonovic and Orlab(1984). This approach has been applied to single reservoir problems and the time frame for decision making was arbitrarily assumed.

The chance-constrained linear decision rule model is another approach which has been recieved much attention in the past decade. It uses a linear decision rule which helps the reservoir problem to be defined in the form of a linear programming problem. It also can incorporate risk into the optimization problem explicitly. Starting from Revelle et al.(1969) who borrowed the idea from Charnes et al.(1958) and introduced this approach to water resources planning and management, many researchers have worked along this line. These include Revelle and Kirby(1970), Eisel(1972), Eastman and Revelle(1973), Gundelach and Revelle(1975) and Houck et al.(1980). Revelle and Gundelach(1975), Houck(1979a), Houck and Datta(1981), and Yazicigil and Houck(1984) extended the linear decision rule to be a multiple linear decision rule where the release is not only a function of a storage volume, but also a function of previous inflows. Although this approach can incorporate risk explicitly, can utlize forecasted information (Houck,1979b; Hoshi and Burges,1979; Yazicigil and Houck,1984), and can apply to multireservoir problems (Nayak and Arora,1971), there are a lot of arguments about this technique. Loucks and Dorfman(1975), Sniedovich(1980) and Stedinger(1984) have argued that it produces a very conservative result. Colorni and Fronza(1976) and Simonovic and Marino(1980) argued that the risk level should not be fixed apriori, but it should be determined from the trade offs between benefits and risks (via risk-loss function). Askew(1974a,1974b) used the stochastic dynamic programming with a failure penalty to control risks (both probability and magnitude of failures) within the desired level. He mis-named his approach to be chance-constrained dynamic programming (Rossman,1977).

Recently the inclusion of risks in multireservoir operation received increased attention from operating agencies such as the United States Bureau of Reclamation (USBR). After experiencing flooding in 1983, USBR began a study for developing operational strategies for the Colorado River reservoir system which can address risk of flooding explicitly. This study indicates that the currently available techniques are not accepted in actual operation practices and more research needs to be done in this area.

From the literature review (discussed in Chapter 2) on the inclusion of risks in reservoir operations, the Anticipated Decision Influence Period (ADIP) concept of Anderberg has the potential to be accepted in actual reservoir operations. However the ADIP concept is now applicable to a single reservoir only. Therefore the ADIP concept needs to be extended to multireservoir operations which is the purpose of this study.

1.7 Study Objectives

The general objective of the study is to develop a methodology for multireservoir operations, particularly for a series of reservoirs. The methodology will contain a mechanism for evaluating risks of failures associated with the release decision explicitly. The risks are defined as both the probability and magnitude of failure. Ideally the decision maker should know how much the benefits to be obtained and the risks to be taken due to his decision. Besides he should know that if he changes the decision, how much will that change effect the benefits and risks. Since the risks and benefits in reservoir operations are not independent, any decision to create more benefits will incur more risks. This information about the benefits and risks associated with each alternative release decision will help the decision maker in making the preferable (hopefully optimum) release decision by trading off the benefits against the risks.

Specifically the study will be focused on the following tasks:

(1) identifying the time frame called Anticipated Decision Influence Period or ADIP for a series of reservoirs such that the benefits and risks associated with the release decision over this time frame can be identified ,

(2) generating the risk information (the exceedance probability of failures, spill and deficit) which is conditioned on the current state of the reservoir system ,

(3) developing a methodology for using the apriori generated exceedance probabilities of spill and deficit to evaluate the alternative release decision for a series of reservoirs,

(4) developing a methodology for incorporation of inflow forecast into the method developed in (3) , and

(5) testing the methodology on the Colorado River system.

CHAPTER II

LITERATURE REVIEW

It is attempted in this chapter to present and discusss the concept and methodology relating to the dissertation topic. Croley(1979) pointed out that there are four general groups of techniques that consider risk in reservoir operations. Those are analytical probability approaches, value of information approaches, Bayesian decision theory and mathematical programming and simulation. Although there are differences in some aspects of the first three approaches, they are closely related to each other. In this review, the first three approaches will be grouped together under the name of analytical and decision theoryapproaches and will be discussed briefly. The last approach, mathematical programming and simulation, where consideration of risk is done explicitly, is considered in more detail.

2.1 Analytical and Decision Theory Approaches

As mentioned earlier, there are three closely related approaches in this group.

2.1.1 Analytical Probability Approaches

These approaches include range analysis, run analysis, storage theory and other analytical techniques (Yevjevich,1972) which require a derivation of the exact distribution functions of reservoir characteristics. The major drawback to these techniques is that many simplifications must be made in order to get exact solutions. Moreover it is very difficult (if it is possible at all) to apply these techniques to solve the very complex problem of multiobjective-multireservoir operations.

One of the classic approaches within this approach is the work of Moran(1954). He derived a matrix of transitional probabilities of reservoir states from the probability distribution of inflow. Jovanovic(1967) first discussed a concept of maximum tolerable risk of failure, no more than a given number of failure years were allowed to occur within a specified short period. Klemes(1975) suggested that reliability of the system should be considered from probability distributions of the risk of failure evaluated for short periods. For the occurrence of failure over project life time, Klemes(1971) suggested using the probability of at least one failure. The review of many other reservoir management models that were related to inventory concepts can be seen from Sobel(1972).

2.1.2 Value of Information

The value of information is related to risk and uncertainties of using limited data in making decisions.

This approach evaluates the value of data in term of expected opportunity loss due to imperfect information, and uses it to trade against the risk and uncertainties when data are limited. Croley(1979) pointed out that the value of information approach usually involved simulation and therefore was considered separately from the analytical probability approaches. Close et al.(1970), Dawdy et al.(1970), Moss and Dawdy(1971) and Tschannarl(1971) studied the effect of record length of input data on the performance of a reservoir. Wiener(1972) and Klemes(1977) pointed out that the incremental value of data was highest when the information was at the lowest level, and returns diminished after a point where the information was sufficient for analysis of the problem.

2.1.3 Bayesian Decision Theory

Closely related to the value of information approaches is Bayesian decision theory method. According to Bayesian decision theory, the goal and alternatives are first defined. The consequential effect of each alternative is evaluated under the uncertainty of data. The decision is made to choose the alternative which best achieves the goal. The decision is then evaluated in term of the expected opportunity loss in order to decide if the information collecting program should be made.

Tschannarl(1971) used Bayesian decision theory to calculate the expected loss in net benefits resulting from imperfect information in reservoir design. Bayesian decision theory approach utilizes the uncertainty of data which can be updated with new information (Shane and Gaver,1970; Gray and Davis,1972; Labadie,1969) or uses the expectation of the risk function to make decisions (Davis et al.,1972; Moore and Brewer,1972).

Duckstein and Kisiel(1971) selected a level of significance in minimizing the risk due to uncertainties. Bogardi and Szidarovsky(1974) pointed out that the confidence levels that characterized uncertainty did not indicate decisions. Closely related to Bayesian decision theory is the induced safety algorithm (Bogardi and Szidarovsky,1972;1974) for minimizing economic losses due to imperfect information.

The value of information and Bayesian decision theory approaches, although they relate to uncertainties and risk, they do not explicitly consider risk. Instead, they use the expected values of risk parameter. Therefore the decision maker may not understand the risk associated with his decision, since the expectation over risk does not provide him with this type of information, Croley(1979).

2.2 Mathematical Programming and Simulation

2.2.1 Linear Programming Under Uncertainty

Linear programming under uncertainty (Dantzig,1963) is one of the first stochastic mathematical programming approach which permits explicitly consideration of stochasticity of variables in analysis of water resource system. With this technique, as described by Eisel(1972), the problem is partitioned into three stages. First decisions are tentatively made by the decision makers. Second the random effects occur and may cause some of the constraints to be violated. Then the second stage decisions are made such that the constraints are not violated. Dorfman(1962) pointed out that the second stage decision might be represented by loss functions for not meeting the supply targets. This is similar to using a penalty to control the failure.

Although linear programming under uncertainty can incorporate the probability distribution of inflow into linear programming, it can only give the maximum expected benefits or the minimum expected costs of reservoir operation. There is no explicit value of risk associated with decision provided.

2.2.2 Chance Constrained Linear Programming

Chance-constrained linear programming is a combination of a linear decision rule (LDR) , chance constraints and linear programming (LP). This formulation was first introduced to reservoir management by Revelle et al.(1969). As applied to a reservoir problem, the simplest form of linear decision rule is:

$$X_t = S_t - b_t$$

where X_t is the water release during period t,

S_t is the storage volume in reservoir at the beginning of period t , and

b_t is a decision parameter for period t chosen to optimize some criteria function.

The continuity equation of a reservoir is:

$$S_{t+1} = S_t - X_t + R_t$$

where R_t is the random inflow with known probability distribution during period t .

By substitution of the linear decision rule into the continuity equation, it yields :

$$S_{t+1} = b_t + R_t$$

Substituting $S_t = b_{t-1} + R_{t-1}$ into the linear decision rule yields the following expression for the release during period t.

$$X_t = R_{t-1} + b_{t-1} - b_t$$

By manipulating the linear decision rule and the continuity equation, the storage volume and the release can be expressed as a function of inflows and decision parameters. The latter are the solution of the linear programming. In general, the chance constraints on storage and release can be formulated as follow:

$$P(S_{t+1} \leq S_{max}) \geq \alpha_1$$

$$P(S_{t+1} \geq S_{min}) \geq \alpha_2$$

$$P(X_t \geq X_{min}) \geq \alpha_3$$

$$P(X_t \leq X_{max}) \geq \alpha_4$$

The first chance constraint can be interpreted as the probability that the storage at the end of period t (or at the beginning of period t+1) will be equal to or less than the maximum allowable storage for conservation purpose must not less than α_1. If α_1 is 0.95, it implies that 5 percent or less risk of spilling is expected (allowed). By substituting $S_{t+1} = b_t + R_t$ into the first constraint, the deterministic equivalence of the first constraint can be derived as the following:

$$P(b_t + R_t \leq S_{max}) \geq \alpha_1$$

$$P(R_t \leq S_{max} - b_t) \geq \alpha_1$$

Since the cumulative distribution function of the inflow is defined as , $F_{R_t}(\text{inflow}) = P(R_t \leq \text{inflow})$, therefore

$$F_{R_t}(S_{max} - b_t) \geq \alpha_1$$

$$S_{max} - b_t \geq F_{R_t}^{-1}(\alpha_1)$$

$$S_{max} - b_t \geq R_t^{\alpha_1}$$

Similarly the deterministic equivalence of the other chance constraints can be written as:

$$S_{min} - b_t \leq R_t^{1-\alpha_2}$$

$$X_{min} + b_t - b_{t-1} \geq R_{t-1}^{1-\alpha_3}$$

$$X_{max} + b_t - b_{t-1} \geq R_{t-1}^{\alpha_4}$$

Using the deterministic equivalence form of constraints, the reservoir problem can be solved by linear programming algorithms such as the simplex method.

Because chance constrained linear programming allows the level of risk to be chosen by the decision maker and seems to be simple to apply in practice, there have heen a lot of extensions and modifications. Revelle and Kirby(1970) modified the original chance constrained LP to handle the evaporation loss from reservoirs, which makes the problem more realistic. Also other performance measures were introduced to be objective functions, instead of minimizing the reservoir capacity, that could be optimized by linear programming. These performance measures include the expected storages and releases, reliable storages and releases, deviations from targets and reliabilities of achieving stated goals.

Eastman and Revelle(1973) derived a direct solution to determine the required reservoir capacity for a special case where the minimum release was equal to the sum of the reliable inflow for a multipurpose reservoir for flood control, water supply and recreation. They also studied the effect of the length of a decision period on the required reservoir capacity. The shorter decision period resulted in the smaller capacity because of the quicker adjustment to the change of inflow. The longer decision period resulted in the larger reliable commitment.

Revelle and Gundelach(1975) proposed a new and more general form of the linear decision rule which considered releases as a function of storage volume at the beginning of the period, current and previous inflows and the decision parameter. Mathematically it can be expressed as:

$$X_t = S_t + \alpha_t R_t - \beta_{t-1} R_{t-1} - \gamma_{t-2} R_{t-2} - \cdots + b_t$$

The new rule allows the weighted total variance of releases to be minimized. It makes possible a large minimum commitment of water, however, in general this new rule results in a larger reservoir. The choice of the new LDR may be viewed as a trade offs between the benefits of larger release commitments and the cost of larger reservoirs. Gundelach and Revelle(1975) extended the direct solution technique for a special reservoir design situation proposed by Eastman and Revelle(1973) to solve a general, single multipurpose reservoir problem using the new LDR proposed by Revelle and Gundelach(1975)

Houck et al.(1980) extended the LDR model to incorporate economic efficiency as the objective of the model. A method of incorporating hydroelectric energy production within the LDR model was presented and the water supply uses of the reservoir system were evaluated and reformulated in such a way that the reliability of meeting the minimum release could be varied from period to period instead of using a constant throughout the year. The extended LDR model was shown to be well within the limits of computational feasibility for large (10 or more facilities) reservoir systems with conflicitng uses and the objective of maximizing net benefits.

Nayak and Arora(1971) applied a chance constrained LDR to determine the optimum capacities of 4 reservoir system which had both parallel and series combinations. Eisel(1972) presented another form of release rule which was different from LDR proposed by Revelle et al.(1969) and the followers. His release rule was set as a linear function of water availability at the beginning of the period and the target demand for that period. Loucks and Dorfman(1975) presented another form of LDR:

$$X_t = S_t + (1-a_t)R_t - b_t$$

They pointed out that that as a_t increased from 0 to 1, the release rule would become more and more conservative, hence more reservoir capacity was required.

Houck(1979a) tried to remedy the cause of conservativeness of the LDR model by explicitly incorporating the streamflow stochasticity and relaxing the restrictions on the operating rules. All of these were done by introducing multiple LDR, each conditioned on any desired seasons' streamflow, into the linear program. The form of multiple LDR is :

$$X_t^{ij} = S_t^j - b_t^i$$

where X_t^{ij} is the release in season t conditioned on streamflows in interval i in season t-1 and interval j in season t-2,

S_t^j is the storage volume at the beginning of the season t conditioned on streanflows in interval j in season t-2 , and

b_t^i is the decision parameter in season t conditioned on streamflows in interval i in season t-1.

Houck and Datta(1981) simulated the operating rules defined by single and multiple LDR models. The multiple LDR models were shown to be superior to the single LDR model. Under identical operating requirements the multiple LDR model specified significantly smaller reservoir capacity than the single LDR model. As the number of LDR's per season increased, the optimum reservoir capacity decreased.

Yazicigil and Houck(1984) utilized multiple LDR which allowed explicitly consideration on streamflow forecasts. By solving the chance constrained linear programming problem over the whole range of interest of reliability levels, the trade off curves relating the minimum reservoir capacity (directly relating to dam costs) and the reliablity of achieving water supply and flood control targets were developed. The generated trade off curves could then be presented to the decision maker to allow the selection of the best reservoir capacity considering technological and financial constraints as well as the trade offs between targets, risks and costs.

Although a lot of extensions, modifications and applications of chance constrained LDR models have been done, there are also a lot of arguments about the conservative nature of this technique. Loucks and Dorfman(1975) evaluated the operating policy obtained from chance constrained models. Their simulations showed that the results of LDR were conservative. More active storage capacity was specified by the solution of the chance constrained LDR model than was actually needed to meet the reliability requiremnets defined by the chance constraints. This conservative characteristic is a basic limitation of these chance constrained LDR models. They stated that one of the principal reasons for the conservative nature of this method was the assumption that each flow in each period would be a critical flow. Even when serial correlation and cross correlation of streamflows were very high, the joint probability of a sequence of flows each having a probability of exceedance equal to the critical flows included in the deterministic equivalences of the corresponding chance constraints was essentially zero.

Sniedovich(1980) investigated the chance constrained LDR model proposed by Eisel(1972). The analytical results indicated that the proposed model might over estimate the tails of the true distribution function of S_t (storage at the beginning of t). Since in the chance constraints, we are particularly interested in the tails of the distribution function of S_t, the model may lead toward a conservative design and operating policy.

Stedinger(1984) evaluated the performance of two LDR's namely; S-Type (Revelle et al.,1969) which the release is a function of a storage and a decision parameter,

$$X_t = S_t - b_t$$

and SQ-Type (Loucks,1970) which the release is a function of a storage, an inflow and a decision parameter ,

$$X_t = S_t + R_t - b_t$$

The latter assumes a perfect forecast of each period's inflow is available. The results indicated that for a range of common problems, even with a perfect forecast, LDR operating policies were not particularly attractive. For the simple water supply/recreation/flood control situation it is considered that the standard operating policy requiring no inflow forecast was much more efficient at achieving modest water supply failure frequencies while minimizing the total shortfall caused by releases less than the target and keeping reservoir storage levels above the minimum target for recreation and out of the reserved flood storage zone. The minimum failure frequency policy allowed even fewer release failure but often incurred a larger total shortfall than the corresponding SQ-Type LDR.

2.2.3 Chance Constrained Dynamic Programming

Askew(1974a) demonstrated the use of stochastic dynamic programming with a penalty to derive the optimum reservoir operating policies which maximized the expected net dollar benefits and at the same time restricted the probabaility of failure to a desired level. He first varied the penalties over a range of values in the stochastic dynamic programming. The derived policies were then simulated to determine the expected net benefit and average number of failures. The larger penalty gave the smaller expected net benefit but less average number of failures. This provided information on trade offs between the expected net benefits and the average number of failures. While this was an excellent portrayal for a decision maker, Croley(1979) argued that the use of a penalty to represent the reluctance to failure did not guarantee an optimum solution. Klemes(1975) pointed out that the second round of computation required in Askew' s simulation of the average number of failures was superfluous. He suggested a new formulation using an optimum reliability as design parameter which was determined by optimization, engineering judgement and operational experience.

Askew(1974b) noted that a considerable savings in computation workcould be realized if the expected net benefits (without penalty) could be computed directly within the stochastic dynamic program. The necessity for any simulation studies are thus avoided. The stochastic dynamic programming problem was reformulated as:

$$f_t(S_t) = \max_{0 \leq X_t \leq S_t + R_n} \sum_{j=1}^{n} P(R_j)[\, B(r_t) - C(X_t) + W1 + (1/1+d)\, f_{t-1}(S_{t-1})]$$

where

$$f_1(S_1) = \max_{0 \leq X_1 \leq S_1 + R_n} \sum_{j=1}^{n} P(R_j)[B(r_1) - C(X_1) - W1]$$

$f_t(S_t)$	is the maximum hypothetical expected net benefits over the remaining t years of the life of the system,
$C(X_t)$	is the cost incurred for a target release of X_t ,
$B(r_t)$	is the benefit from an actual release of r_t,
$P(R_j)$	is the probability of obtaining a net annual inflow of R_j ,
R_n	is the maximum possible inflow ,
d	is the annual discount rate ,
W1	is the hypothetical penalty for system failure ,
t	takes on the sequence of values 1,2,...,50, where N and 1 being the first and last years of the life of the project, respectively.

For $S_t + R_j - X_t > S_{max}$

$$r_t = X_t \;;\; S_{t-1} = S_{max} \;;\; W1 = 0$$

For $0 \leq S_t + R_j - X_t \leq S_{max}$

$$r_t = X_t \;;\; S_{t-1} = S_t + R_j - X_t \;;\; W1 = 0$$

For $S_t + R_j - X_t < 0$

$r_t = S_t + R_j$; $S_{t-1} = 0$; $W1 = W$, and the system is held to have failed.

The true expected net benefit(B_N) resulting from any policy is not therefore $f_t(S_t)$, but it can be computed in conjunction with and in parallel with the recursive equations presented above once the optimum target release for the current year $X_t^*(S_t)$ has been determined. This process is accomplished as follows :

$$B_N(S_t) = \sum_{j=1}^{n} P(R_j)[B(r_j)-C(X_t^*(S_t))+(1/1+d)B_N(S_{t-1})]$$

where

$$B_N(S_1) = \sum_{j=1}^{n} P(R_j)[B(r_1) - C(X_1^*(S_1))]$$

and $B_N(S_{50})$ is the total expected net benfits over life of the project. The expected number of failures over the remaining t years, $F_A(S_t)$, can be calculated by:

$$F_A(S_t) = \sum_{j=1}^{n} P(R_j)[F+F_A(S_{t-1})]$$

where

$$F_A(S_1) = \sum_{j=1}^{n} P(R_j).F$$

F is the indicator function with a value of zero if no violation of the constraint occurs and unity if the constraint violation occurs.

Askew(1974b) thus used an iterative search technique to find the value of the penalty (W) by varying the value of the penalty for failure (W) until the maximum value of $B_n(S_{50})$ was found and was limited to the maximum permissible expected number of failures (γ) during the life of the system. Askew named this methodology as a chance constrained dynamic programming. In fact, the model did not use a chance constraint like $F_A(S_{50}) \leq \gamma$ directly in the optimization and so the method is not analogous to a chance constrained linear programming. Sniedovich and Davis(1975) showed how to incorporate a true chance constraint into the optimization by defining risk variables as state variables and imposing constraints on these state variables that applied on a sequential basis, for example $F_A(S_i) \leq \gamma$ for $i=1,2,...,50$.

Askew(1975) presented another formulation of stochastic dynamic programming in which the discount factor (risk premium) was varied instead of a penalty term. He again called it a chance constrained dynamic programming. Although Askew recognized the question of optimality when applying penalties or risk premiums (discount factors), he believed that the formulation of a chance constrained dynamic programming in which the optimum solution could be assumed was possible.

Rossman(1977) provided a critical reworking of chance constrained dynamic programming within the context of Lagrangian duality theory. He also pointed out that the stochastic dynamic programming with failure penalty approach was limited to problems having of expected value type constraints rather than the chance constraints on the probability of certain events. The means for obtaining optimum randomized release rules in addition to the deterministic form were presented. Finally Rossman mentioned that the approach of Sniedovich and Davis(1975) for incorporating the chance constraints into the optimization was intractable because of computation loads.

2.2.4 Reliability Programming

Colorni and Fronza(1976) introduced an approach for determining the optimal contract for a monthly operated reservoir, called reliability programming. This reliability programming is similar to the chance constrained model proposed by Revelle et al.(1969), except the reliabilities are not fixed apriori. In reliability programming the reliabilities are considered as extra decision variables. The optimum operation results from a compromise between profit and risk through a risk loss function (through the evaluation of the losses associated with the risk of choosing an infeasible solution). A methodology for deriving risk-loss functions associated with the violations of a freeboard constraint (flood risk) and a water supply storage constraint (drought risk) were developed by Simonovic and Marino(1981)

The reliability programming formulation of Colorni and Fronza is the following :

$$\max_{X,S,\boldsymbol{\alpha}} \left[\sum_{t=1}^{12} f_t(X_t) - l(\boldsymbol{\alpha}) \right]$$

s.t.

$$m_t \leq S_t \leq C - v_t$$

$$S_{t+1} - S_t + X_t \leq P_t^{-1}(\alpha)$$

$$X_t \geq 0$$

$$S_{13} = S_1$$

$$0 \leq \alpha \leq 1$$

where

X_t is the contract volume to be release during the t^{th}-month of the year ,

$f_t(X_t)$ is the net benefit deriving from the reservoir operation,

S_t is the storage at the beginning of the t^{th}-month,

$l(\alpha)$ is the yearly loss associated with the risk level , α ,

m_t is the given minimum admissible storage at the beginning of the t^{th}-month ,

v_t is the given minimum freeboard , and

C is the given capacity of a reservoir.

The complexity of nonlinearity in the above program was eliminated by assuming that the net benefits and risk losses were concave and convex functions of their arguments. They proved that the above assumption was valid in a range of a ,i.e. $\alpha^* \leq \alpha \leq 1$ where $P_t^{-1}(\alpha)$ was usually concave.

Simonovic and Marino(1980) presented an extension of the reservoir reliability program for multireservoirs.

Unlike Colorni and Frinza(1976) who used a single reliability constraint to express the reliability of the whole system, they used two reliability constraints (flood risk and drought risk) . The reliability program formulation of a multipurpose reservoir management problem was written as:

$$\max_{X,\alpha,\beta} \sum_{t=1}^{12} f_t(X_t) - l_1(\alpha) - l_2(\beta)$$

s.t.

$$P(S_t \leq C-v_t) \geq \alpha$$

$$P(S_t \geq m_t) \geq \beta$$

$$X_{min,t} \leq X_t \leq X_{max,t}$$

$$0 \leq \alpha \leq 1 \text{ and } 0 \leq \beta \leq 1$$

where

$f_t(X_t)$ is the net benefit function associated with monthly releases , X_t ,

$l_1(\alpha)$ is the yearly risk loss function associated with the reliability level , α ,

$l_2(\beta)$ is the yearly risk loss function associated with the reliability level , β ,

$X_{min,t}$ and $X_{max,t}$ are the minimum and maximum possible discharge in the time interval (t-1 to t).

A two dimensional Fibonaccian search procedure was used to obtain the reliabilities of the elements of the system, and a mathematical programming technique was used to calculate the optimal monthly releases. Although the algorithm can be applied to problems with more than two reliability constraints, the computational requirements may limit its applicability to higher dimensional problem. The program is nonlinear, but the complexity associated with solving the problem can be reduced substantially, as discussed by Sengupta(1972) and Colorni and Fronza(1976) , by assuming that the benefits and risk losses are concave and convex functions of their arguments respectively.

Simonovic and Marino(1982) applied a reliability programming technique to a multiple, multipurpose reservoir system. The reliability programming formulation included an objective function based on economic efficiency (maximization of the difference between net benefits and the yearly risk losses) subject to the reliability constraints. Only one run of the reliability program supplied the user (decision maker) with reservoir releases and reliabilities of reservoir operations. When compared with other techniques (e.g., chance constrained model) the reliability programming has the advantage of directly computing the optimal values of the reliabilities and the corresponding reservoir releases. The final solution is the trade offs between benefits associated with the system's purposes and risk losses associated with the reliabilities.

Simonovic and Orlab(1984) applied the reliability program to determine optimal water quality controls for a reservoir, given an economic efficiency criteria including agricultural production losses and risk losses associated with encroachment on reservations for flood control and other uses. The reliability program allowed the direct determination of the corresponding downstream water quality and trade off between competing water uses under various conditions of economic penalty and hydrologic uncertainty.

Although reliability programming can incorporate the risk explicitly into the optimization in such a way that optimum operation is derived from the trade offs between benefits and risk assoiciated with the operation, the derivation of the risk-loss function is subjective and very difficult to identify apriori.

Marino and Mohammadi(1983) recognized three drawbacks in the reliability programming. Those were: (1) risk-loss function requirements, (2) constant reliabilty level, and (3) reliability of hydroelectric energy production. They presented a new reliability program to solve those drawbacks. Two stage chance constrained LP-DP was used to determine the optimum reliability levels for flood control and droughts. The chance constrained LP was used to optimize the release under given chance constraints on flooding and drought. The size of reliability levels were varied parametrically within the predetermined minimum and maximum levels. The DP was then used to determine the optimum reliability level. The objective function for the DP was to maximize the weighted sum of reliabilities.

2.2.5 Multiobjective Programming

There are many multiobjective programming techniques that have been proposed in the literature. They have been classified into three classes, by Cohon and Marks(1975) , as follows:

(1) generating techniques which include weighting methods, constraint method, derivative of a functional relationship for the non-inferior set and adaptive search ,

(2) techniques which rely on prior articulation of preferences including goal programming, assessing utility functions, estimation of optimal weights, eletre method and surrogate worth trade off method ,

(3) techniques which rely on progressive articulation of preferences including step methods, iterative weighting methods and sequential multiobjective problem solving (SEMOPS).

However only a few researchers have tried to consider risk explicitly using multiobjective programming. Haimes et al.(1975) and Hall(1977) showed a way to incorporate risk directly into multiobjective optimization by considering the probability of failure/success to meet a minimum prescribed level of service, such as the firm water or firm energy. This probability can be generated by Monte Carlo simulation techniques, Askew et al.(1971). The probability of failure/success can be treated as one of the objectives as follow:

$$\max_{X} \left[1-P_n(X) \ , \ F(X) \right]$$

s.t.

constraints on input hydrology, reservoir capacity and non-negativity constraints on initial reservoir conditions,

where

$P_n(X)$ is the probability of failure to meet the minimum service level X,

$F(X)$ is the expected net benefits of selecting a level of service of X.

Since $P_n(X)$ and $F(X)$ are fundamentally different quantities, this is a vector optimization of non-commensurable functions. Therefore they suggested that this problem could be treated by the surrogate worth trade off method, Haimes and Hall(1974). Other forms of risk can be incorporated into the multiobjective optimization in similar fashion.

Croley and Rao(1977a,1977b) proposed a methodology called " stochastic trade off " to derive a multipurpose (two purposes, flood control and recreation) reservoir operating rule. First the trade off function was derived by optimizing the objective of flood control at various levels of attainment of the recreation objective. The problem was set in form of ε -constraint approach as:

$$\text{MAX } U_F(d_1,d_2,\ldots\ldots,d_N)$$

s.t.

$$U_R(d_1, d_2, \ldots\ldots\ldots, d_N) \geq \varepsilon$$

where

U_F is the total utility of the flood control objective over the entire operational horizontal,

U_R is the total utility of the recreation objective over the entire operational horizon , and

$d_i (i=1,2,\ldots,N)$ is the decision at the i^{th} stage of the system operation.

By inspecting the trade off function, the decision maker can subjectively select the best trade off level. The risk associated with the trade off level was then evaluated by repeating the analysis for many synthetic input realizations. Many trade off functions were generated. Then the values of flood control objective for each value of the recreation constraint could be treated as an ordered sample, from which the probability of flood control objective (flood control loss) being equal or exceeded , for each recreational constraint level , was indicated. After all objective trade-offs and their associated risks were evaluated, the desired trade off level for reservoir operation could be selected based on subjective trade offs of objectives and the associated risks. Finally the operating rule was derived (for the selected trade-offs and risk levels) using an implicit stochastic optimization.

2.2.6 Anticipated Decision Influence Period (ADIP)

Anderberg(1979) developed a methodology relating to reservoir operation called " Anticipated Decision Influence Period" or simply " ADIP ". This concept is related to the identification of the time frame for decision making in reservoir operation. This time frame should not be arbitrarily selected. It should be systematically analyzed from the reservoir characteristics, hydrologic conditions, projected demands and the operating policy. As a matter of fact, any decision to release more (or less) water now will have influence on the probability of spill and of deficit up to a certain time in the future. Beyond this certain time in future, the present decision is assumed to have no effect.

One characteristic of a reservoir is that whenever an inflow is greater than the demand the reservoir stage will rise. If the demand is greater than the inflow, the stage will drop. This rising-falling cycle is a seasonal characteristic of a reservoir. Starting at any initial storage , the stage may rise until spilling occurs or the stage may drop until the reservoir goes dry and a deficit occurs. The former is called a period of excess and the latter is called a period of deficit. However this situation (spill/deficit) may not occur every year depending on the available storage, inflow , demand and operating policy.

Suppose a reservoir is in the period of spill and it is expected that a spill will occur some time in the near future. What the operator should do is to modify the schedule by releasing more than the target release in such a way that at the end of spill period the reservoir stage is at full level. If he can do this , nothing after the period of spill will be effected, however more economic benefits will be gained from flood prevention, additional increase in hydroelectric power generation and water consumption. The benefits from hydropower and water supply, however depend on how long in advance the planning of an additional release can be made so that the market can be contracted. Similarly if a deficit is expected in the near future (at the end of period of deficit), the operator should plan to cut back the release so that the shortage will not be as serious as expected. Thus for both anticipated spills and deficits, a specific time period is defined over which a feasible release policy has impact, but beyond which it would have no impact.

Three types of ADIP in reservoir operation were defined by Anderberg(1979). ADIP Type I is defined as the duration of one or more periods of excess in sequence followed by a period of deficit. This decision period provides an opportunity for an operator to increase actual releases above the designed target releases. ADIP Type II is defined as the duration of one or more periods of deficit in sequence followed by a period of excess. In this decision period, it is necessary to decrease the actual release below the designed target level. ADIP Type III is a period which neither an ADIP Type I or Tpye II is recognized within the time of significant impact (a time period over which the current policy will have a significant impact on the future reservoir state). The actual release corresponds to the target release. Once ADIP is identified, the probability of cumulative spill and deficit at the end of ADIP can be determined. This is a useful information for real time reservoir operation.

Anderberg(1979) also suggested the use of mathematical programming to determine real time reservoir operating rules by trading off between the present benefits and future risk of spill or deficit. The ADIP concept was extended by Ballestero(1981) and Scott(1983).

Ballestero(1981) used Monte Carlo simulation to identify ADIP and the operational failure(which is defined as a spill or a deficit) probability during ADIP for different initial conditions and the non-exceedance probability of the cumulative failure (spill/deficit) volume at the end of ADIP as a function of initial storage conditions. Whenever the failure (spill/deficit) probability for given initial storage condition is greater than the critical failure (spill/deficit) level, the risk-based rule should be employed. With the use of the non-exceedance probability of the cumulative failure volumes, the failure volumes are identified at various probability level. The failure volumes at a selected probability level are then redistributed over ADIP by a selected release rule. The risk-based release rules are then tested for their effectiveness in reducing the failure probability during the current ADIP and also the effect on the failure probability in the subsequent ADIP. The risk-based rules which reduce the failure probability of the current and subsequent ADIP below the critical level are the acceptable policy. The way to apply risk-based release rules as proposed by Ballestero(1981) is a trial error procedure. For each selected risk level and the associated failure(spill/deficit) volume, the whole analysis has to be repeated according to the selected release rule to see whether the failure probability of the current and subsequent ADIP is below the pre-selected critical probability level. This technique is time consuming and inconvenient in practice.

Scott (1983) used Monte Carlo simulation and the transitional matrix of the storage to identify the ADIP and the exceedance probability of spill/deficit at the end of ADIP as a function of initial storage volume and the initial month . With the probability of spill and deficit and forecasts of inflows and demands, he proposed a simple equation for evaluating and probably optimizing the potential for altering the time dependent predetermined water release schedule. The equation is:

$$S'_{t_0} = S_{t_0} - \Delta I - \Delta R$$

where

S'_{t_0} is the actual current monthly storage,

S_{t_0} is the recalculated current monthly storage,

ΔI is the forecasted cumulative change in monthly or seasonal inflow over an ADIP,

ΔR is the forecasted cumulative change in monthly or seasonal releases over an ADIP, which is a function of the actual requested water releases and the additional release (decision variable).

This equation will help an operator to display the effect of additional release on the probability of spill/deficit at the end of current ADIP and at the end of subsequent ADIP. Finally for ADIP Type I , the amount of additional release will be decided by the decision maker based on the tradeoffs between the benefits of making additional release and decreasing a probability of spill (of desired magnitude) at the end of ADIP Type I and the risk of increasing the probability of deficit (of desired magnitude) at the end of subsequent ADIP Type II.

All the studies which have been done on ADIP are focused only on a single reservoir for water supply and hydropower. This concept will be more valuable if it is modified to solve the problem of a system of reservoirs which has purposes other than water supply and hydropower. It is noted that the ADIP concept is the most promising approach to solve real time reservoir operation problem. It can provide some type of adaptive control, include forecasts of future flows and projected future risks of operational failure. All this information will help a manager make better decisions.

CHAPTER III

RESEARCH METHODOLOGY

3.1 Purposes of Reservoir Operations

The essence of reservoir operations is to have enough empty space in the reservoir when a large runoff is expected and have enough water in the reservoir when a dry period is expected. The operator's duty is to make this come true. A set of operating rules has been used in conjunction with the operator's skill and experiences in operating the reservoir such that it can provide a reliable source of supply.

If not enough empty space in the reservoir is available before an expected large runoff, a spill will occur. This may or may not be detrimental depending on the designed purpose of the reservoir. Although a reservoir is not designed to store all of the incoming water, still the operator's duty is to take full advantage of the existing reservoir system and try to minimize the spill since the spill represents a loss of potential power and water supply. However, demands can always be met during a spill period and the customers will not recognize that their water or power is coming from a spill period or from a non-spill period.

On the other hand, there might be a case where the reservoir storage is at a level where no more water can be extracted from the reservoir than is entering the reservoir. The purpose of reservoir operations is to avoid this situation. However if this occurs, the reservoir will literally disappear from the analysis because the water available is the same whether the reservoir is there or not. This situation will always occur if not enough water is stored in the reservoir to meet the demands during a dry period.

Anderberg(1979) pointed out that the task of the operator is to make decisions on releases such that the immediate benefits that can be extracted from the reservoir have to be balanced against the future benefits to be extracted in such a way that the total benefits over a period of time will meet the objectives of the reservoir systems.

The immediate benefits can be evaluated from the current state of the reservoir systems; that is reservoir content, inflow, demand and the physical capacity of the system.

The evaluation of the future benefits can be best understood in context with the concept of Adaptive Control Process. The essence of Adaptive Control Process is that when the time arrives for a new evaluation of the states of the system and a decision to be made, the previous decision should have allowed the system to react such that the options available will not prevent the objectives to be fulfilled, Anderberg(1979). For reservoir operations this means that the current release decision should take into account the possibility that the expected states of the reservoir system might not be realized in the future in order to avoid a situation where the operator has no desirable options left when the future arrives.

If the future was totally predictable, that is deterministic, there would be no use for Adaptive Control Process. The future could be predicted once and for all. However, the real world shows very few signs of deterministic activities, and thus risk and uncertainties have to be accounted for.

As pointed out, one of the key elements in successfull reservoir operations lies in the evaluation of the future benefits to be expected, including avoidance of excessive risk. These future benefits must be balanced against the immediate benefits of the operational decisions. Thus, a basic task is to find the characteristics of the future for a reservoir system.

3.2 Background of ADIP Concept

Basically in reservoir operations the currentrelease decision will effect the future characteristics of the reservoir system. Any information related to the future characteristics of the reservoir, if known, will effect the current release decision. This is the logic behind the concept called ` Anticipated Decision Influence Period ' which was developed by Anderberg(1979). Two future characteristics of a reservoir which are important to know and have been the objective of studies by Anderberg(1979), Ballestero(1981) and Scott(1983) are the time frame over which the future benefits should be evaluated and the future state of the reservoir within the time frame.

Anderberg(1979) stated that the time frame in reservoir operations should not be arbitrarily selected, but on the contrary, can and must be precisely recognized in an analysis of reservoir operational decisions. The time frame which Anderberg called ADIP depends on inflows, demands, storage capacity, initial storage and the operating rule. Deterministically, once the time frame is identified, the future state of the reservoir within that time frame can be determined according to the selected operating rule. The future state of the reservoir is an indication of how good the operating plan is for that reservoir. If the future state of the reservoir is not satisfied, the operator can revise the operating plan until he satisfies the combination of the immediate benefits of the operating plan and the potential benefits of the future state of the reservoir. Remember that the introduction to the ADIP concept above is based on the deterministic point of view

For sake of illustration, the logic of ADIP will first be explained from the deterministic point of view. Then the more complicated explanation about the ADIP concept from stochastic point of view will follow afterward.

3.2.1 ADIP From Deterministic Point of View

From the deterministic point of view, knowing the initial storage of reservoir, the operating rule (or the target release) and the future inflow (based on the assumption that the inflow is deterministic and can be perfectly predicted), one can determine with certainty that how much and when the spill or deficit will occur. Asume that the reservoir storage trace from the deterministic assumption follows Figure 3.1.

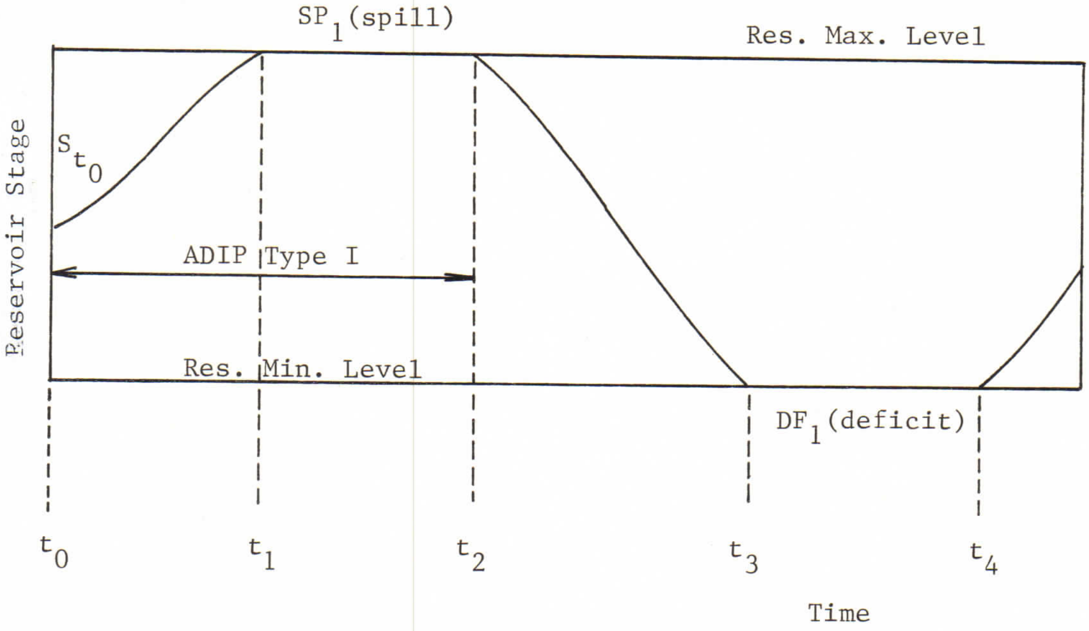


Figure 3.1 The Hypothetical Storage Trace in The Period of Excess Followed by The Period of Deficit

Let t_0 be the current time period and S_{t_0} be the reservoir storage at time t_0. The time from t_0 to t_2 is defined as a period of excess, where the inflow is greater than the demand. Likewise, the time from t_2 to t_4 is defined as a period of deficit, where the inflow is less than the demand. Assuming the reservoir stage follows the storage trace in Figure 3.1, the spill SP_1 occurs between t_1 and t_2 and the deficit DF_1 occurs during t_3 and t_4. It is impossible to store the spill SP_1 during t_1 to t_2 to save the deficit during t_3 and t_4. If the operator has a choice in operating the reservoir, he should increase the release over the target during t_0 to t_2 to avoid the spill and decrease the release below the target during t_2 to t_4 to avoid the severe deficit. If the amount of additional release during t_0 to t_2 is not greater than SP_1, nothing after time t_2 will change.

If this is the case, the time frame in making release decision should be limited only to the time between t_0 and t_2. The types of decisions will be (1) to maintain the target release schedule and let SP_1 spill or (2) to increase the release above the schedule by SP_1 to prevent spilling between t_1 and t_2. It is obvious that the second decision is preferred since more benefits are obtained from increasing the release by SP_1 and decreasing the spill by SP_1, if the future will follow Figure 3.1 exactly. Anderberg(1979) called the time period between t_0 and t_2 of

Figure 3.1 as " Anticipated Decision Influence Period Type I or ADIP Type I ".

Similarly if the reservoir stage follows the storage trace in Figure 3.2, the decision period should not be longer than t_2 to t_4. The type of decision is to cutback the release from the target release by DF_1 to prevent the reservoir goes dry and a deficit occurs during t_3 and t_4. By doing so, the deficit DF_1 will be distributed over the time t_2 to t_4. Although the total deficit is the same, the magnitude of deficit due to the cutback release is a lot

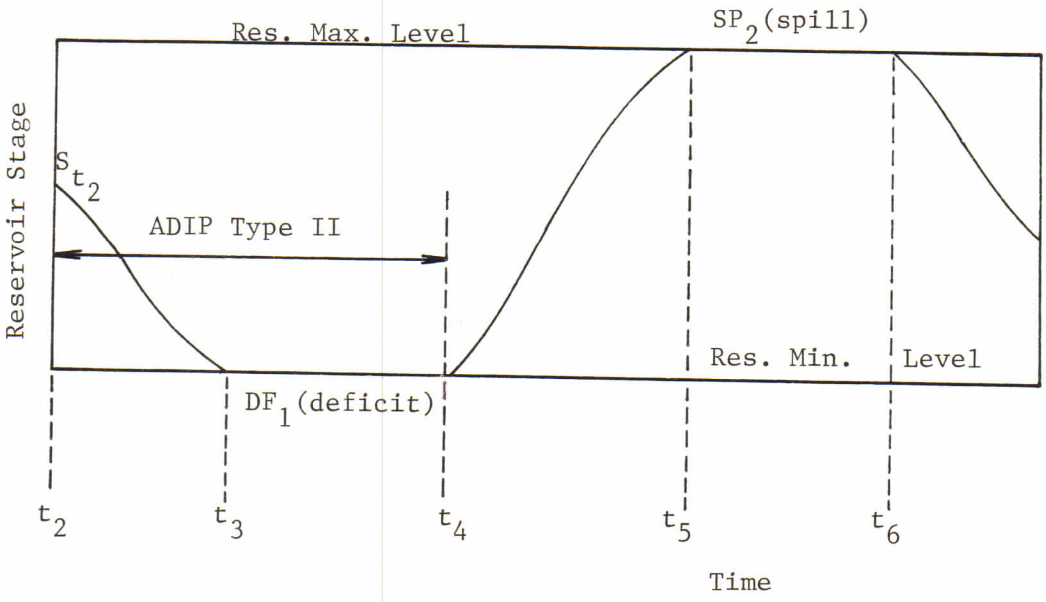


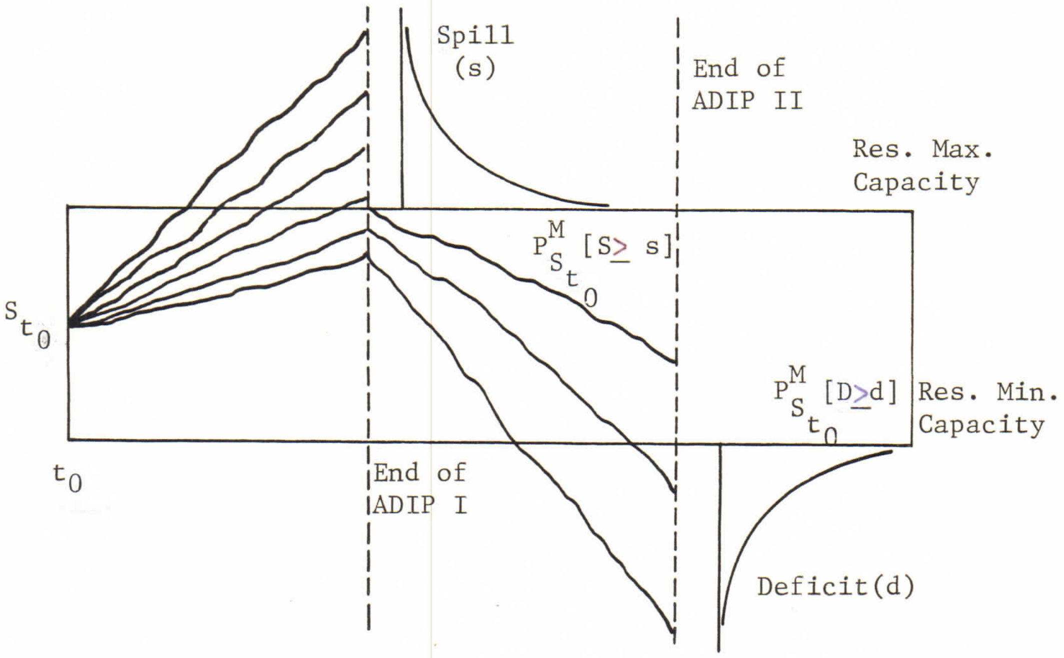
Figure 3.2 The Hypothetical Storage Trace in The Period of Deficit Followed by The Period of Excess

less severe. It is noted that nothing after time t_4 is changed. Anderberg(1979) called the time period between t_2 and t_4 as " Anticipated Decision Influence Period Type II or ADIP Type II ".

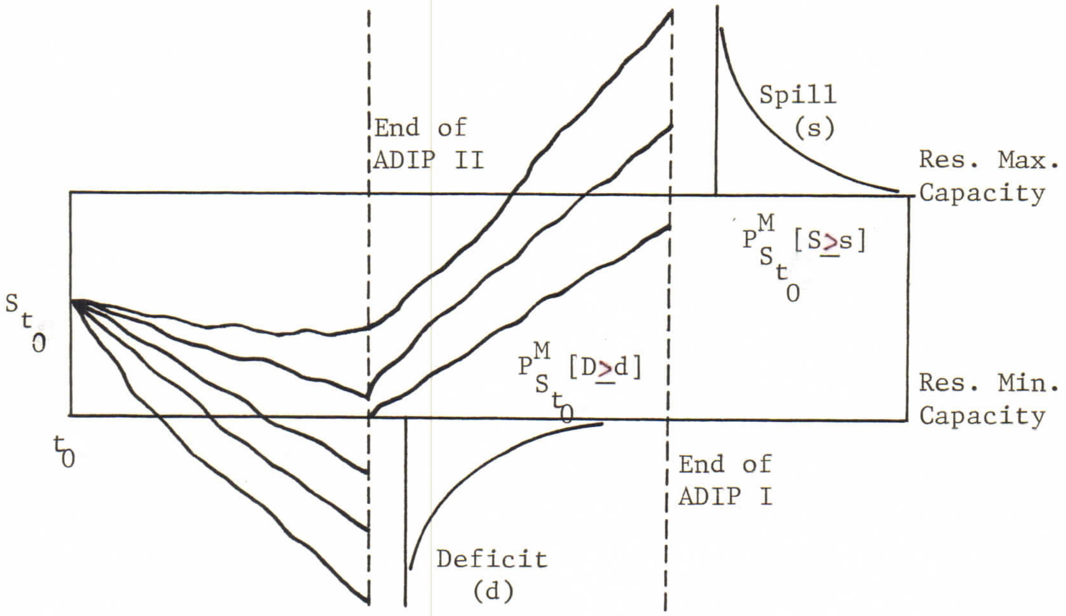
It can be seen from the deterministic point of view that the type of decisions in reservoir operations is either to reduce the spill or to reduce the deficit but never to handle both decisions at the same time by trying to store the spill in the current ADIP Type I to save the deficit in the subsequent ADIP Type II.

3.2.2 ADIP From Stochastic Point of View

An inflow to a reservoir is random. Therefore there is no way to know for sure when and to what extent how much a spill and a deficit will take place. With the knowledge of the stochasticity of inflow, a large number of inflow sequences can be generated. Each sequence will give one storage trace similar to Figures 3.1 or 3.2. The probability distribution of the ADIP-end can be determined from the generated storage traces. With a pre-specified criteria such as the expected value or the most probable value, the end of ADIP can be identified. The exceedance probabilities of the cumulative spill at the end of ADIP Type I and the cumulative deficit at the end of ADIP Type II as a function of initial storage and initial month can be determined, see Figure 3.3. This information will be useful for anticipating the spill and deficit when the initial storage and initial month are known. Since the spill and



(a) The Initial month (M) is in ADIP Type I



(b) The Initial month (M) is in ADIP Type I

Figure 3.3 The Exceedance Probabilities of Spill at The End of ADIP Type I and Deficit at The End of ADIP Type II As A Function of Initial Storage S_{t_0} and Initial Month deficit are not known with certainty, to decide whether the additional or cutback release should be made depends on the probabilities of spill and deficit and the benefits associated with the decision. Opposite to the deterministic case, the additional or cutback release is not only impact on the storage and the failure probabilities in the current ADIP (the term "failure" in this study means an operational failure which is defined as a spill or a deficit), but those in the subsequent ADIP also. For example the additional release during ADIP Type I will decrease the probability of spill at the end of ADIP Type I but at the same time it will increase the probability of deficit in the subsequent ADIP Type II. Therefore the risks (which is defined in this study as the probability and magnitude of the operational failure) and benefits associated with the additional or cutback release in both the current and subsequent ADIP have to be evaluated before the final decision on the additional or cutback release is made.

The time frame for reservoir operation decision making from the stochastic point of view is not as easy to identify as that from the deterministic point of view. Only the probabilistic statement about the ADIP-end can be made. Since most of the decision is to avoid the risks of failure or to maintain the risks within the minimum desirable level, particularly the risk of deficit, the negative impact beyond the subsequent ADIP is usually small. Therefore, from the stochastic point of view, the time frame in decision making should be limited only to the current and subsequent ADIP in such a way that the release decision is planned only for the current ADIP but the effect of the release decision in the current ADIP on the subsequent ADIP has to be evaluated and taken into consideration in making the final release decision.

3.2.3 Identification of ADIP

Originally Anderberg(1979) classified ADIP into 3 types. ADIP Type I is defined as the duration of one or more periods of excess in sequence followed by a period of deficit. ADIP Type II is defined as the duration of one or more periods of deficit in sequence followed by a period of excess. ADIP Type III is a period where neither ADIP Type I nor II is recognized within the time of significant impact, a time period over which a predicted state of the reservoir will have a significant impact on the current policy.

Most of the reservoirs are designed to supply a dependable amount ofwater (firm yield or firm power) provided that the inflow is not smaller than the designed flow, which is usually the most critical flow in the record. The case where a reservoir goes dry is very rare. The spill, on the other hand, happens more often.

The normal characteristic of such reservoirs is a long series of spill before one deficit occurs. The theoretical ADIP Type I is very long, many years, which results in the insignificant predicted future state and it becomes useless. Moreover for a reservoir which has a tremendous carry-over storage, many times the mean annual flow, the periods of spill and deficit will change according to the stages of reservoir development. In early stage where the demand is smaller than the mean inflow, the normal characteristic of the reservoir is the spill, the deficit will never occur. Once the demand is developed to be close to the mean inflow, the chance of having spill followed by deficit or deficit followed by spill is very small. At the ultimate stage where the demand overweighs the mean annual flow, the spill rarely occurs. The deficit becomes the normal characteristic of the reservoir. Therefore it is very difficult to identify the theoretical ADIP defined by Anderberg(1979).

When one scrutinize the concept of ADIP, one can see that the filling and drawdown cycles which are the seasonal characteristics of any reservoir can be used for identifying the decision period similar to the theoretical ADIP. The filling cycle is defined as the period where the inflow is greater than the demand. The end of filling cycle is the most probable time that the spill will occur. Likewise the drawdown cycle is the most probable time that the deficit will occur. By this definition, the filling and drawdown cycles are equivalent to the periods of excess and deficit respectively. Knowing that there is some probability that a spill will occur at the end of filling cycle and there is some probability that a deficit will occur at the end of subsequent drawdown cycle, one can use those probabilities to decide whether the release should be increased or decreased to avoid the operational failure. The effect of the additional or cutback release on the probabilities of spill and deficit should be evaluated. The release decision can be made by trading off the benefits of making the additional or cutback release against the risk of the operational failure.

Scott(1983) redefined the definition of ADIP such that the filling cycle is ADIP Type I and the drawdown cycle is ADIP Type II. With this new definition, ADIP Type I and Type II are more easily identified than using the original definition. The criteria for identifying ADIP according to the new definition can be stated as follows:

ADIP Type I is the period where the inflow is greater than or equal to the target demand (or target release) during a year.

ADIP Type II is the period where the inflow is less than the target demand during a year.

Figure 3.4 shows the way to identify ADIP graphically based on the above definition. The probability distribution of the ADIP-end can be determined and finally the end of ADIP can be identified from the month which has the highest probability to be the end of ADIP.

3.2.4 Determination of The Characteristics of The Spill and Deficit

The long historical records of inflow or the generated inflow traces can be used for identifying ADIP once the

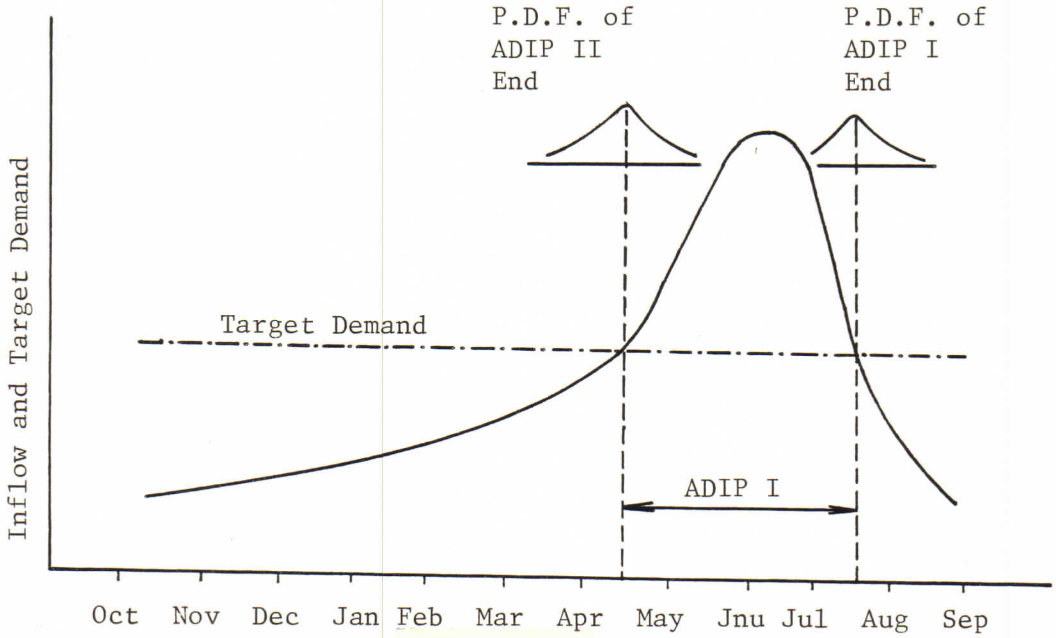


Figure 3.4 Identification of ADIP

target demand or the target release is known. The operating rule such as releasing to meet the target demand whenever possible will be chosen and simulated. Starting from the first month of ADIP Type I, the reservoir mass balance will be performed month by month to the last month of ADIP Type I based on the infinite reservoir concept. According to the infinite reservoir concept, a reservoir is allowed to store more water than the maximum capacity or less than the minimum capacity. The amount greater than the maximum capacity or less than the minimum capacity is considered as a spill or a deficit respectively. If the storage content at the end of ADIP Type I is greater than the reservoir maximum capacity, it will be truncated at the maximum capacity. The storage content above the maximum capacity represents the accumulated spill during ADIP Type I . The mass balance analysis then proceeds to the end of ADIP Type II. The storage content below the minimum capacity represents the accumulated deficit during ADIP Type II. For each level of the initial storages (varying from minimum to maximum capacity) in the initial month, the mass balance analysis is performed for many inflow traces. The frequency distribution of the accumulated spill at the end of ADIP Type I and that of the accumulated deficit at the end of ADIP Type II which are conditioned on the initial storage and the initial month are analyzed. The initial month will vary from the first month to the last month of ADIP Type I.

Similarly the mass balance will be performed from the first month to the last month of ADIP Type II. If the storage content at the end of ADIP Type II is below the minimum storage capacity, it will be truncated at the minimum capacity. The storage content below the minimum capacity represents the accumulated deficit during ADIP Type II. The mass balance analysis then proceeds to the end of subsequent ADIP Type I. The mass balance analysis is performed for many inflow sequences in each level of the initial storage in the initial month. The frequency distribution of the accumulated deficit at the end of ADIP Type II and that of the accumulated spill at the end of ADIP Type I which are conditioned on the initial storage and the initial month are analyzed.

From the conditional frequency distribution of the accumulated spill during ADIP Type I and that of the deficit during ADIP Type II, the exceedance probability of the accumulated spill and that of the accumulated deficit are determined. Remember that the exceedance probabilities of spill and deficit are conditioned on the initial storage and the initial month.

The exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II are used together to evaluate the release decision over the current ADIP Type I and the subsequent ADIP Type II or over the current ADIP Type II and the subsequent ADIP Type I.

Knowing the storage content at the beginning of the current month, the previously generated exceedance probabilities will tell what is the probability of various levels of spill at the end of ADIP Type I and what is the probability of various levels of deficit at the end of ADIP Type II. This information indicates how good the pre-selected operating rule is. If the probability of significant spill at the end of current ADIP Type I is high but the probability of significant deficit at the end of subsequent ADIP Type II is low and the reservoir operator has a choice to alter the operating plan, it is obvious that he will increase the release over the target release during ADIP Type I (the inflow is in excess of the demand) to reduce the probability and magnitude of the anticipated spill. Similarly if the probability of significant deficit at the end of the current ADIP Type II is high, the operator might decide to decrease the release below the target to avoid a severe deficit. By doing so, although the deficit is not prevented, it will be distributed over ADIP Type II instead of taking place in a particular month. The decision to increase or decrease the release over or below the target will be determined by trade off analysis between the benefits and risks associated with the additional or cutback release which will be mentioned in the next paragraph.

3.2.5 Evaluation of The Benefits and Risks Associated With The Release

As mentioned in the previous paragraph, the exceedance probabilities of spill and deficit as a function of the initial storage and initial month can be used for evaluating the release plan. If the target release plan is too risky (high probability of spill or deficit), an alternative plan should be made.

If the current month is in ADIP Type I and the probability of spill during ADIP Type I is high, the alternative plan might be to increase the release over the target release schedule to reduce the probability of spill. The effect of the additional release during ADIP Type I on the probability of deficit during ADIP Type II can be assessed by using the exceedance probability of deficit. The benefits and the risks associated with the additional release during ADIP Type I can be assessed. The benefits will be assessed in term of having additional water for hydropower production and water supply downstream and reducing a probability and magnitude of a severe spill. The risks will be assessed in term of increasing a probability and magnitude of deficit in the subsequent ADIP Type II. Different alternative plans (or different levels of the additional releases) should be tested. The benefits and risks associated with each alternative plan including the target release plan (or Do Nothing alternative) will be the very useful information for the decision maker in deciding whether the target release plan should be changed and what the additional releases should be made based on the trade off analysis between the benefits and risks.

Similarly if the current month is in ADIP Type II and the probability of significant deficit during ADIP Type II is high, the alternative plan to cutback the release from the target release should be studied. The effect of various levels of cutback release on the change in the probability of deficit during ADIP Type II and that of spill during subsequent ADIP Type I can be assessed using the exceedance probabilities of spill and deficit. It is noted that the cutback release plan does not help reduce the total deficit during ADIP Type II but it distributes the deficit over ADIP Type II to avoid a severe deficit. Also the benefits and risks associated with different cutback release alternatives are the very useful information for a decision maker in deciding whether the cutback release should be made and what should be the magnitude of the cutback release.

3.2.6 Potential For Applying ADIP Concept to A Series of Two Reservoirs

ADIP concept is a kind of 2 stage decision making process. In the first stage, the decision on the operating rule such as releasing to meet the target demand whenever possible is made. The operating rule is then simulated over the pre-defined time period called " ADIP " with a large number of inflow traces. The risk of future operational failures (spill and deficit) as a function of storage and month is determined from the simulation result. Knowing the current state of the reservoir, the apriori determined risk of future operational failures will tell how good the pre-selected operating rule is. If the pre-selected operating rule gives very risky future operational failures, the operating rule should be modified. The second stage decision is to determine how to update the pre-selected operating rule such that the benefits and risks associated with the alternative plans are explicitly considered.

The previous explanation about ADIP concept is limited to a case of single reservoir. However, logically this concept could be applied to a series of reservoirs without any difficulty. Depending on the inflow, the intervening flow and the operating rule of the upper and lower reservoirs, the stages of the upper and lower reservoirs may rise and fall correspondingly or they may rise and fall differently. If the first case is true, the two reservoirs in series should be considered as a single equivalent reservoir in identification of ADIP. By this identification method, it is assuming that the two reservoirs in series have the same ADIP which is equal to the single equivalent reservoir ADIP. If the second case is true, ADIP of the upper and lower reservoirs have to be identified separately according to the inflows and target outflows of each reservoir.

After ADIP of a series of reservoirs is identified, the exceedance probabilities of spill and deficit of each reservoir can be determined by Monte carlo simulation techniques. The operating rule of a series of two reservoirs is first chosen. The mass balance analysis of the upper and lower reservoirs is performed simulteneously for different inflow traces, different initial storages and different initial months. The exceedance probabilities of spill and deficit which are conditioned on the initial storage and initial month for each reservoir obtained from Monte Carlo simulation can be used to evaluate the release decision of a series of two reservoirs similar to a case of a single reservoir.

In evaluation of the release decision of a series of two reservoirs, the upper reservoir is considered first assuming that the upper reservoir is a single independent reservoir. Therefore the method for evaluating and updating a single reservoir release decision mentioned previously is directly applied to the upper reservoir. The effect of altering the upper reservoir target release on the lower reservoir has to be taken into account. This can be done by assuming that the additional or cutback release from the upper reservoir takes place immediately at the beginning of the current month. This assumption is valid if the evaporation is minor. With this assumption the initial storages of the upper and lower reservoirs are effected immediately by the additional or cutback release but the actual releases are still equal to the target releases. After taking into account the additional or cutback release from the upper reservoir, the lower reservoir is assumed independent from the upper reservoir. The method to evaluate and alter the release decision of the lower reservoir can be done similar to a case of single reservoir.

3.3 Identification of ADIP of A Series of Reservoirs

There are two approaches for identifying ADIP of a series of reservoirs. This study will focus only for a case of two reservoirs in series. The first approach is to identify ADIP of the upper and lower reservoirs according to the inflows, the target release of each reservoir and the criteria for identifying ADIP given in section 3.2.3. This approach will give different ADIPs for each reservoir depending on the variation of the inflows and the target release of each reservoir. By this method, the change in the actual release from the target release will effect ADIP.

Particularly if the change in the release takes place in the upper reservoir, it will change not only the upper reservoir ADIP but the lower reservoir ADIP also. This is because the inflow to the lower reservoir will change according to the outflow from the upper reservoir. Another word ADIP identified by this approach is very sensitive to the change in the upper reservoir release. In actual reservoir operation, it is usually possible that the actual release will be higher or lower than the target release depending on the forecast of inflow, the available storage, the change in demand, the operating rule and particularly the flood and drought control regulation.

Basically if the intervening flow is not significant, the outflow from the upper reservoir becomes the inflow to the lower reservoir. The target outflow from the upper reservoir is usually determined from the downstream target demand. A severe spill and deficit in the lower reservoir usually will not occur if the upper reservoir release policy is to meet the downstream target demand. A severe spill or deficit in the lower reservoir will occur only when there is the spill or deficit in the upper reservoir. Therefore ADIP of the upper and lower reservoirs should not be much different from each other if the intervening flow to the lower reservoir is not very significant. If this is the case, this approach should not been used for identifying the series of two reservoirs' ADIP.

The second approach for identifying ADIP of a series of two reservoirs is to consider a series of two reservoirs as a single equivalent reservoir. The ADIP of a single equivalent reservoir can be identified from the aggregated inflow and the aggregated demand of a single equivalent reservoir. This idea should be acceptable, if the inflows to the upper and lower reservoirs are highly correlated and so are the demands. The highly correlated inflows and highly correlated demands will produce highly correlated storages between the upper and lower reservoirs which will result in a highly correlated upper and lower reservoirs' ADIP. By this approach, each reservoir in a series of reservoirs has the same ADIP which is the same as the equivalent reservoir ADIP. This ADIP is insensitive to the change in the inflow and the target outflow of each individual reservoir but it is sensitive to the change in the system inflow and the system target demand. As mentioned before if the intervening flow is not very significant and the joint operating rule is used for a series of reservoirs, the single equivalent reservoir ADIP will not be much different from the individual reservoir ADIP identified by the first approach.

Therefore it is considered that the second approach for identifying ADIP has advantages over the first approach and is chosen as the method for identifying ADIP for this study. The historical inflow of long records or the generated inflow traces can be used for identifying ADIP of a series of two reservoirs.

3.4 Monte Carlo Simulation of A Series of Two Reservoirs

According to the criteria for identifying ADIP given in section 3.2.3, ADIP Type I is equivalent to the filling cycle and ADIP Type II is equivalent to the drawdown cycle. The filling and drawdown cycles are the seasonal characteristics of a reservoir which will be repeated themselves every year. The Anticipated Decision Influence Period is in the order of a few months. The monthly time step will be used in Monte Carlo simulation to determine the probability distribution of reservoir storage and that of operational failures (spill and deficit). This idea is supported by the sensitivity analysis of the distribution of reservoir storage of Burges(1972) who concludes that:

> " analysis encourages monthly rather than seasonal (or annaual) modelling due to the difference in required storage, respectively. "

A large number of equally likely sequences of monthly inflow, each sequence having a length of one year, will be generated for using in identification of ADIP and determining the characteristics of future operational failures (spill and deficit). Any number of inflow traces can be generated however the decision on the number of generated inflow traces to use in the analysis, is economic.

For a fixed length of analysis, the increase in the numbers of traces is roughly proportional to the increase of the cost(s). For a fixed number of traces, an increase in the length of the time period of analysis roughly geometrically increases the computational costs, as discovered by Ballestero(1981) during his research. Therefore, some trade offs must be made between the number of traces and the accuracy of empirical distributions for a given certain budget.

Burges and Linsley(1975) indicated that 500 traces were necessary to describe future distributions. They looked at storage distribution with traces of size 100, 250, 500 and 1,000. By concluding that the monthly storage distributions of 1,000 traces was not much different from those of 500 traces, the 500 trace limit was set. Askew et al.(1971) used 200 traces in their study of reservoir systems and indicated that 600 traces might be better when specifically interested in occurrence probabilities in the 0 to 15 percent level.

Weighing all the previously mentioned facts, and a critical look at the budget and how many generations would be neceesary for the present study, 500 traces were chosen.

After ADIP of a series of two reservoirs is identified based on the criteria given in section 3.2.3 and the method of identification of ADIP given in section 3.3, the reservoir operating rule such as " to meet the target release whenever possible " is first selected. The monthly mass balance of a series of two reservoirs is performed for all the generated inflow traces. The mass balance is performed from the first month to the last month of ADIP Type I and proceeds to the end of ADIP Type II or from the first month to the last month of ADIP Type II and proceeds to the end of ADIP Type I based on the infinite reservoir concept which allows the reservoirs store water above the maximum and below the minimum capacities. At the end of ADIP Type I, if the storage content is above the maximum capacity, it will be truncated at the maximum capacity. The storage volume above the maximum capacity is considered as the spill. The spill from the upper reservoir will be transferred to the lower reservoir. At the end of AIP Type II, if the storage content is below the minimum capacity, it will be trancated at the minimum capacity. The storage volume below the minimum capacity is considered as the deficit. The deficit from the upper reservoir will be transferred to the lower reservoir.

The mass balance analysis will be done for different initial storages (vary from the minimum to maximum capacity at a selected increment) and different initial months (every month in ADIP Type I and ADIP Type II). The frequency distribution of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II as a function of initial storage and intial month are analyzed.

Finally the exceedance probabilities of cumulative spill at the end of ADIP Type I and cumulative deficit at the end of ADIP Type II for the upper reservoir as a function of the upper reservoir initial storage and initial month and those exceedance probabilities for the lower reservoir as a function of the upper and lower reservoir initial storages and initial month are the result of Monte Carlo simulation.

3.5 Method For Evaluating The Release Decision of A Series of Two Reservoirs

This section provides a general guideline for using exceedance probabilities of spill and deficit as a function of the initial storage and initial month to anticipate the characteristics of future operational failures(spill and deficit) once the initial storage is known. If the probability of future operational failure(spill or deficit) is high , the decision might be to increase or decrease the actual release above or below the target release to reduce the probability of future spill or deficit. Also the exceedance probabilities of spill and deficit can be used for assessing the effect of increasing or decreasing the actual release above or below the target release in term of the change in operational failure probabilities. Two methods to reach the final decision will be introduced. The first method is to use the failure probability criteria. The second method is to trade off benefits against risks.

3.5.1 Future Failure Probability Criteria Approach

The use of the probability criteria aids in the recognition of the degree of risk which is to be accepted before implementing corrective actions. If the reservoir is to be regulated in a totally inflexible manner, the probability criteria could be set at unity. No matter what the future operational failure probability is, no deviation will be made from the pre-selected operating policy. Setting operational failure criteria at any probability less than unity introduces a degree of flexibility. Ballestero(1981) used the maximum steady state spill and deficit probability as the criteria, which when violated, prompted an increase or decrease of releases, respectively. He showed by the failure probability history plot through five years of operations that ignoring the first peak in the plot, due to the influence of the large initial condition, the other peaks have nearly constant level. However the length of time to attain the steady state levels is a function of reservoir size (assuming stationary inputs and outputs), many years may be required for large reservoirs and possibly only one season for very small reservoirs with minimal over the year storage.

The future failure probability criteria may be derived from the long term experience in operating the reservoir systems and the preference of decision makers. If the future failure probability criteria is identified by either Ballestero's maximum steady state failure probability or the decision's maker preference, it will be used to decide when the additional or cutback release should be made and to determine the magnitude of the additional or cutback release also.

According to the ADIP concept, the planning for operation will start at the beginning of the ADIP. For ADIP Type I, knowing the initial storages at the beginning of the first month of ADIP Type I, the exceedance probability of cumulative spill at the end of ADIP Type I and that of cumulative deficit at the end of ADIP Type II of both reservoirs can be read from the apriori generated exceedance probabilities. The exceedance probability of spill will tell how good the pre-selected operating plan is in terms of the future spill probability. If the exceedance probability of spill exceeds the spill probability criteria, the additional release should be made to reduce the exceedance probability of spill within the probability criteria. The effect of additional release during ADIP Type I on the exceedance probability of deficit during ADIP Type II should be examined to make sure that the additional release during ADIP Type I will not increase the exceedance probability of deficit during ADIP Type II beyond the deficit probability criteria. In case the decision to keep the exceedance probability of spill within the spill probability criteria results in violation of the deficit probability criteria, it should be the decision maker who decides whether the spill or deficit probability criteria should be violated according to the benefits and risks associated with the decision and the operational objectives.

Similarly for ADIP Type II, the exceedance probability of deficit at the end of ADIP Type II and that of spill at the end of subsequent ADIP Type I of both reservoirs can be read from the apriori generated exceedance probabilities, given that the initial storages at the beginning of the first month of ADIP Type II is known. If the exceedance probability of deficit at the end of ADIP Type II violates the deficit probability criteria, the scheduled release should be cutback. The effect of the cutback release during ADIP Type II on the exceedance probability of spill during the subsequent ADIP Type I should be examined to make sure that the cutback release will not increase the exceedance probability of spill at the end of ADIP Type I beyond the spill probability criteria or else the risk of violating the deficit probability criteria has to be traded against the risk of violating the spill probability criteria.

To use the apriori generated exceedance probabilities to assess the effect of additional or cutback release on the change in the exceedance probabilities of spill and deficit, it is assumed that the additional or cutback release takes place entirely at the beginning of the current month. According to this assumption, the additional or cutback release will decrease or increase the initial storage immediately by the amount of additional or cutback release. This assumption does not account for evaporation and bank storage effects on the change in storage or it is assumed that the evaporation and bank storage effects are minor.

If the additional or cutback release takes place in the lower reservoir only, the new initial storage of the lower reservoir can be calculated by the following equations:

$$S'_{t_0,l} = S_{t_0,l} - X_l \tag{3.1a}$$

or $$S'_{t_0,l} = S_{t_0,l} + Y_l \tag{3.1b}$$

where

S_{t_0} is the actual current monthly storage,

S'_{t_0} is the recalculated current monthly storage,

X is the additional release over ADIP Type I ,

Y is the cutback release over ADIP Type II, and

A subscript " l " is refering to the lower reservoir.

If the additional or cutback release takes place in the upper reservoir, it will change not only the initial storage of the upper reservoir but that of the lower reservoir also. The new initial storage contents of the upper and lower reservoirs when there is an additional or cutback release from the upper reservoir can be calculated by the following equations:

$$S'_{t_0,u} = S_{t_0,u} - X_u \tag{3.2a}$$

or $$S'_{t_0,u} = S_{t_0,u} + Y_u \tag{3.2b}$$

$$S'_{t_0,1} = S_{t_0,1} + X_u \qquad (3.3a)$$

or $$S'_{t_0,1} = S_{t_0,1} - Y_u \qquad (3.3b)$$

where

S'_{t_0}, S_{t_0}, X, Y and 1 are previously defined, and

A subscript " u " is refering to the upper reservoir.

Note that the new initial storages are not real storages. They are surrogate initial storages calculated just to facilitate the use of the apriori generated exceedance probabilities of spill and deficit in assessing the effects of the additional and cutback releases on the probabilities of future spill and deficit. If the additional or cutback release does not take place at the beginning of the current month as assumed or the evaporation and bank storage effects are not minor, the additional or cutback release determined from the method above has to be adjusted due to the effects of evaporation and bank storage and the distribution of the additional or cutback release over ADIP, which will be mentioned in next section.

Starting from the first month of ADIP Type I, the upper and lower reservoir initial storages are the determining factor to tell whether the additional release from either the upper or lower reservoir or both is needed based on the selected probability criteria. Suppose that the additional release from the upper reservoir is decided in order not to violate the upper reservoir spill probability criteria. The effect of the upper reservoir additional release on the lower reservoir has to be examined to determine whether it may cause the lower reservoir spill exceedance probability to exceed the lower reservoir spill probability criteria. If this is the case, an additional release has to be made from the lower reservoir. Note that the additional releases mentioned above are first assumed to take place entirely at the beginning of the current month. However the actual additional release may take place any time or may take place uniformly during ADIP Type I instead of taking place at the beginning of the current month as assumed. The adjustment of the additional release is needed if the additional release does not take place entirely at the beginning of the month as assumed or the effects of evaporation and bank storage are not minor.

At the end of the first month of ADIP Type I, new information about the inflow and storage contents of the reservoirs are available, the apriori generated exceedance probabilities for the second month of ADIP Type I can be used to determine the probability of various levels of spill at the end of ADIP Type I and that of various levels of deficit at the end of ADIP Type II. The additional releases from both reservoirs for the second month can be determined similar to those determined for the first month of ADIP Type I. Similarly the additional releases can be updated at the beginning of each month of ADIP Type I.

The planning for cutback releases for both reservoirs during ADIP Type II can be done similarly to the planning for additional releases during ADIP Type I mentioned before. Also the cutback release plan can be updated every month.

3.5.2 Trading off Benefits Against Risks Approach

When the operational failure probability criteria is not available, the release decision of a series of two reservoirs can be assessed by trading off benefits against risks. Different levels of additional release (if the current period is in ADIP Type I) have to be examined. First it is assumed that the additional releases take place at the beginning of the current month. The additional release will have a direct effect on the initial storage. If the additional release takes place in the lower reservoir, it will effect only the lower reservoir initial storage. If it takes place in the upper reservoir, it will effect both the upper and lower reservoir initial storages. The new initial storages can be calculated by using Equations 3.1 to 3.3. With the new initial storages, the exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II can be determined from the apriori generated exceedance probabilities. The benefits, in terms of the additional release for hydropower generation and water supply use downstream and the reduction in the probability of spill at the end of ADIP type I, and risks, in term of increasing the probability of deficit at the end of ADIP Type II, associated with each level of the additional releases can be determined and compared to the case without additional release. This will be very useful information for decision maker to decide a preferable level of the additional release based on trading off benefits against risks associated with each level of the additional release.

After the upper reservoir additional release is decided, its effect on the lower reservoir has to be examined. If there is high probability of spilling from the lower reservoir, the additional release from the lower reservoir has to be made. Again different levels of additional release from the lower reservoir will be examined. The benefits and risks associated with each level of additional releases will be determined and compared to the case of no additional release. This information will help decision makers decide on a preferable level of additional release from the lower reservoir based on trading off benefits against risks.

Similarly, for ADIP Type II , if there is a high probability of deficit at the end of ADIP Type II, the cutback release should be planned. Different levels of the cutback release will be examined to see what is the benefit and risk associated with each level of the cutback release compared to the case of no cutback release. Trade offs between benefits and risks will be evaluated to decide a preferable level of cutback release. The effect of the cutback release from the upper reservoir on the lower reservoir has to be studied. If it causes high probability of deficit in the lower reservoir, the cutback release from the lower reservoir has to be decided in similar manner to that mentioned for the upper reserevoir.

In summary, this approach uses the apriori generated exceedance probabilities of spill and deficit in assessing the selected operating rule and the alternative release decisions. Consequently, the benefits in terms of the additional release for hydropower production and water supply use and the reduction in the probability and magnitude of spill at the end of ADIP Type I and the risks in term of increasing the probability and magnitude of deficit at the end of ADIP Type II associated with each of the alternatives can be identified. It is assumed in this study that decision makers are capable to trade the benefits to be obtained against the risks to be taken associated with each alternative. This task might not be easy, if the decision maker does not have a perception about the risks which is defined in this study as the probability and magnitude of operational failures (spill and deficit). However it is possible that the risks (the probability and magnitude of operational failures) can be translated into the expected cost of operational failures. Different magnitudes of spill can be simulated through a detailed simulation model to determine how much damage to the spillway and flood plains downstream will be and what will be the costs of those damages. Likewise different magnitudes of deficit can be simulated to determine how much the hydropower deficit and damage to the water uses downstream will be and what will be the cost of alternative sources of water and power. With the known probability associated with various levels of spill or deficit used in the simulation, the expected costs of spill or deficit can be calculated. The decision makers now should be able to trade the benefits against the expected cost of operational failures associated with each alternative. However this study will not cover the detail on how to translate the risks of operational failures into the expected costs of operational failures.

3.6 Method for Adjusting The Effects of Evaporation and Bank Storage

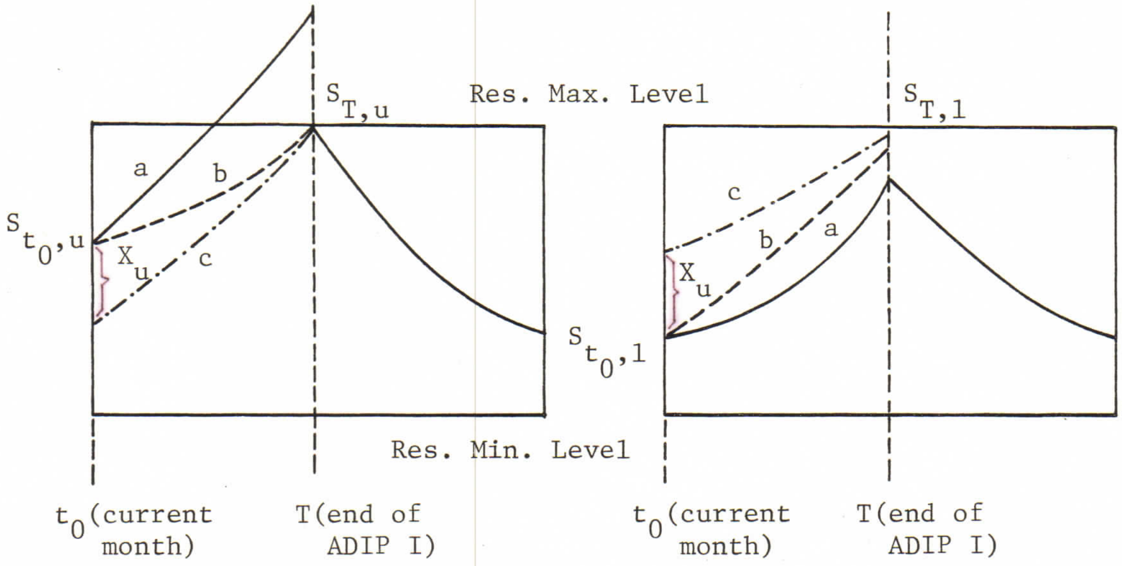
In order to use the apriori generated exceedance probabilities of spill and deficit which are conditioned on initial storage and initial month in assessing the effects of additional and cutback releases on the future state of the reservoir system, it is assumed that the additional and cutback releases take place at the beginning of the current month. According to this assumption the additional and cutback releases will cause an abrupt change in the reservoir storage and a corresponding change in the probabilities of spill and deficit at the end of ADIPs. For a case of a series of reservoirs, the additional and cutback releases from the upper reservoir will change not only the initial storage and the probabilities of spill and deficit of the upper reservoir, but those of the lower reservoir also.

Note that the assumption of having the additional and cutback releases take place at the beginning of the current month is just to facilitate the use of the apriori generated exceedance probabilities of spill and deficit in assessing the effects of the additional and cutback releases on the probabilities of future failures of a reservoir. It is not an actual desire to have the additional and cutback releases at the beginning of the current month as stated in the assumption. The actual additional and cutback releases may take place any time between the beginning of the current month and the end of the current ADIP. The schedule of the additional and cutback releases should be determined from the actual demand, the release capacity of the power plant, the economic value of the additional and cutback releases and the sale contract for water and power. However, if the evaporation and bank storage are small, it will make no difference on the amount of additional and cutback releases whether those releases occur at the beginning of the current month or uniformly occur within the current ADIP.

The problem is if the evaporation and bank storage are not small, there will be a substantial difference between assuming that the additional and cutback releases occur at the beginning of the current month and assuming that they occur uniformly during the current ADIP. If this is the case, the effects of evaporation and bank storage on the additional and cutback releases when those release schedules are different from the assumption should be determined and the adjustment should be made.

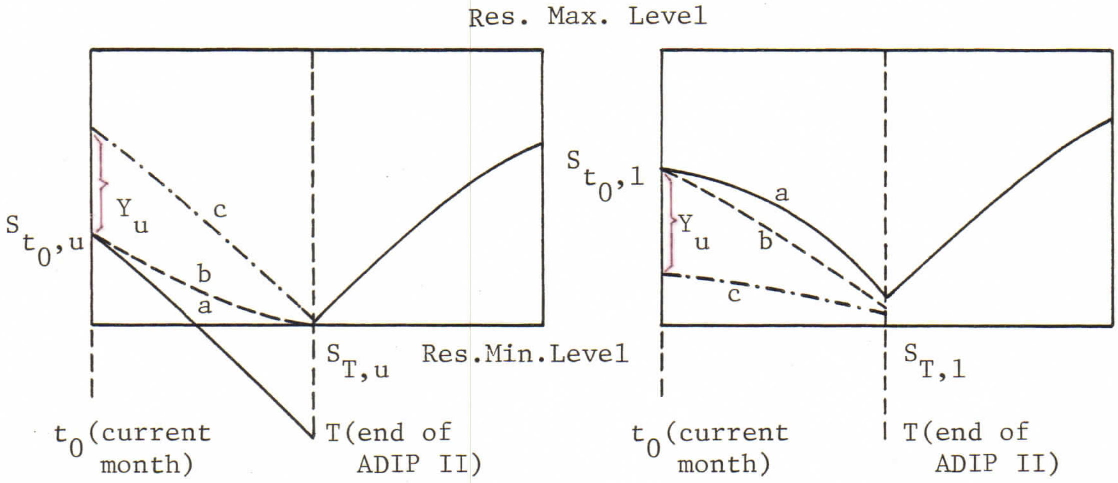
According to the assumption, the additional release from the upper reservoir would abruptly lower the upper reservoir storage and raise the lower reservoir storage by the volume of the additional release. If the actual additional release schedule does not take place at the beginning of the current month as stated in the assumption, the calculated (based on the assumption) upper reservoir evaporation will be under estimated and the calculated lower reservoir evaporation will be over estimated. The calculated bank storage loss is, on the other hand, over estimated for the upper reservoir and under estimated for the lower reservoir. The opposite is true for the cutback release. The cutback release from the upper reservoir would abruptly increase the upper reservoir storage and decrease the lower reservoir storage. The result is the calculated upper reservoir evaporation and bank storage gains are over estimated while the calculated lower reservoir evaporation and bank storage are under estimated.

To clarify the statements in the previous paragraph, see Figures 3.5 and 3.6. Suppose that the initial storages of the upper and lower reservoirs are $S_{t_0,u}$ and



(a) Upper Reservoir (u) (b) Lower Reservoir (1)

Figure 3.5 The Storage Traces in ADIP Type I for Different Upper Reservoir Additional Release(X_u) Schedules



(a) Upper Reservoir (u) (b) Lower Reservoir (1)

Figure 3.6 The Storage Traces in ADIP Type II for Different Upper Reservoir Cutback Release (Y_u) Schedules

$S_{t_0,1}$ respectively. For an additional release case, Figure 3.5, suppose that without any additional release plan, the reservoir storage traces of both the upper and lower reservoirs will follow the solid line a. Assuming that the X_u additional release from the upper reservoir takes place at the beginning of the current month, the storage traces will follow the dash-dot-dash line c. If the X_u additional release from the upper reservoir is uniformly distributed between the current month and the end of current ADIP, the storage traces will follow the dashed line b. The storage traces represented by lines a and c show the two extreme situations. At the upper reservoir, the solid line a represents the maximum calculated evaporation and the dash-dot-dash line c represents the minimum calculated evaporation. The opposite is true for the lower reservoir, the dash-dot-dash line c represents the maximum calculated evaporation and the solid line a represents the minimum calculated evaporation. The actual additional release will be between these two extreme situations such as that represented by the storage trace b.

For a cutback release case, Figure 3.6, the cutback release based on the assumption that it takes place at the beginning of the current month gives the maximum calculated evaporation in the upper reservoir (line c) but gives the minimum calculated evaporation in the lower reservoir which is the opposite to the additional release case in Figure 3.5.

The effect of additional release on the bank storage is opposite to that on the evaporation. The storage trace c in Figure 3.5 gives the maximum calculated bank storage loss in the upper reservoir but the minimum in the lower reservoir. The effect of cutback release on the bank storage is similar to that on the evaporation . The storage trace c in Figure 3.6 gives the maximum and minimum calculated bank storage gains in the upper and lower reservoirs respectively.

The adjustment on the evaporation and bank storage needs to be done whenever the assumption that the additional and cutback releases take place at the beginning of the current month is not valid, or the evaporation and bank storage are not minor.

3.6.1 Considerations for The Upper Reservoir Additional and Cutback Release Adjustment

Actually the additional and cutback release plans are more likely to follow the pattern of the storage trace b than that of the storage trace c, see Figure 3.5. However to make use of the apriori generated exceedance probabilities of spill and deficit, the additional and cutback release plans are assumed to follow the storage trace c. This is because the operating policy used in the simulation is to meet the target demand (or target release) whenever possible. Once the additional or cutback release is decided, the total release will be different from the target release and the exceedance probabilities generated by Monte Carlo simulation are not useful any more.

Therefore it has to be assumed that the additional or cutback release takes place entirely at the beginning of the current month so that the release during the rest of the current ADIP is equal to the target release. With this assumption, the apriori generated exceedance probabilities of spill and deficit are still useful. However if the evaporation and bank storage are not minor, their effects on the additional and cutback releases have to be evaluated and the adjustment is needed.

Upper Reservoir Additional Release Adjustment

Two additional release schedules are assumed for sake of comparison and adjustment. The first assumption is that the additional release takes place at the beginning of the current month as represented by the storage trace c of Figure 3.5. The second assumption is that the additional release is uniformly distributed over the current ADIP or takes place at any time between the beginning of the current month and the end of the current ADIP. By this assumption, the storage trace follows the dashed line b of Figure 3.5. It is noted that the actual additional release is likely to follow the second assumption. The mass balance of the upper and lower reservoirs are:

for the first assumption,

$$S_{T,u} = S_{t_0,u} - X_u + I_u - E_u^{\,c} - BL_u^{\,c} - R_u \tag{3.4}$$

$$S_{T,l} = S_{t_0,l} + X_u + R_u + I_l - E_l^{\,c} - BL_l^{\,c} - R_l \tag{3.5}$$

for the second assumption,

$$S_{T,u} = S_{t_0,u} - X'_u + I_u - E_u{}^b - BL_u{}^b - R_u \qquad (3.6)$$

$$S''_{T,l} = S_{t_0,l} + X'_u + R_u + I_l - E_l{}^b - BL_l{}^b - R_l \qquad (3.7)$$

where

S_T and S''_T are the final storage at the end of the current ADIP according to the first and the second assumptions respectively,

S_{t_0} is the initial storage,

I is the inflow,

E is the evaporation,

BL is the bank storage loss,

R is the target release,

X is the additional release according to the first assumption,

X' is the additional release according to the second assumption,

The subscript " u " and " l " are refering to the upper and lower reservoirs respectively, and

The superscript " b " and " c" are refering to the storage traces b (the second assumption) and c (the first assumption) respectively.

By comparing Equations 3.4 and 3.6, if the evaporation and bank storage losses are minor or $(E_u{}^c + BL_u{}^c)$ is approximately equal to $(E_u{}^b + BL_u{}^b)$, the X_u will be approximately equal to X'_u because $S_{t_0,u}$, $S_{T,u}$, I_u and R_u

are the same in both equations. The first additional release assumption can be used to represent the more realistic additional release assumption such as the second assumption.

On the other hand, if the evaporation and bank storage losses are not minor (or $E_u{}^c << E_u{}^b$ and $BL_u{}^c >> BL_u{}^b$), from Equations 3.4 and 3.6 we obtain that:

$$X'_u = X_u - (E_u{}^b - E_u{}^c) + (BL_u{}^c - BL_u{}^b)$$

where

$BL_u{}^c - BL_u{}^b = CB_u . X_u$

and CB_u is the bank storage coefficient for the upper reservoir.

Therefore the above equation can be rewritten as:

$$X'_u = X_u - (E_u{}^b - E_u{}^c) + CB_u . X_u \qquad (3.8)$$

Whenever the evaporation and the bank storage losses are not minor and the assumption that the additional release takes place at the beginning of the current month is not valid, the additional release determined from the first assumption (X_u) has to be adjusted by the differences of the evaporation and bank storage losses between the two assumptions as shown in Equation 3.8.

For the lower reservoir, if $E_l{}^c$ is much greater than $E_l{}^b$ and $BL_l{}^c$ is much less than $BL^b{}_l$, the magnitude of spill at the end of ADIP Type I according to the second assumption will be greater than that estimated by the first assumption by the amount ΔS_1 where

$$\Delta S_1 = (X'_u - X_u) + (E_1^c - E_1^b) + (BL_1^c - BL_1^b)$$

and where

$$BL_1^b - Bl_1^c = CB_1 . X_u$$

and CB_1 is the bank storage coefficient for the lower reservoir.

Therefore,

$$\Delta S_1 = (X'_u - X_u) + (E_1^c - E_1^b) - CB_1 . X_u \qquad (3.9)$$

Upper Reservoir Cutback Release Adjustment

Two assumptions on the cutback release are made similar to the case of additional release. The first assumption is the cutback release takes place at the beginning of the current month. The storage trace of this assumption follows the dash-dot-dash line c. The second assumption is the cutback release is uniformly distributed over the current ADIP or takes place at any time during the current ADIP. The storage trace of this assumption follows the dashed line b. Note that the actual cutback release schedule is more likely to follow the second assumption. The mass balance of the upper and lower reservoirs for both assumptions can be written as follows:

for the first assumption,

$$S_{T,u} = S_{t_0,u} + Y_u + I_u - E_u{}^c + BG_u{}^c - R_u \qquad (3.10)$$

$$S_{T,l} = S_{t_0,l} - Y_u + R_u + I_l - E_l{}^c + BG_l{}^c - R_l \qquad (3.11)$$

for the second assumption,

$$S_{T,u} = S_{t_0,u} + Y'_u + I_u - E_u{}^b + BG_u{}^b - R_u \qquad (3.12)$$

$$S''_{T,l} = S_{t_0,l} - Y'_u + R_u + I_l - E_l{}^b + BG_l{}^b - R_l \qquad (3.13)$$

where

Y is the cutback release according to the first assumption,

Y' is the cutback release according to the second assumption,

BG is the bank storage gain, and

S_T, S''_T, S_{t_0}, I, E, R, superscripts " b " and " c" and subscripts " l " and " u " are previously defined.

Similar to the case of the additional release, if the evaporation loss and the bank storage gain are not minor, that is $E_u{}^c$ is much greater than $E_u{}^b$ and $BG_u{}^c$ is much greater than $BG_u{}^b$, the cutback release for the upper reservoir according to the first assumption has to be adjusted by the following equation. From Equations 3.10 and 3.12 we obtain :

$$Y'_u = Y_u - (E_u{}^c - E_u{}^b) + (BG_u{}^c - BG_u{}^b)$$

where

$$BG_u{}^c - BG_u{}^b = CB_u \cdot Y_u$$

The above equation can be rewritten as:

$$Y'_u = Y_u - (E_u^c - E_u^b) + CB_u.Y_u \tag{3.14}$$

For the lower reservoir, if E_l^c is much less than E_l^b and BG_l^c is much less than BG_l^b, the magnitude of deficit at the end of ADIP Type II according to the second assumption will be greater than that estimated by the first assumption by ΔD_l where

$$\Delta D_l = (BG_l^b - BG_l^c) - (E_l^b - E_l^c) - (Y'_u - Y_u)$$

and where

$$BG_l^b - BG_l^c = CB_l.Y_u$$

Therefore

$$\Delta D_l = CB_l.Y_u - (E_l^b - E_l^c) - (Y'_u - Y_u) \tag{3.15}$$

3.6.2 Considerations for The Lower Reservoir Additional and Cutback Release Adjustments

With no additional (cutback) release from the upper reservoir, the storage of the lower reservoir follows the solid line trace a. Assuming that $X_u(Y_u)$ is the additional (cutback) release volume from the upper reservoir and it takes place at the beginning of the current month, the storage follows trace c. If the upper reservoir additional (cutback) release does not take place entirely at the beginning of the current month but is uniformly distributed over the ADIP instead, the lower reservoir storage follows trace b.

Assuming that the probability of the lower reservoir spill (deficit) is high, the additional (cutback) release for the lower reservoir has to be made to avoid the spill (deficit). If the lower reservoir additional (cutback) release is equal to $X_l(Y_l)$, the storage traces of the lower reservoir will follow lines c' or b' depending on the assumptions that the additional (cutback) release takes place at the beginning of the current month or is uniformly ditributed over the current ADIP, see Figures 3.7 and 3.8. If the evaporation and bank storage are not minor, the additional and cutback releases of traces b' and c' will be different. The adjustment for the additional and cutback releases for the lower reservoir can be done similarly to that of the upper reservoir.

Lower Reservoir Additional Release Adjustment

The mass balance of the lower reservoir for two different release assumptions can be written as follows:

for the first assumption (the lower reservoir additional release takes place at the beginning of the current month),

$$S_{T,l}=S_{t_0,l}+X'_u+R_u-X_l+I_l-E_l^{c'}-BL_l^{c'}-R_l \qquad (3.16)$$

for the second assumption (the lower reservoir additional release is uniformly distributed during the current ADIP),

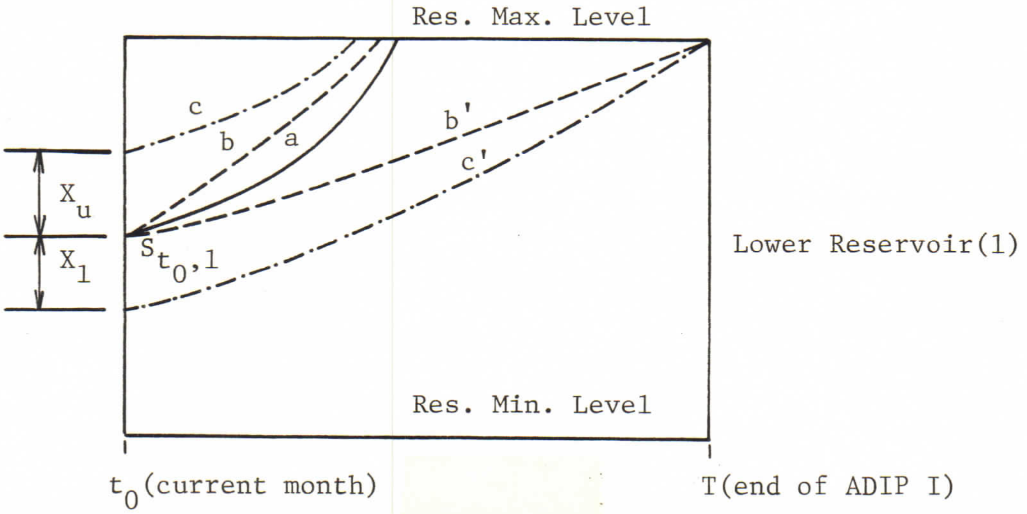


Figure 3.7 The Storage Traces in ADIP Type I of The Lower Reservoir for Different Additional Release Schedules

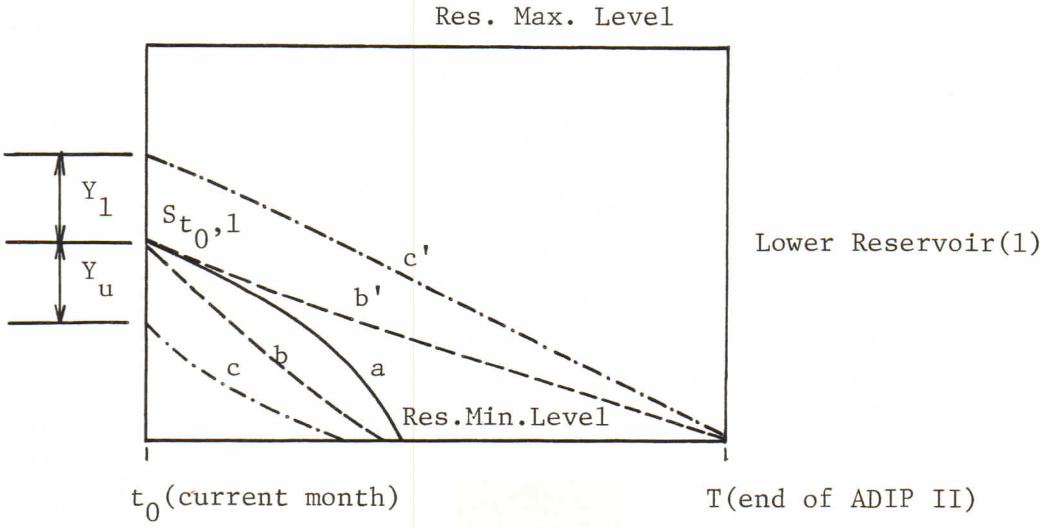


Figure 3.8 The Storage Traces in ADIP Type II of The Lower Reservoir for Different Cutback Release Schedules

$$S_{T,1}=S_{t_0,1}+X'_u+R_u-X'_1+I_1-E_1^{b'}-BL_1^{b'}-R_1 \qquad (3.17)$$

where

$S_T, S_{t_0}, X, X', R, I$, E and BL are previously defined, and the superscripts " b' " and " c' " are refering to the storage traces " b' " (the second assumption) and " c' " (the first assumption) in Figures 3.7 and 3.8 respectively.

If the evaporation and bank storage are minor or $(E_1^{c'} + BL_1^{c'})$ is approximately equal to $(E_1^{b'} + Bl_1^{b'})$, X_1 is approximately equal to X'_1. If the evaporation and bank storage are not minor or $E_1^{b'}$ is much greater than $E_1^{c'}$ and $Bl_1^{c'}$ is much greater than $BL_1^{b'}$, then from Equations 3.16 and 3.17 we obtain that,

$$X'_1 = X_1 - (E_1^{b'} - E_1^{c'}) + (BL_1^{c'} - BL_1^{b'})$$

where

$$BL_1^{c'} - BL_1^{b'} = CB_1 . X_1$$

Finally,

$$X'_1 = X_1 - (E_1^{b'} - E_1^{c'}) + CB_1 . X_1 \qquad (3.18)$$

Lower Reservoir Cutback Release Adjustment

The mass balance of the lower reservoir for two different release assumptions can be written as follows:

for the first assumption,

$$S_{T,1}=S_{t_0,1}-Y'_u+R_u+Y_1+I_1-E_1^{c'}+BG_1^{c'}-R_1 \qquad (3.19)$$

for the second assumption,

$$S_{T,l}=S_{t_0,l}-Y'_u+R_u+Y'_l+I_l-E_l^{b'}+BG_l^{b'}-R_l \qquad (3.20)$$

If the evaporation and bank storage are not minor or $E_l^{c'}$ is much greater than $E_l^{b'}$ and $BG_l^{c'}$ is much greater than $BG_l^{b'}$, then we have, from Equations 3.19 and 3.20, that

$$Y'_l = Y_l - (E_l^{c'} - E_l^{b'}) + (BG_l^{c'} - BG_l^{b'})$$

where

$$BG_l^{c'} - BG_l^{b'} = CB_l \cdot Y_l$$

Finally,

$$Y'_l = Y_l - (E_l^{c'} - E_l^{b'}) + CB_l \cdot Y_l \qquad (3.21)$$

Equations 3.18 and 3.21 can be used to adjust the additional and cutback releases when the evaporation and bank storage are not minor or the assumption that the additional or cutback release takes place at the beginning of the current month is not valid.

3.6.3 Approximation of The Adjustment for Evaporation

With the same initial condition, $S_{t_0,u}$ and $S_{t_0,l}$, and the same target release, the storage trace varies according to the random variation of inflow trace and so does the evaporation. Since the inflow is unknown (or it is only known probabilistically), the evaporation cannot be calculated accurately. To minimize the maximum error of the estimated evaporation, the mean inflow should be used in estimation of evaporation.

For various levels of the initial storages in a given month, the mass balance of both the upper and lower reservoirs are analyzed simultaneously using the mean inflow and the target demand. The total evaporation occurring between the current month and the end of the current ADIP for different levels of the initial storages is calculated. The mass balance analysis is repeated for different initial months.

Using the mean inflow of 78 years of historical records from 1906 to 1983 and the 1985 depletion schedule estimated by USBR, the total evaporation between the current month and the end of current ADIP for Lake Powell (the upper lake) for various levels of Powell initial storages and initial months are shown in Figures 3.9 and 3.10 and that for Lake Mead (the lower lake) for various levels of Mead initial storages and initial months are shown in Figures 3.11 and 3.12.

Those evaporation plots in Figures 3.9 to 3.12 can be used to approximate the difference in the evaporation of traces b and c in Equations 3.8, 3.9 , 3.14 and 3.15 which are needed for adjusting the additional and cutback releases of Lakes Powell and Mead. The evaporation of storage traces a and c can be read directly from Figures 3.9 to 3.12 since the releases of the storage traces a and c are the same as the target release used in calculating the evaporation of Figures 3.9 to 3.12. The storage trace b, on the other

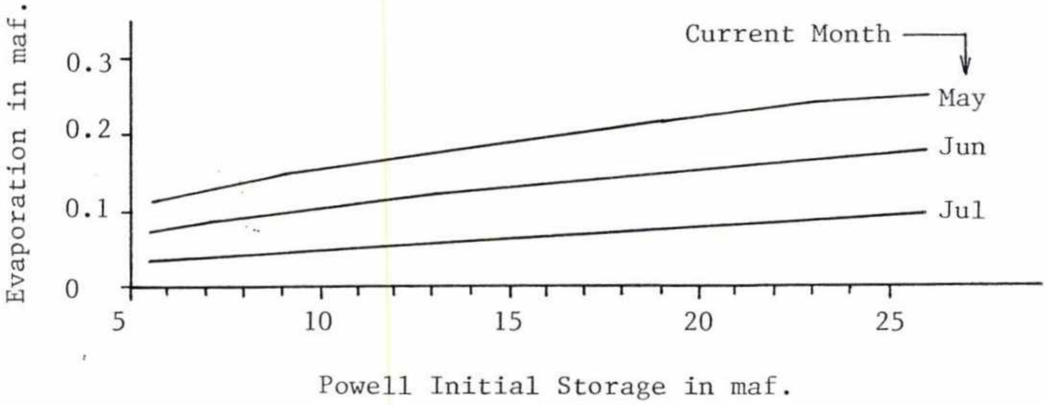


Figure 3.9 Approximated Total Powell Evaporation from The Current Month to The End of ADIP Type I (July)

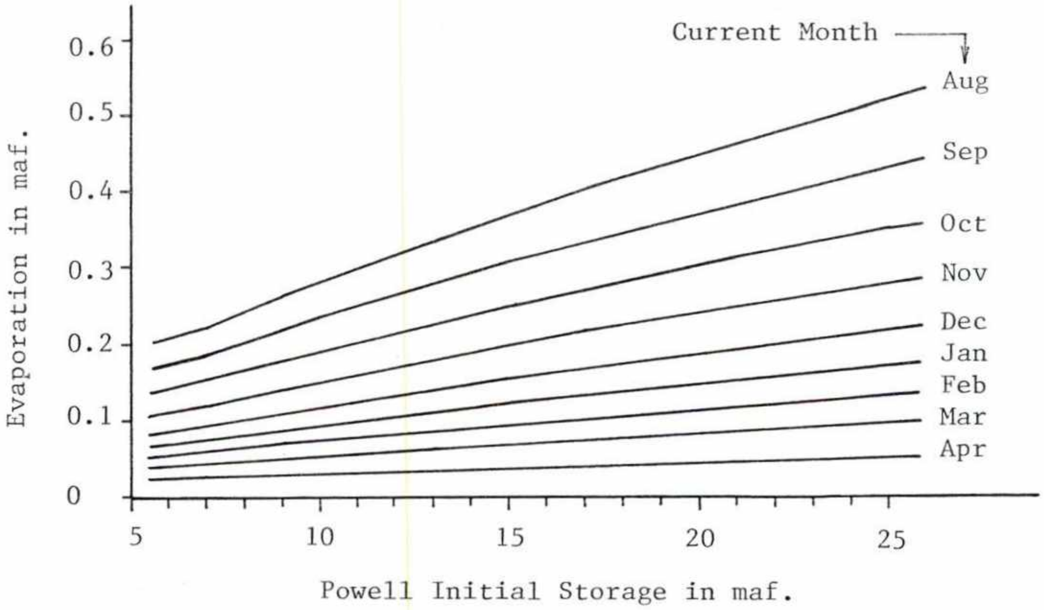


Figure 3.10 Approximated Total Powell Evaporation from The Current Month to The End of ADIP Type II (July)

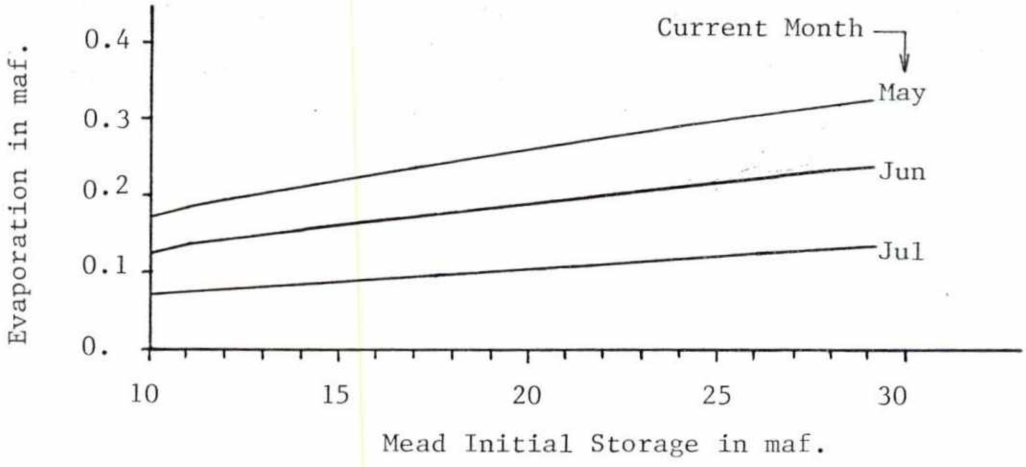


Figure 3.11 Approximated Total Mead Evaporation from The Current Month to The End of ADIP Type I(April)

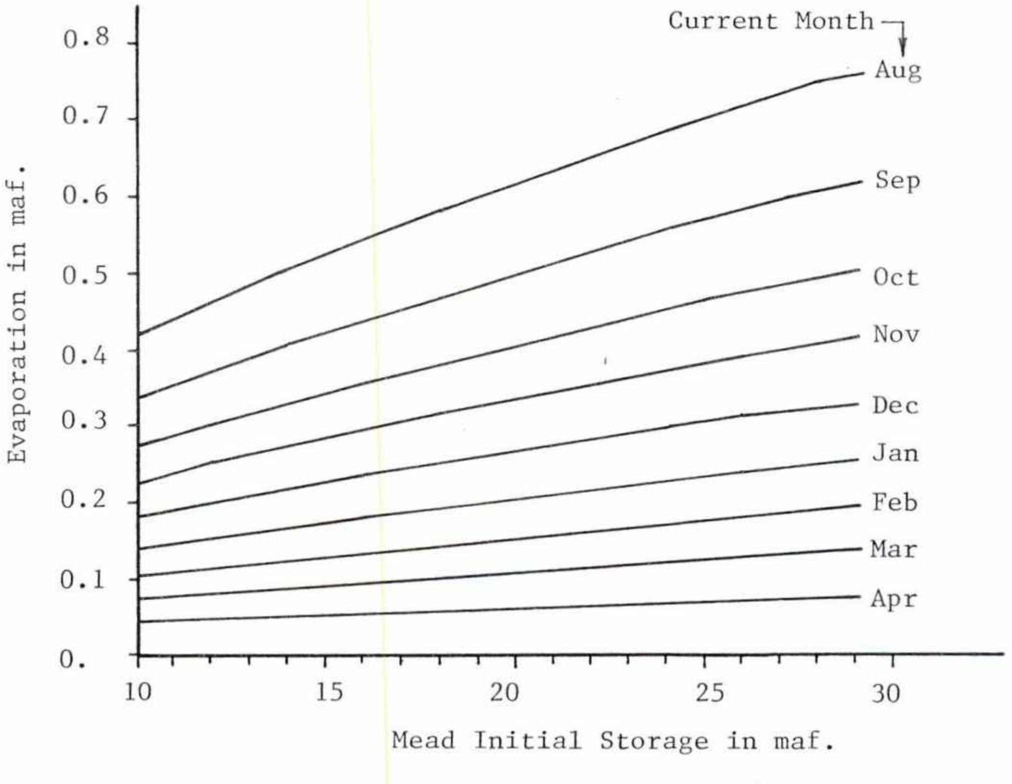


Figure 3.12 Approximated Total Mead Evaporation from The Current Month to The End of ADIP Type II(April)

hand, has the releases different from the target release because of the additional or cutback release. Although it is not known exactly what the storage trace b is unless the additional and cutback release schedules are known, it is obvious that the storage trace b will lie in between the storage traces a and c depending on how soon or how late the additional or cutback release is made. If the additional or cutback release is made early, the storage trace b will be close to the storage c. If it is made late, the storage trace b will be close to the storage trace a.

Without knowing what the storage trace b is ,it might be better to assume that the total evaporation of the storage trace b is approximately equal to the average of the total evaporation of the storage traces a and c which can be obtained from Figures 3.9 to 3.12. Based on this assumption, the adjustment for evaporation on the additional release can be approximated by:

$$(E_u^{\,b} - E_u^{\,c}) = 0.5(E_u^{\,a} - E_u^{\,c}) \qquad (3.22)$$

$$(E_l^{\,c} - E_l^{\,b}) = 0.5(E_l^{\,c} - E_l^{\,a}) \qquad (3.23)$$

and those on the cutback release can be approximated by;

$$(E_u^{\,c} - E_u^{\,b}) = 0.5(E_u^{\,c} - E_u^{\,a}) \qquad (3.24)$$

$$(E_l^{\,b} - E_l^{\,c}) = 0.5(E_l^{\,a} - E_l^{\,c}) \qquad (3.25)$$

Similarly for the lower reservoir, the storage trace b' will lie in between traces a and c', the adjustment for evaporation is approximated by the equations below:

for the additional release case,

$$(E_1^{b'} - E_1^{c'}) = 0.5(E_1^{a} - E_1^{c'}) \tag{3.26}$$

for the cutback release case,

$$(E_1^{c'} - E_1^{b'}) = 0.5(E_1^{c'} - E_1^{a}) \tag{3.27}$$

3.6.4 Illustration of The Adjustment for The Additional and Cutback Releases

To illustrate how to adjust the additional and cutback releases when the evaporation and bank storage are not minor or the assumption that those releases take place at the beginning of the current month is not valid, the following examples are presented. Assume that Lakes Powell and Mead storage contents at the beginning of May (the first month of ADIP Type I) are 25.00 and 26.00 maf (million acre-feet) respectively. Suppose that the probability of spilling from Lake Powell at the end of ADIP Type I (or July) is high. It is decided from the probabilities of spill and deficit and the benefits and risks associated with the additional release that a total of 2.00 maf additional release will be made. Based on the first assumption, Powell storage at the beginning of May will decrease to 23.00 maf.

Consider that the evaporation and bank storage losses are not minor. The adjustment on 2.00 maf additional release from Lake Powell is needed. According to Equation 3.8,

$$X'_u = X_u - (E_u{}^b - E_u{}^c) + CB_u \cdot X_u$$

where

X_u is 2.00 maf additional release volume from Lake Powell,

$$(E_u{}^b - E_u{}^c) = 0.5(E_u{}^a - E_u{}^c)$$

From Figure 3.9 , we obtain that

$E_u{}^a$ = 0.245 maf (where Powell storage is 25.00 maf at the beginning of May),

$E_u{}^c$ = 0.240 maf (where Powell storage is 23.00 maf at the beginning of May),

$CB_u = 0.08$

Finally,

$$X'_u = 2.0 - 0.5(0.245-0.240) + 0.08*2.0$$

$$X'_u = 2.0 - 0.0025 + 0.16$$

$$= 2.1575 \text{ maf.}$$

The final additional release is 2.16 maf instead of 2.00 maf because the additional release is not made immediately at the beginning of May. It is noted from the number above that the effect of evaporation itself is small compared to the bank storage loss.

The 2.16 maf Powell additional release which is uniformly distributed between the beginning of May and the end of ADIP Type I is equivalent to the 2.00 maf additional release which takes place at the beginning of May. According to the first assumption, the 2.00 maf additional release from Lake Powell will decrease the Powell initial storage to 23.00 maf and increase the Mead initial storage to 28.00 maf at the beginning of May. With the new initial storages, the exceedance probabilities of Mead spill and deficit can be obtained from the apriori generated exceedance probabilities in Tables B1 to B12 of Appendix B. If the evaporation and bank storage of Lake Mead are not minor, the magnitude of Mead spill at any exceedance probability level has to be adjusted since the actual additional release from Lake Powell does not really take place at the beginning of May. The magnitude of Mead spill at the end of ADIP Type I will be increased approximately by

$$\Delta S_1 = (X'_u - X_u) + (E_1^c - E_1^b) - CB_1 . X_u$$

where

$X'_u = 2.16$ maf

$X_u = 2.00$ maf

$CB_1 = 0.065$

$(E_1^c - E_1^b) = 0.5(E_1^c - E_1^a)$

From Figure 3.11 ,

$E_1^c = 0.32$ maf (where Lake Mead initial storage is 28.00 maf at the beginning of May),

$E_1^a = 0.305$ maf (where Lake Mead initial storage is 26.00 maf at the beginning of May).

Finally, we get

$$\Delta S_1 = (2.16-2.00) + 0.5(0.32-0.305) - 0.065(2.00)$$
$$= 0.16 + 0.0075 - 0.13$$
$$= 0.0375 \text{ maf.}$$

Therefore the magnitude of Lake Mead spill at the end of ADIP Type I for any given exceedance probability of spill will increase approximately by 0.0375 maf compared to the magnitude of spill read from the storage trace c (the first assumption).

To illustrate how to adjust the additional release for Lake Mead, assume that after deciding to make 2.00 maf additional release from Lake Powell (based on the first assumption) the new initial storages of Lakes Powell and Mead are 23.00 and 28.00 maf, respectively. With these new initial storages at the beginning of May, suppose that there is very high probability of spilling from Lake Mead by the end of ADIP Type I and it is decided to make 3.00 maf additional release from Lake Mead.

Consider that the evaporation and bank storage losses are not minor. The adjustment on 3.00 maf additional release from Lake Mead is needed. According to Equation 3.18,

$$X'_1 = X_1 - (E_1^{b'} - E_1^{c'}) + CB_1 . X_1$$

where

X_1 = 3.00 maf additional release from Lake Mead based on the first assumption,

$(E_1^{b'} - E_1^{c'}) = 0.5(E_1^{a} - E_1^{c'})$

From Figure 3.11,

E_1^{a} = 0.305 maf (where Lake Mead initial storage is 26.00 maf at the beginning of May),

$E_1^{c'}$ = 0.285 maf (where Lake Mead initial storage is 23.00 maf at the beginning of May), and

$CB_1 = 0.065$

Finally , we get that

$$\begin{aligned} X'_1 &= 3.0 - 0.5(0.305 - 0.285) + 0.065(3.00) \\ &= 3.0 - 0.5*0.02 + 0.065*3.0 \\ &= 3.185 \text{ maf.} \end{aligned}$$

Therefore with Lakes Powell and Mead initial storages of 25.00 and 26.00 maf at the beginning of May, 2.16 maf additional release for Lake Powell and 3.19 maf for Lake Mead are recommended based on the assumption that the additional releases are uniformly distributed over the ADIP.

Similarly to the adjustment for the additional release, the adjustment for the cutback release can be made.

3.7 Incorporation of A Forecast Into the ADIP Concept

The fundamental of the ADIP-based method is based on the apriori generated distribution of the future states which depend on the selected operating plan, the current conditions and the system stochasticity. The probable disposition of the future states for a given current condition can be useful to evaluate the risks of the present operating plan. If the probability of heavy spill is high, we should start releasing more water from the present to the end of period of spill. By doing so, an additional benefit from that additional release will be obtained and the probability and magnitude of heavy spill (flooding) will be reduced. However the benefit of the additional release has to be weighed against the adverse effects which will be created by the additional release. On the other hand, if the probability of a large deficit is high, the release should be cutback in such a way that the deficit is distributed over the period of deficit instead of having one or two severe deficits.

The distribution of the future states (or future operational failures) is generated from the entire stochasticity of inflow. This gives the general idea of all the future possibility of the system states and operational failures. Although this information is useful, it is not very concise and may not be very efficient to use for decision making. The forecast technology can narrow down the range of stochasticity of inflow. Actually if the forecast is perfect, one knows exactly what the future inflow is and one can use an optimization technique to find the optimum operating plan. The ADIP-based method becomes useless. However there exists an error in any forecast and the error becomes bigger when the lead time of the forecast is long into the future. Using the ADIP-based method for establishing the operating plan will become more effective when used with the forecasted information.

According to the ADIP concept, the future states (or the future operational failures) of a system can be predicted for a given initial condition. As presented in Figure 3.13, the initial storage at the beginning of ADIP Type I (or the end of April) is S_{t_0}. The ADIP Type I end storages vary from points "a" to "b" depending on the variation of May to July inflow traces (May-July are ADIP Type I). Point " a " is the result of the highest inflow

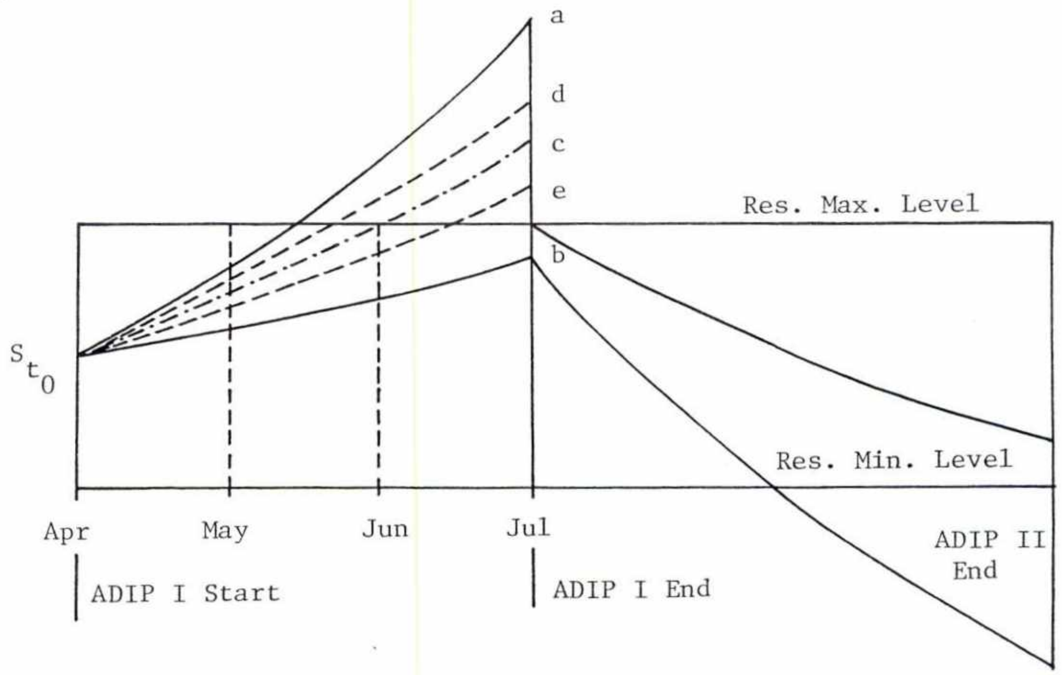


Figure 3.13 The Storage Traces Generated from Monte Carlo Simulation and The Forecasted Inflow

trace and point " b " is the result of the lowest inflow trace. The intermediate inflow traces result in the end of ADIP Type I storages between points " a " and " b ".

If the forecast of inflow from May to July is available, the forecasted storage trace for ADIP Type I can be determined from the monthly mass balance analysis of May to July. The forecasted ADIP Type I ending storage is represented by point " c " in Figure 3.13. The confidence limits of the forecasted ADIP Type I ending storages, represented by points " d " and " e " in Figure 3.13, can be determined from the mass balance of the confidence limits of the forecasted inflow. It can be seen from Figure 3.13 that the forecasted ADIP Type I ending storage and its confidence limits are only the subset of the ADIP Type I ending storage generated from the entire stochastic variation of May to July inflow traces. The forecast of inflow excludes the very small probability of future states and future operational failures of the system from consideration. Note that if the excluded event is realized, the adverse effect can be serious.

The method to incorporate the forecast into the ADIP concept was first introduced by Scott(1983). He proposed the equation to calculate a surrogate initial storage content due to the deviation of the forecasted monthly inflow from the mean monthly inflow and the deviation of the forecasted monthly release from the monthly target release over the period of current ADIP as shown below.

$$S'_{t_0} = S_{t_0} - \Delta I - \Delta R \tag{3.28}$$

where

S_{t_0} is the actual current monthly storage,

S'_{t_0} is the recalculated current monthly storage,

ΔI is the forecasted cumulative change in monthly inflow over an ADIP and where, say,

$$\Delta I = \sum_{i=\text{ADIP start}}^{\text{ADIP end}} (\bar{y}_i - fy_i) \text{ and where}$$

$\bar{y}_i$ is the mean monthly inflow,

fy_i is the forecasted monthly inflow,

ΔR is the forecasted cumulative change in monthly releases over an ADIP and where, say,

$$\Delta R = \sum_{i=\text{ADIP start}}^{\text{ADIP end}} (cd_i + x_i) \text{ and where}$$

$cd_i = (ar_i - \text{Max}\{\alpha_i X, \beta_i E_f/\xi_i\})$ and where

ar_i is the actual requested water releases which may be different from the long term contracted release which is $\text{Max}\{\alpha_i X, \beta_i E_f/\xi_i\}$

$\alpha_i X$ is the monthly contracted release for water and

$\beta_i E_f/\xi_i$ is the monthly contracted release for energy

x_i is the additional release.

Suppose the ΔR is zero (no deviation of the forecasted monthly release from the monthly target release over an ADIP) and the forecasted monthly inflow is greater than the mean monthly, the surrogate current initial storage S'_{t_0} will be greater than the actual current monthly storage S_{t_0} by ΔI. Given that the initial storage at the beginning of ADIP Type I is S_{t_0}, the storage contents at the end of ADIP Type I are assumed to lie in between points " a " and " b " in Figure 3.14 depending on the variation of inflow traces during ADIP Type I. With the same stochastic property of the inflow traces and the same target release, the surrogate

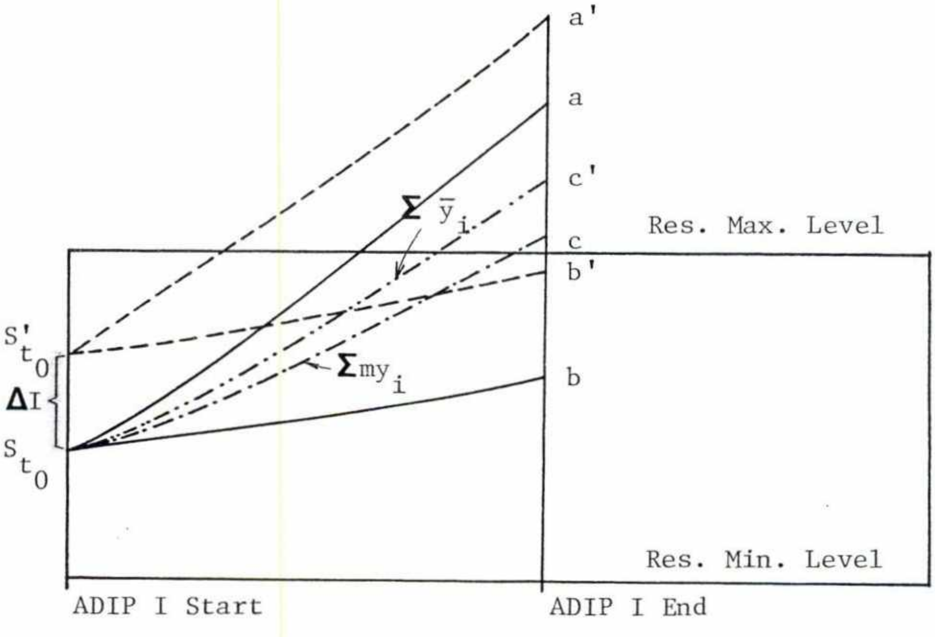


Figure 3.14 The Actual Storage Traces Versus The Surrogate Storage Traces

initial storage S'_{t_0} gives the storages at the end of ADIP Type I between points " a' " and " b' ", as shown in Figure 3.14.

ADIP Type I ending storages between points " a' " and "b'" are only the surrogate ending storages. Physically, even though the forecasted monthly inflow is greater than the mean monthly inflow, it cannot produce the ADIP Type I ending storage out of the range of points " a " and " b ". This is because the ADIP Type I ending storages between points " a " and " b " are determined from all possible inflow traces. The mean inflow trace and the forecasted inflow trace are only parts of the inflow traces used for determining the ADIP Type I ending storages between points " a " and " b " . The Scott's reason for using the surrogate storage S'_{t_0} is that whenever the forecasted inflow trace is greater than the mean inflow trace, the probability of spill at the end of ADIP Type I should be higher than the apriori generated exceedance probability of spill indicates. Scott's method of using the surrogate initial storage can only give the surrogate exceedance probability of spill, when the forecasted inflow is considered, not the true value of the exceedance probability of spill.

On the other hand, when the forecasted inflow is less than the mean inflow, the surrogate initial storage S'_{t_0} will be smaller than the actual current storage S_{t_0}. The exceedance probability of spill associated with the S'_{t_0} will be smaller than that of spill associated with the S_{t_0}.

Opposite to the case of spill, the smaller S'_{t_0} gives the larger exceedance probability of deficit and the bigger S'_{t_0} gives the smaller exceedance probability of deficit.

In this study, a differrent method for incorporation of forecasted information into the ADIP concept is presented. This method works on the approximate value of the exceedance probability of spill (or deficit) instead of the surrogate value. The basis of this method is that the forecasted cumulative inflow from the current month to the end of the current ADIP can be divided into 4 quartiles; upper quartile (highest inflow trace), second quartile, third quartile and lower quartile (lowest inflow trace). Also the distribution of the operational failure (spill/deficit) at the end of ADIP can be divided into 4 quartiles. The quartiles of the spill at the end of ADIP Type I are defined as:

The exceedance probability of spill	Quartiles
0 to <0.25	upper
o.25 to <0.50	second
0.50 to <0.75	third
0.75 to <1.00	lower

The quartiles of the deficit at the end of ADIP Type II are defined in opposite way as:

The exceedance probability of deficit	Quartiles
0.75 to <1.00	upper
0.50 to <0.75	second
0.25 to <0.50	third
0 to <0.25	lower

It is assumed that the upper, second, third and lower quartiles of the spill at the end of ADIP Type I are produced by the upper, second, third and lower quartiles of the cumulative inflow from the current month to the end of the current ADIP Type I. Similarly the upper, second, third and lower quartiles of the deficit at the end of ADIP Type II are produced by the upper, second, third and lower quartiles of the cumulative inflow from the current month to the end of the current ADIP Type II.

The forecast of inflow will be used for adjusting the apriori generated exceedance probabilities of operational failure (spill/deficit) based on the assumption given in the previous paragraph. When the forecasted cumulative inflow over an ADIP falls within one of the 4 quartiles, let say the second quartile, the exceedance probability of operational failure (spill/deficit) of that quartile will assume the adjusted exceedance probability of operational failure of 0 to 1.0 . The zero is the adjusted exceedance probability of the lowest exceedance probability of that quartile (0.25 for the second quartile of the spill) and 1.00 is the adjusted exceedance probability of the highest exceedance probability of that quartile (<0.50 for the second quartile of the spill). The exceedance probability of operational failure outside that quartile is assumed to be zero.

To ease the way to adjust the exceedance probability of operational failure (spill/deficit), the following formula are suggested. The formula for adjusting the exceedance probability of spill at the end of ADIP Type I, $P[S \geq s]$, based on the forecast of inflow trace over ADIP Type I are :

(1) if the forecasted inflow trace is in the upper quartile,

$$P'[S \geq s] = P[S \geq s]*4 \qquad (3.29)$$

(2) if the forecasted inflow trace is in the second quartile,

$$P'[S \geq s] = \{P[S \geq s] - 0.25\}*4 \qquad (3.30)$$

(3) if the forecasted inflow trace is in the third quartile,

$$P'[S \geq s] = \{P[S \geq s] - 0.50\}*4 \qquad (3.31)$$

(4) if the forecasted inflow trace is in the lower quartile,

$$P'[S \geq s] = \{P[S \geq s] - 0.75\}*4 \qquad (3.32)$$

Whenever the adjusted exceedance probability of spill at the end of ADIP Type I, $P'[S \geq s]$, is greater than 1.0 or less than 0, it is assumed to be zero.

The formula for adjusting the exceedance probability of deficit at the end of ADIP Type II, $P'[D \geq d]$, based on the forecast of inflow trace over ADIP Type II are:

(1) if the forecasted inflow trace is in the upper quartile,

$$P'[D\geq d] = \{P[D\geq] - 0.75\}*4 \tag{3.33}$$

(2) if the forecasted inflow trace is in the second quartile,

$$P'[D\geq d] = \{P[D\geq d] - 0.50\}*4 \tag{3.34}$$

(3) if the forecasted inflow trace is in the third quartile,

$$P'[D\geq d] = \{P[D\geq d] - 0.25\}*4 \tag{3.35}$$

(4) if the forecasted inflow trace is in the lower quartile,

$$P'[D\geq d] = P[D\geq d]*4 \tag{3.36}$$

Whenever the adjusted exceedance probability of deficit at the end of ADIP Type II, $P'[D\geq d]$, is greater than 1.0 or less than 0, it is assumed to be zero.

To illustrate how to adjust the exceedance probability of spill and deficit, two examples are presented .

Example 1 Given that the Powell storage at the beginning of May (the first month of ADIP Type I) is 22.00 maf, the exceedance probabilities of various levels of spill at the end of July (the last month of ADIP Type I) are:

$P_{22.00}[S\geq 0] = 0.33$

$P_{22.00}[S\geq 1.00] = 0.22$

$P_{22.00}[S\geq 2.00] = 0.13$

$P_{22.00}[S\geq 3.00] = 0.08$

If the forecasted cumulative inflow during ADIP Type I (from May to July) falls into the upper quartile, the adjusted exceedance probabilities of spill at the end of July are:

$P'_{22.00}[S \geq 0] = 0.33*4 =$ ~~1.32~~ 0

$P'_{22.00}[S \geq 1.00] = 0.22*4 = 0.88$

$P'_{22.00}[S \geq 2.00] = 0.13*4 = 0.52$

$P'_{22.00}[S \geq 3.00] = 0.08*4 = 0.32$

If the forecatsed cumulative inflow from May to July falls into the second quartile, the adjusted exceedance probabilities of spill at the end of July are;

$P'_{22.00}[S \geq 0] = (0.33 - 0.25)*4 = 0.32$

$P'_{22.00}[S \geq 1.00] = (0.22 - 0.25)*4 =$ ~~-0.12~~ 0

$P'_{22.00}[S \geq 2.00] = (0.13 - 0.25)*4 =$ ~~-0.48~~ 0

$P'_{22.00}[S \geq 3.00] = (0.08 - 0.25)*4 =$ ~~-0.68~~ 0

If the forecasted cumulative inflow from May to July falls into the third or lower quartile, the adjusted exceedance probabilities of spill at the end of July are all zero.

Example 2 Given that the Powell storage at the beginning of August (the first month of ADIP Type II) is

6.00 maf, the exceedance probabilities of deficit at the end of April (the last month of ADIP Type II) are:

$P_{6.00}[D \geq 0] = 0.80$

$P_{6.00}[D \geq 1.00] = 0.55$

$P_{6.00}[D \geq 2.00] = 0.11$

$P_{6.00}[D \geq 3.00] = 0.01$

If the forecasted cumulative inflow during ADIP Type II (from August to April) falls into the upper quartile, the adjusted exceedance probabilities of deficit at the end of April are;

$P'_{6.00}[D \geq 0] = (0.80 - 0.75)*4 = 0.20$

$P'_{6.00}[D \geq 1.00] = (0.55 - 0.75)*4 =$ ~~-0.80~~ 0

If the forecasted cumulative inflow from August to April falls into the second quartile, the adjusted exceedance probabilities of deficit at the end of April are;

$P'_{6.00}[D \geq 0] = (0.80 - 0.50)*4 =$ ~~1.20~~ 0

$P'_{6.00}[D \geq 1.00] = (0.55 - 0.50)*4 = 0.20$

$P'_{6.00}[D \geq 2.00] = (0.11 - 0.50)*4 =$ ~~-1.56~~ 0

If the forecasted cumulative inflow from August to April falls into the third quartile, the adjusted exceedance probabilities of deficit at the end of April are;

$$P'_{6.00}[D \geq 0] = (0.80 - 0.25)*4 = \cancel{2.20}\ 0$$

$$P'_{6.00}[D \geq 1.00] = (0.50 - 0.25)*4 = 1.00$$

$$P'_{6.00}[D \geq 2.00] = (0.11 - 0.25)*4 = \cancel{-0.56}\ 0$$

If the forecasted cumulative inflow from August to April falls into the lower quartile, the adjusted exceedance probabilities of deficit at the end of April are;

$$P'_{6.00}[D \geq 0] = 0.80*4 = \cancel{3.2}\ 0$$

$$P'_{6.00}[D \geq 1.00] = 0.50*4 = \cancel{2.0}\ 0$$

$$P'_{6.00}[D \geq 2.00] = 0.11*4 = 0.44$$

$$P'_{6.00}[D \geq 3.00] = 0.01*4 = 0.04$$

The method for using the forecast of inflow to update the apriori generated exceedance probability of operational failures mentioned above is for the case of a single reservoir. However this method can be applied to a case of two reservoirs in series when it is assumed that the side flow (intervening flow) to the lower reservoir is small compared to the inflow to the upper reservoir. When the forecast of inflow to the upper reservoir is made, it can be used for adjusting the apriori generated exceedance probability of operational failures of the upper reservoir first by the method explained previously.

Assume that a target release rule is used for operating a series of two reservoirs, that is the upper reservoir will release water to the lower reservoir according to the target release as long as spill and deficit do not occur. If the inflow trace is close to the mean inflow trace, it may not cause any spill or deficit from the upper reservoir, the release from the upper reservoir will be the same as the target release. Spill or deficit in the lower reservoir will not be expected. When the inflow to the upper reservoir is large, there is more probability of spilling to the lower reservoir. The lower reservoir receives more water from the upper reservoir and the probability of spilling from the lower reservoir becomes larger. Similarly when the inflow to the upper reservoir is small, the probability of deficit in the upper reservoir becomes larger. That will create a higher probability of deficit in the lower reservoir also. This is because the inflow to the lower reservoir depends on the release from the upper reservoir.

Based on the above assumptions, the future characteristics of operational failure (spill/deficit) of the lower reservoir depends on the inflow to the upper reservoir. On the basis of this conclusion it can be said that the upper, second, third and lower quartiles of the spill at the end of ADIP Type I (or those of the deficit at the end of ADIP Type II) of the lower reservoir are produced by the upper, second, third and lower quartiles of the upper reservoir cumulative inflow over an ADIP. The adjustment to the apriori generated exceedance probability of spill/deficit of the lower reservoir can be done exactly the same as that of the upper reservoir based on the forecasted cumulative inflow to the upper reservoir.

CHAPTER IV

APPLICATION OF THE METHODOLOGY TO THE COLORADO RIVER SYSTEM (POWELL AND MEAD IN SERIES)

This chapter will demonstrate the use of the methodology developed in Chapter 3 for a series of two reservoirs. It will include how to identify the time frame for reservoir operation decision making called ADIP for a series of two reservoirs, how to generate the characteristics of the future operational failures which are conditioned on the present conditions and how to use the apriori generated future operational failure (spill/deficit) characteristics to set up the operational plan for a series of two reservoirs.

The Colorado River System is chosen to be the case study. Although there are a number of reservoirs linked in series and parallel in the Colorado River Basin, the study will focus on a series of two large reservoirs, Lakes Powell and Mead. Lakes Powell and Mead are defined, in this study, as large reservoirs because the total storage capacities are much larger than the mean annual inflows and the projected annual demands. Lakes Powell and Mead have a combined total storage volume (including the dead storage) of 55 maf (million acre feet) while the total mean annual inflow is

15.8 maf and the projected depletion schedule of 1985 is 11.2 maf.

4.1 Background of The Colorado River System Operations.

The Colorado River System is operated based on the " Law of the River ", a series of treaties, compacts, decisions and regulations which govern operations of the river. The " Law of the River" establishes the priority of the competing purposes served by the river system and balances the demands on the system 's water supply among the seven Basin States and Mexico. Although conflicts among these purposes are common, the generally accepted priorities for operations of the system are minimum flood control, water supply (including compact requirements), power generation and recreation[1].

The operations of Lakes Powell and Mead in particular are determined by the forecast of inflow to Lakes Powell and Mead, and the objectives of meeting the minimum downstream demands below Lake Mead, satisfying the minimum flood control requirements for Lake Mead (a minimum of 5.35 maf on January 1st according to the Corps of Engineers Flood Control Regulations for Hoover dam, this 5.35 maf flood control space can be shared in part by the upstream storage

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[1] The 1984 Colorado River Operation Study (Draft), The United States Bureau of Reclamation, Denver, Colorado 1985.

reservoirs), achieving an assumed minimum objective release of 8.23 maf. per year from Lake Powell (specified by the criteria for Coordinated Long Range Operation of Colorado River Storage Reservoirs), and balancing the contents of Lakes Powell and Mead by the end of September so long as the storage levels in the upper basin are kept above levels determined by the Secretary of the Interior to satisfy Section 602(A) of Public Law 90-537.

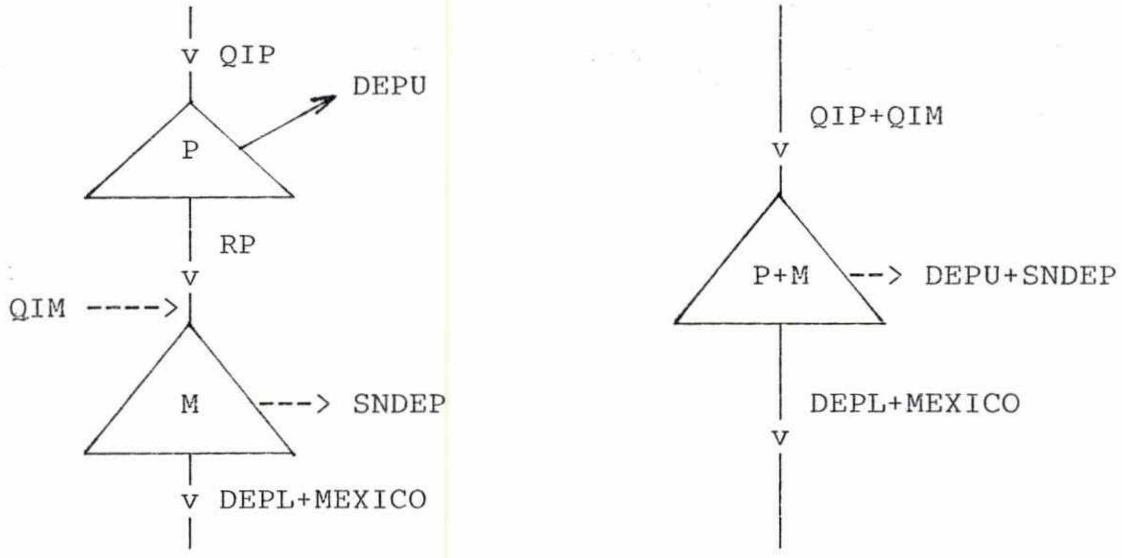
4.2 Identification of ADIP for Lakes Powell and Mead

According to the criteria for identifying the ADIP given in section 3.2.3, ADIP Type I is the period where the inflow is most likely greater than or equal to the target release during a year and ADIP Type II is the period where the inflow is most likely less than the target release during a year. There are two approaches to identify the ADIP for Lakes Powell and Mead in series. The first approach considers Lakes Powell and Mead as a single equivalent reservoir and identifies the ADIP of a single equivalent reservoir from the aggregated inflow and the aggerated outflow. The second approach considers the upper reservoir (Lake Powell) as an independent reservoir and identifies the ADIP of Lake Powell first from the inflow and the target release of Lake Powell. Since most of the inflow into the lower reservoir (Lake Mead) is not random, but rather regulated by the upper reservoir (Lake Powell), the

ADIP of Lake Mead cannot be identified independently from Lake Powell. As a matter of fact, a spill from Lake Mead will occur only when the aggregated inflow is greater than the aggregated outflow and the aggregated available empty space in both lakes. A deficit from Lake Mead will occur only when the aggregated inflow and aggregated available storage are less than the aggregated target release. Therefore the ADIP of Lake Mead should be identified from the aggregated inflow and the aggregated outflow or simply the ADIP of Lake Mead is the same as a single equivalent reservoir ADIP mentioned in the first approach. The first approach gives the same ADIP for both Lakes Powell and Mead while the second approach may give different ADIPs.

For the case of Lakes Powell and Mead, the mean annual flow (natural flow) at Lees Ferry (a few miles downstream of Lake Powell) during 1906-1983 is approximately 15.0 maf. The intervening flow between Lake Powell and Lake Mead is comprised of 5 components, the natural flows of the Paria River, Little Colorado River, Virgin River, Blue Springs and Gains at Lake Mead. Total mean annual intervening flow to Lake Mead during 1906-1983 is 0.84 maf. The intervening flow is small compared to the inflow to Lake Powell. The spill and deficit of Lake Powell are dictated by the inflow and the target release of Lake Powell and the spill and deficit of Lake Mead are dictated by Lake Powell release and demand downstream from Lake Mead since the intervening flow is small. The target release from Lake Powell is usually determined from the lower basin demands. It should not result in heavy spill or deficit in Lake Mead if Lake Powell target release is maintained. Spill or deficit in Lake Mead will take place only when a spill or deficit takes place in Lake Powell. Simply the spill and deficit characteristics of Lake Mead should correspond to those of Lake Powell. Considering all these facts, Lakes Powell and Mead should have the same ADIP which is identified from the aggregated inflow and the aggregated outflow of a single equivalent reservoir representing Lakes Powell and Mead based on the criteria for identifying ADIP given in section 3.2.3.

Figure 4.1 shows the components of inflow-outflow of Lakes Powell and Mead in series via the aggregated inflow-outflow of the single equivalent reservoir representing Lakes Powell and Mead. Five-hundred years of synthetically generated monthly flow at Lees Ferry and intervening flow to Lake Mead were used for identification of the ADIP. The details of flow generation are given in section 4.3.1. The 1985 depletion schedules of the system of Lakes Powell and Mead estimated by the USBR are used to represent the target demands of the system. By comparing the monthly aggregated inflow to the monthly aggregated demand of Lakes Powell and Mead for 500 years, the frequency of the beginning months of ADIP Type I and II are determined by Subroutine FIADIP. Note that this frequency is calculated from the number of times the aggregated inflow is first greater than or equal to the aggregated demand or is first less than the demand in



(a) Powell and Mead in Series (b) Powell-Mead Equivalent Reservoir

Criteria for Identifying ADIP

ADIP Type I : $QIP + QIM \geq DEPU + SNDEP + DEPL + MEXICO$

ADIP Type II : $QIP + QIM < DEPU + SNDEP + DEPL + MEXICO$

Notation

QIP is the inflow to Lake Powell (P).

QIM is the intervening flow between Powell and Mead (M).

RP is the target release from Lake Powell.

DEPU is the depletion schedule for the upper basin.

DEPL is the depletion schedule for the lower basin.

SNDEP is the depletion schedule for the Southern Nevada.

MEXICO is the delivery schedule for Mexico.

Figure 4.1 The Components of Inflow - Outflow of Powell and Mead in Series Via Those of Powell - Mead Equivalent Reservoir.

500 years. The month which has the highest frequency of inflow first greater than or equal to the demand is the beginning month of ADIP Type I. The month which has the highest frequency of inflow first less than the demand is the beginning month of ADIP Type II.

Using 500 years of generated monthly inflows and the 1985 USBR projected depletion schedule, the most probable beginning months of ADIP Type I and II are January and February respectively. According to the stochastic pattern of inflow and the criteria used in identification of the ADIP, it appears that only January is classified as ADIP Type I and the period from February to December is classified as ADIP Type II. However when considering the inflows themselves, January is the driest month on the average over 500 years of generated inflows. Since the projected demand of January is the lowest of the year, this leads to the situation where January has the highest frequency to be the first month of ADIP Type I but a spill will never actually take place in January. To avoid choosing January as ADIP Type I, an additional criteria was established, that is ADIP Type I and ADIP Type II must have a period of more than one month. With this additional criteria, the relative frequency of inflow first greater than or equal to the demand and the relative frequency of inflow first less than the demand of each month of the year are shown in Table 4.1. May which has the highest relative frequency of inflow first greater than or equal to the

Table 4.1 The Relative Frequencies of Inflow First Greater Than or Equal to The Demand and Inflow First Less Than The Demand of Each Month of The Year

Month	The Relative Frequencies (%) of	
	Inflow First Greater Than or Equal to The Demand	Inflow First Less Than The Demand
Oct.	10.6	9.0
Nov.	6.2	6.2
Dec.	0.4	27.0
Jan.	21.4	1.0
Feb.	10.0	2.8
Mar.	9.0	4.2
Apr.	27.4	0.6
May	29.0	0.2
Jun.	6.0	1.6
Jul.	0.2	14.0
Aug.	0.0	34.8
Sep.	3.4	13.4

demand is the beginning month of ADIP Type I. August which has the highest relative frequency of inflow first less than the demand is the beginning month of ADIP Type II. Therefore,

ADIP Type I is the period from May to July, and

ADIP Type II is the period from August to April.

However, when considering Table 4.1, the relative frequency of April is only slightly less than that of May. The sensitivity of changing the ADIP on the generated exceedance probabilities is discussed in section 4.3.4.

The ADIP of the Lake Powell and Mead equivalent reservoir will change according to the change in the target demand. The sensitivity of the Powell-Mead equivalent reservoir ADIP on the change in the target demand was studied. In the analysis, 500 years of the generated inflows and the USBR projected depletion schedules of 1985 to 1999, as shown in Appendix A, representing 15 different levels of the target demands were used. Without the additional criteria, the ADIP changes from January as ADIP Type I and February to December as ADIP Type II to April to July as ADIP Type I and August to March as ADIP Type II when the demand changes from the level of 1985 to 1986 projected depletion schedule which is about a 2% increase. The ADIP changes to May to July as ADIP Type I and August to April as ADIP Type II when the demand increases to the level of the 1988 projected depletion schedule which is about a 6% increase from the 1985 depletion schedule. The ADIP is insensitive to the change of demand from 1988 to 1999. With the additional criteria, the ADIP is rather insensitive to the change of demand throughout the 15 year projection, that is ADIP Type I is May to July and ADIP Type II is August to April.

The ADIP is sensitive to the change of demand and the criteria used. The ADIP identified using the additional criteria (ADIP Type I and II have a period of more than one month) which is rather insensitive to the change of demand will be used for the rest of this study. Therefore the ADIP

Type I and II are May to July and August to April respectively.

Although May and August have the highest frequency to be the beginning months of ADIP Type I and II, the relative frequencies of May and August are 29 and 35 percent respectively. There is high chance that the beginning months of ADIP Type I and II are not May and August. These numbers indicate the limited reliability of the ADIP identified by the method used in this study. Whenever the actual beginning months of ADIP Type I and II are not May and August, the spill and deficit estimated by Monte Carlo simulation based on the expectation that ADIP Type I is May to July and ADIP Type II is August to April will be under-estimated as shown in Figure 4.2.

It is noted that based on this method of ADIP identification the reliability of the ADIPs and the apriori generated exceedance probabilities of spill and deficit depend on the stochastic pattern of inflow and the selected target release. Although there is high percentage that the magnitudes of spill and deficit given from the apriori generated exceedance probabilities of spill and deficit will be under-estimated, they are still useful for evaluating the pre-selected operating plan (pre-selected target release) and alternative release decisions. The exceedance probabilities of spill and deficit at least give the direction on how to adjust the target release such that the probability and the magnitude of failure (spill/deficit) are

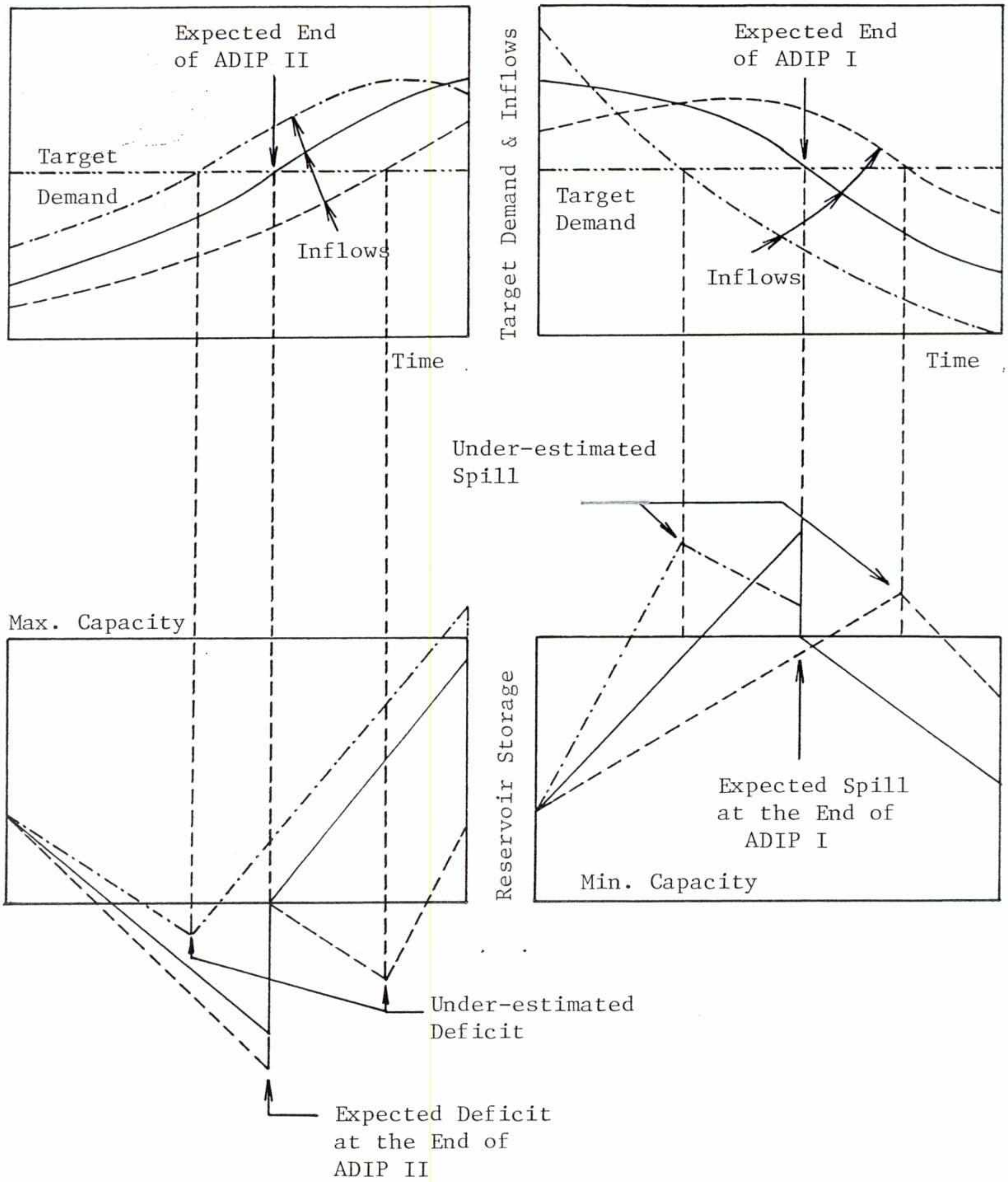


Figure 4.2 Spill and Deficit Characteristics When The Actual End of ADIP Type I and Type II Are Deviated From The Expected End of ADIP

reduced, although they are not avoided. The second stage decision made by comparing the benefits and risks associated with each alternative release decision should be better than the first stage decision (the pre-selected operating plan).

4.3 Generation of The Future Failure Probability

A Monte Carlo method was used for generating Lakes Powell and Mead future operational failure (spill/deficit) probabilities which are conditioned on the stage of the reservoirs and the month of a year. According to the Monte Carlo method for this study, a large number of equally likely sequences of inflow to Lakes Powell and Mead were generated; the operating rule for Lakes Powell and Mead was selected; the selected operating rule was simulated with a large number of equally likely sequences of generated inflows over the pre-identified ADIP; and finally the frequency analysis of the operational failures (spill and deficit) which is conditioned on the reservoir storages and month is performed. The procedure to generate inflows, select the operating rule, simulate the operating rule with the generated inflows and perform the frequency analysis of spill and deficit are presented.

4.3.1 Generation of Inflow to Lake Powell and Intervening Flow Between Lakes Powell and Mead

The Lane Applied Stochastic Techniques (LAST) computer package developed by Bureau of Reclamation, Lane(1983), was used for generating the inflow to Lake Powell (actually it generates the natural flow at Lees Ferry, a few miles downstream of Lake Powell) and the intervening flow between Lakes Powell and Mead. The generation procedure is; first, generate the annual values of the inflow at Lees Ferry and the intervening flow to Lake Mead and second, disaggregate the generated annual values into monthly values.

A Lag two AR model with Full Matalas approach, Matalas(1967), which has the following basic equation was used for generating the annual inflows.

$$X_i = AX_{i-1} + BX_{i-2} + Ce_i \tag{4.1}$$

where

X is the normalized key station annual inflow data matrix (d_1 by one), d_1 is the number of key stations,

A is the coefficient matrix (dimensions d_1 by d_1),

B is the coefficient matrix (dimensions d_1 by d_1),

C is the coefficient matrix (dimensions d_1 by d_1),

e is the column matrix of random normal numbers (d_1 by one) having zero mean and unity variance, and

i is the subscript indicating observation year.

In generation of the annual inflows, the natural flow at Lees Ferry and the intervenning flow between Lake Powell and Mead were treated as key stations. Therefore d_1 is equal to 2.

The generated annual values of inflow at Lees Ferry and the intervening flow between Lakes Powell and Mead will be disaggregated into the monthly values by the approach which closely follows the Valencia and Schaake(1973) disaggregation scheme as extended by Mejia and Rouselle(1976). The Valencia-Schaake basic equation is

$$M_{i+1} = FN_{i+1} + Gg_{i+1} + HM_i \qquad (4.2)$$

where

M is the normalized seasonal inflow data matrix (d_4 by one) where d_4 is number of stations times number of seasons in the current annual to seasonal generation group,

F is the coefficient matrix (d_4 by d_5) where d_5 is number of stations in the current seasonal generation group,

N is the normalized annual data matrix (d_5 by one),

G is the coefficient matrix (d_4 by d_4),

g is the column matrix of random normal numbers (d_4 by one) having zero mean and unit variance,

H is the coefficient matrix (d_4 by d_4), and

i is the subscript indicating observation year.

In actual application, the Full Valencia-Schaake model approach is wasteful in terms of computer storage and preserves more moments than are really desirable. Some modification was made for the disaggregation scheme used in LAST computer package to reduce the computer time. Instead of generating the 12 monthly values of inflow from the annual value at the same time, the condensed model used in the LAST package generates the month by month inflow from the previously generated annual inflow. The basic equation which is actually used by the LAST package is written (in terms of seasons) as

$$M_t = F_t N_t + G_t g_t + H_t M_{t-1} \tag{4.3}$$

This equation is a version of Equation 4.2 in which many of the parameters in matrices F, G and H have been set to zero. The subscript " t " denotes the current season being generated. Thus, M_t is only a portion of matrix M; matrix M contains the whole year's seasonal data while M_t contains only one season's data. N_t is a matrix of annual data for the year to which the current season's data belongs. M_{t-1} is a matrix of the previous season's data (which would be the last season from the previous year if the current season is the first season of a year).

The parameter matrices F_t, G_t and H_t have one set of values for each season. These matrices are only a small portion of the total F, G and H matrices.

The 78 years of historical monthly inflows at Lees Ferry and intervening flow between Lakes Powell and Mead during 1906 to 1983 are normalized using log and power transformations before being used in estimation of parameters for the generation models. Five hundred years of monthly inflow at Lees Ferry and intervening flow between

Lakes Powell and Mead are finally generated by LAST computer package using ten lead years. The statistics, especially those of mean and standard deviations calculated by the methods of moments are very well preserved in the generation models as shown in Table 4.2.

This 500 years of generated inflows will be used to identify the ADIP of Lakes Powell and Mead in Section 4.2 and to generate the spill and deficit probabilities in Section 4.3.3.

4.3.2 Pre-selected Operating Rule for Powell-Mead Simulation

According to the ADIP concept, the reservoir operating rule must be first selected, then the selected operating rule is simulated for a large number of equally likely sequences of inflow such that the stochastic characteristics of spill and deficit as a function of the initial storage and initial month are generated. As mentioned in Section 4.1, the operation of Lakes Powell and Mead are determined by the forecast of inflows and the four objectives of meeting the downstream demands, satisfying the flood control requirement, achieving the objective release of 8.23 maf/year from Lake Powell and balancing the contents of Lakes Powell and Mead by the end of September. However, in generation of the future operational failure probability, the simple operating rule such as meeting the target release is selected. The reason for using this simple operating rule is that the pre-selected operating rule will be

Table 4.2 The Statistics of Historical and Generated Flows

(a) Natural Flow at Lees Ferry in maf.

Month	Historical Flow		Generated Flow	
	Mean	Std.Dev.	Mean	Std.Dev.
Oct.	0.560	0.281	0.566	0.281
Nov.	0.452	0.125	0.457	0.147
Dec.	0.358	0.073	0.356	0.072
Jan.	0.334	0.061	0.331	0.061
Feb.	0.373	0.094	0.381	0.130
Mar.	0.627	0.212	0.623	0.202
Apr.	1.210	0.505	1.205	0.563
May	3.096	1.123	3.052	1.144
Jun.	4.160	1.557	4.081	1.499
Jul.	2.189	0.935	2.201	1.032
Aug.	1.061	0.425	1.058	0.424
Sep.	0.635	0.331	0.637	0.313
Total	15.056		14.948	

(b) Intervening Flow Between Lakes Powell and Mead in maf.

Month	Historical Flow		Generated Flow	
	Mean	Std.Dev.	Mean	Std.Dev.
Oct.	0.047	0.040	0.046	0.035
Nov.	0.053	0.018	0.059	0.043
Dec.	0.057	0.034	0.059	0.029
Jan.	0.069	0.025	0.066	0.023
Feb.	0.094	0.052	0.103	0.077
Mar.	0.097	0.062	0.108	0.095
Apr.	0.087	0.060	0.089	0.074
May	0.097	0.057	0.110	0.098
Jun.	0.038	0.025	0.042	0.042
Jul.	0.058	0.024	0.059	0.030
Aug.	0.072	0.037	0.076	0.053
Sep.	0.067	0.031	0.070	0.034
Total	0.836		0.887	

assessed using the generated future operational failure probability. If the probability of spill or deficit in the near future is high, it indicates that the pre-selected operating rule is not good and the adjustment on the pre-selected operating rule is needed. The way to adjust is either to increase or decrease the actual release above or below the target release depending on the anticipated future condition.

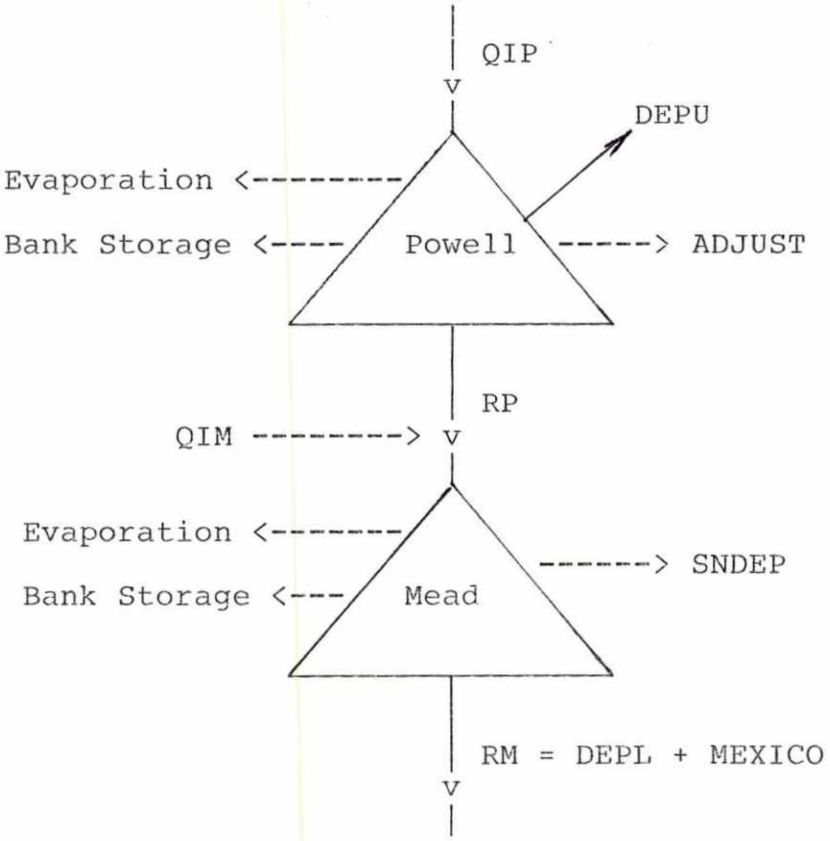
By the reason discussed above, the selected operating rule for Lakes Powell and Mead for this study has the following features:

(1) Lake Powell will release the minimum objective release of 8.23 maf annually unless the spill occurs,

(2) Lake Mead will release the minimum downstream demands (Lower Basin depletion schedule plus 1.515 maf annually delivery to Mexico) and the Southern Nevada depletion schedule unless a spill occurs.

The monthly distribution coefficients of 8.23 maf/year objective release from Lake Powell, Lower Basin depletion schedule, delivery to Mexico and Southern Nevada depletion schedule are shown in Appendix A. The components of the inflow-outflow of Lakes Powell and Mead are shown in Figure 4.3.

On the basis of the selected operating rule, it is noted that the operation of Lake Powell is independent from Lake Mead. Lake Powell will release only 8.23 maf/year at fixed monthly amounts unless a spill or deficit occurs.



where

QIP is the natural flow at Lees Ferry,

RP is Powell minimum objective release of 8.23 maf/year,

RM is Mead release,

ADJUST is the adjustment for the effect of the upstream reservoir storages on the natural flow at Lees Ferry, and

QIM, DEPU, DEPL, SNDEP and MEXICO are previously defined.

Figure 4.3 Powell - Mead Inflow and Outflow Components

Lake Mead on the other hand depends on the state of Lake Powell.

4.3.3 Simulation of Lakes Powell and Mead

In order to produce the conditional probability of storage at the end of the ADIPs and the exceedance probability of the accumulated spill at the end of ADIP Type I and that of the accumulated deficit at the end of ADIP Type II as a function of initial storage and initial month, Subroutine SIMULAT was developed.

An infinite reservoir concept is used in the simulation model (SIMULAT) which allows a reservoir to store more water than the maximum capacity or less than the minimum capacity. The amount greater than the maximum capacity or less than the minimum capacity is considered as the spill and the deficit respectively. At the end of ADIP Type I and II, the storage is truncated at the maximum capacity if it is above the maximum level and at the minimum capacity if it is below the minimum level.

Note that ADIP Type I of the Powell-Mead equivalent reservoir is the period from May to July and ADIP Type II is the period from August to April. Subroutine SIMULAT starts simulating Lake Powell first based on the pre-selected operating rule and the selected initial storage in May. The simulation proceeds from the initial month to the end of ADIP Type I (July). The storage contents at the end of ADIP Type I are stored. The spill is calculated and the storage is truncated at the Powell maximum capacity (25.902 maf, this is the total capacity) if it is above the maximum capacity at the end of ADIP Type I. The simulation is continued to the end of ADIP Type II (April). Also the storage content at the end of ADIP Type II is stored and the deficit is calculated if the storage is below the minimum capacity (5.574 maf). The simulation is repeated for 500 equally likely years of synthetically generated inflow for the same initial storage and initial month. The conditional probability of Powell storages at the end of ADIP Type I and Type II as a function of Powell initial storage in May is determined. Twenty class intervals are used in determining the conditional probability. The exceedance probabilities of spill at the end of ADIP Type I and deficit at the end of ADIP Type II are determined from the conditional probability. It is noted that the term " probability " mentioned in the above statement and that will be mentioned later on is actually the relative frequency. Eight discrete initial storages (a dead storage is included) for Lake Powell, those are 5.57, 8.00, 10.00, 18.00, 20.00, 22.00, 24.00 and 25.90 maf, which cover the Powell storage from the minimum to maximum capacity are used in the simulation. The storage between 10.00 and 18.00 maf is excluded because the chance of spill and deficit when Powell storage is in that zone is almost zero.

For each level of Powell initial storage in May, Lake Mead is simulated for the selected Mead initial storage in May. Since the storage content, the spill and deficit of

Lake Mead depend on the Powell initial storage, the spill and deficit from Lake Powell for the same simulation year are transferred as an input to Lake Mead, (the Powell spill will increase Mead storage at the end of ADIP Type I and Powell deficit will decrease Mead storage at the end of ADIP Type II). The conditional probabilities of Mead storages at the end of ADIP Type I and II as a function of Powell and Mead initial storages in May are determined. Eight discrete initial storages (a dead storage is included) for Lake Mead, those are 10.02, 12.00, 14.00, 22.00, 24.00, 26.00, 28.00 and 29.05 maf, are simulated for each discrete initial storage of Lake Powell. Unlikely combinations of Powell and Mead initial storages such as Powell empty but Mead full or vice versa are excluded from the simulation.

At the end of the simulation for the first initial month (May), the exceedance probabilities at various discrete levels of spill and deficit for Lake Powell as a function of Powell initial storage in May and those for Lake Mead as a function of Powell and Mead initial storages in May are determined. The simulation is repeated for each initial month of ADIP Type I.

Similarly, for ADIP Type II, the simulation of Lake Powell and Mead will start from the initial month in ADIP Type II to the end of ADIP Type II and proceeds to the end of ADIP Type I for various discrete levels of Powell and Mead initial storages. The simulation is repeated for each initial month of ADIP Type II. The flow chart of Powell-Mead simulation is shown in Figure 4.4.

In this study, 500 years of generated inflows and the 1985 USBR-estimate depletion schedule are used. The exceedance probabilities of spill at the end of ADIP Type I and deficit at the end of ADIP Type II as a function of initial storage and initial month for Lake Powell are shown in Figures B1(a,b) to B12(a,b) of Appendix B and those for Lake Mead in Tables B1(a,b) to B12(a,b) of Appendix B.

4.3.4 Discussion of The Result of Exceedance Probability Generation

That the exceedance probabilities of spill and deficit as a function of initial storage(s) and initial month for Lake Powell as shown in Figures B1 to B12 and for Mead as shown in Tables B1 to B12 of Appendix B are generated based on the pre-selected operating rule and the 500 years of synthetically generated monthly inflows. The exceedance probabilities of Lake Powell spill and deficit in Figures B1 to B12 indicate that there is very small probability of a Powell spill when the initial storage of Lake Powell is less than 18.00 maf and there is very small probability of a Powell deficit when the initial storage is greater than 10.00 maf. Powell storage contents can be classified into 3 zones according to the above result. Zone I is the zone of anticipated spill when Lake Powell storage is between 18.00 to 25.90 maf. Zone II is the zone of anticipated no spill and deficit when Lake Powell storage is between 10.00 to

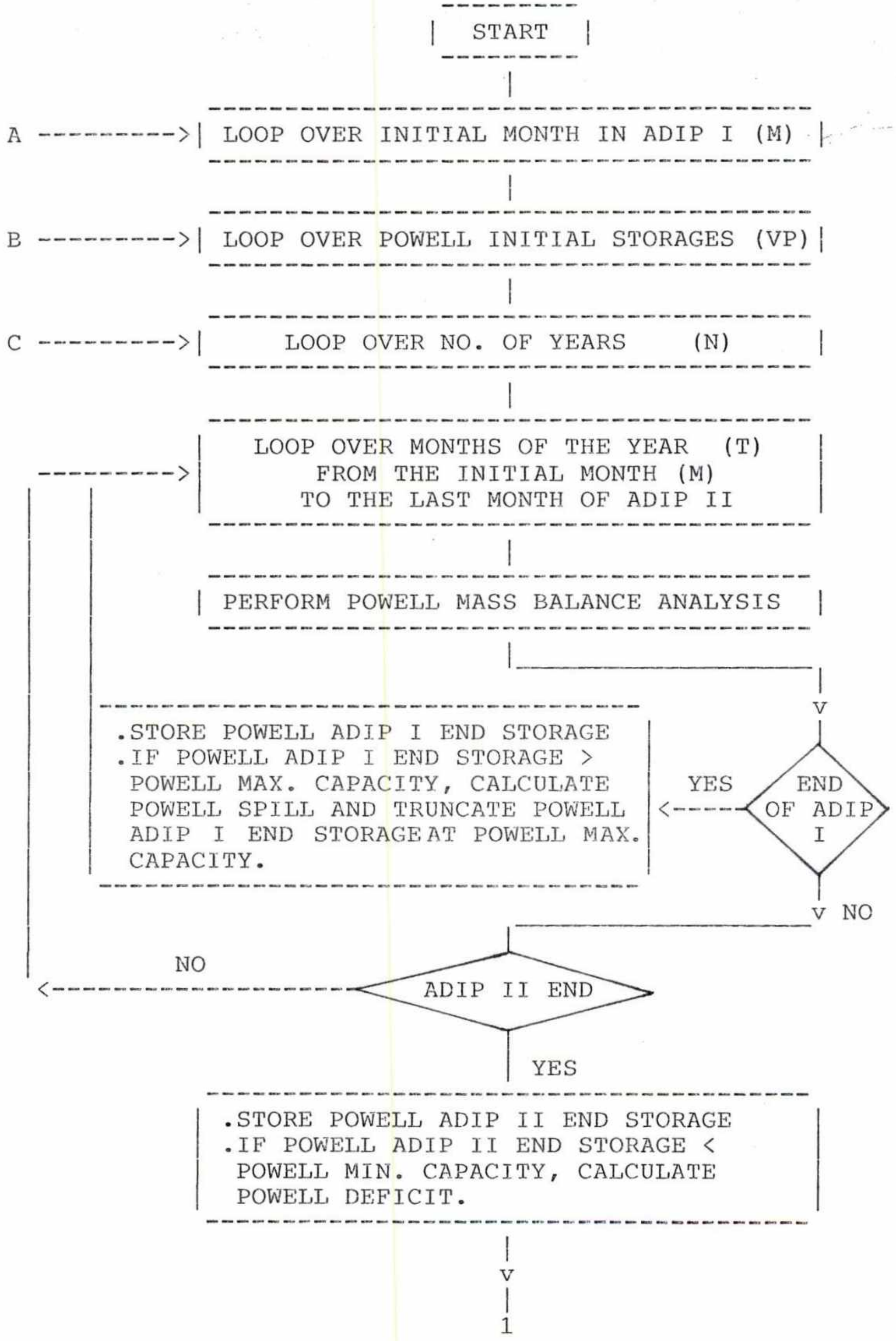


Figure 4.4(a) Simulation Flow Chart for ADIP Type I

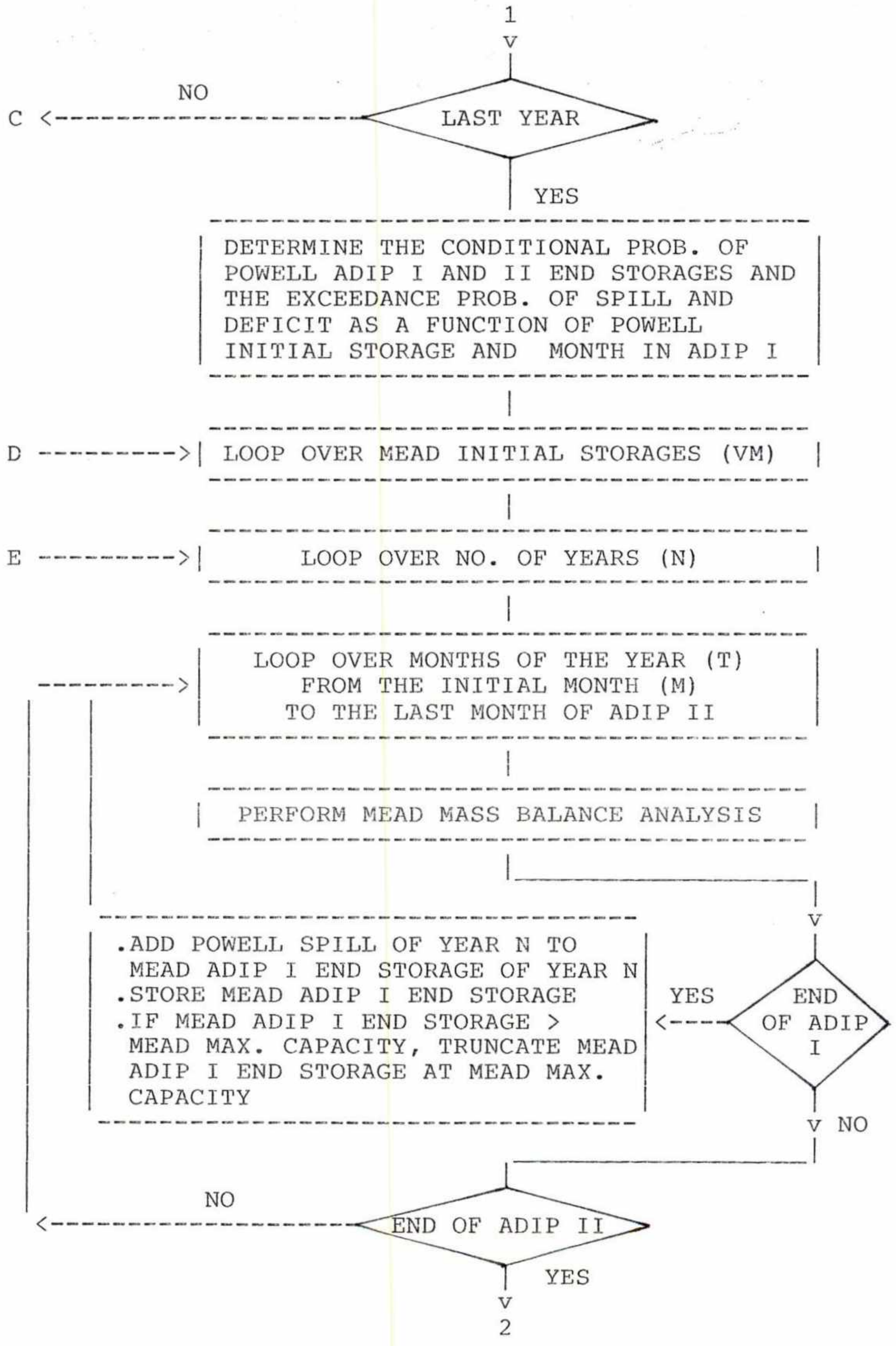


Figure 4.4(a) cont. Simulation Flow Chart for ADIP Type I

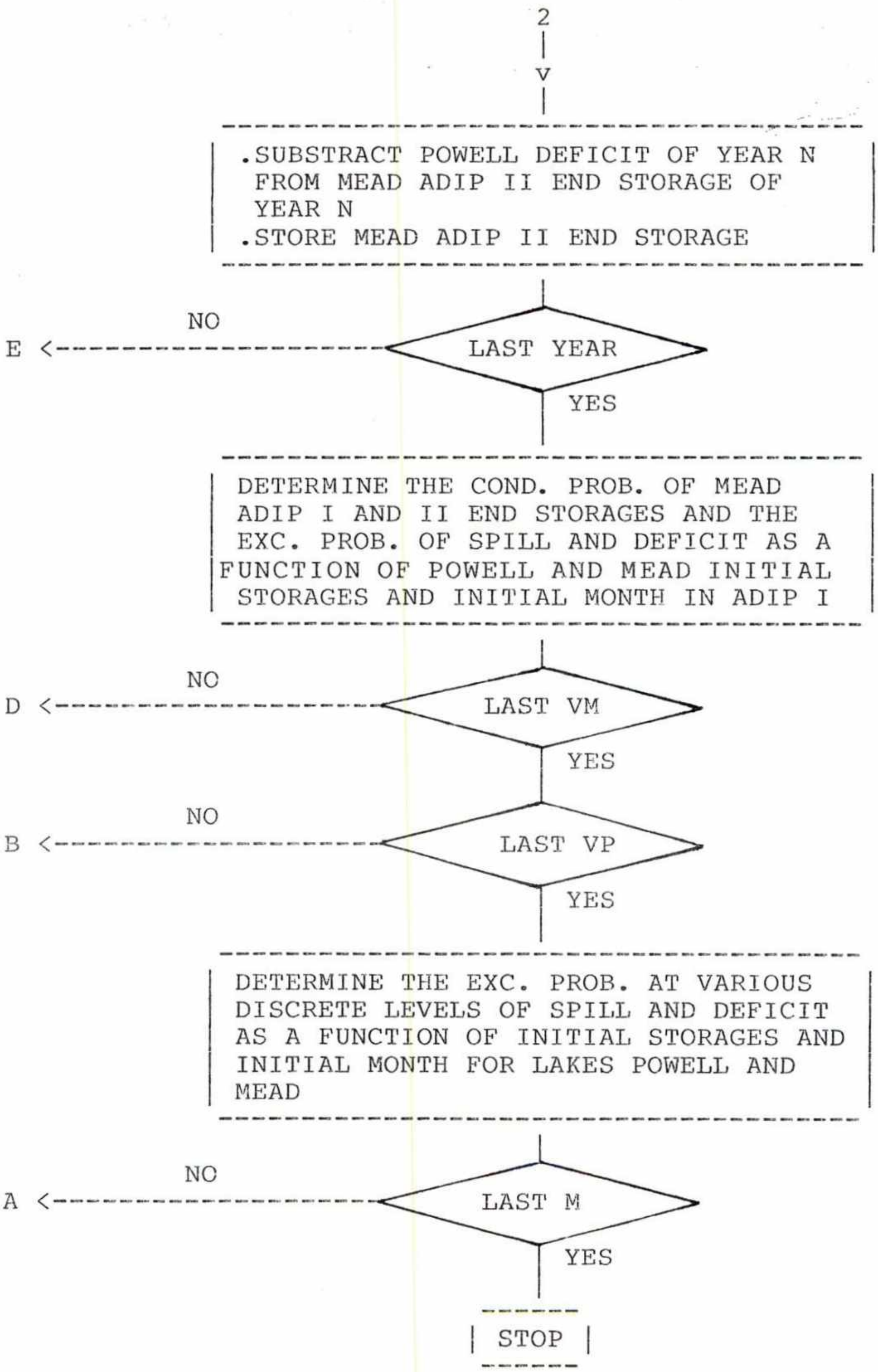


Figure 4.4(a) cont. Simulation Flow Chart for ADIP Type I

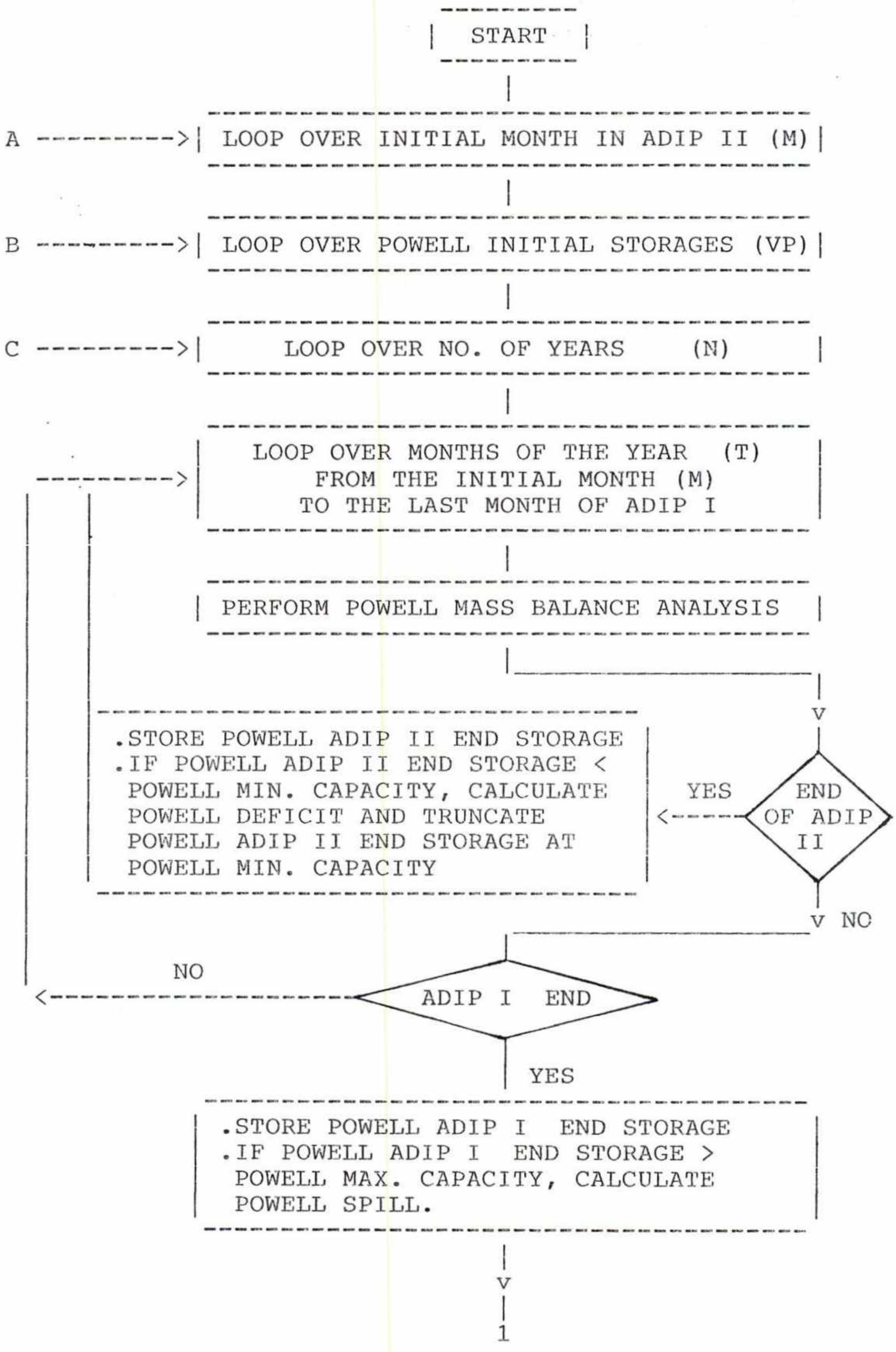


Figure 4.4(b) Simulation Flow Chart for ADIP Type II

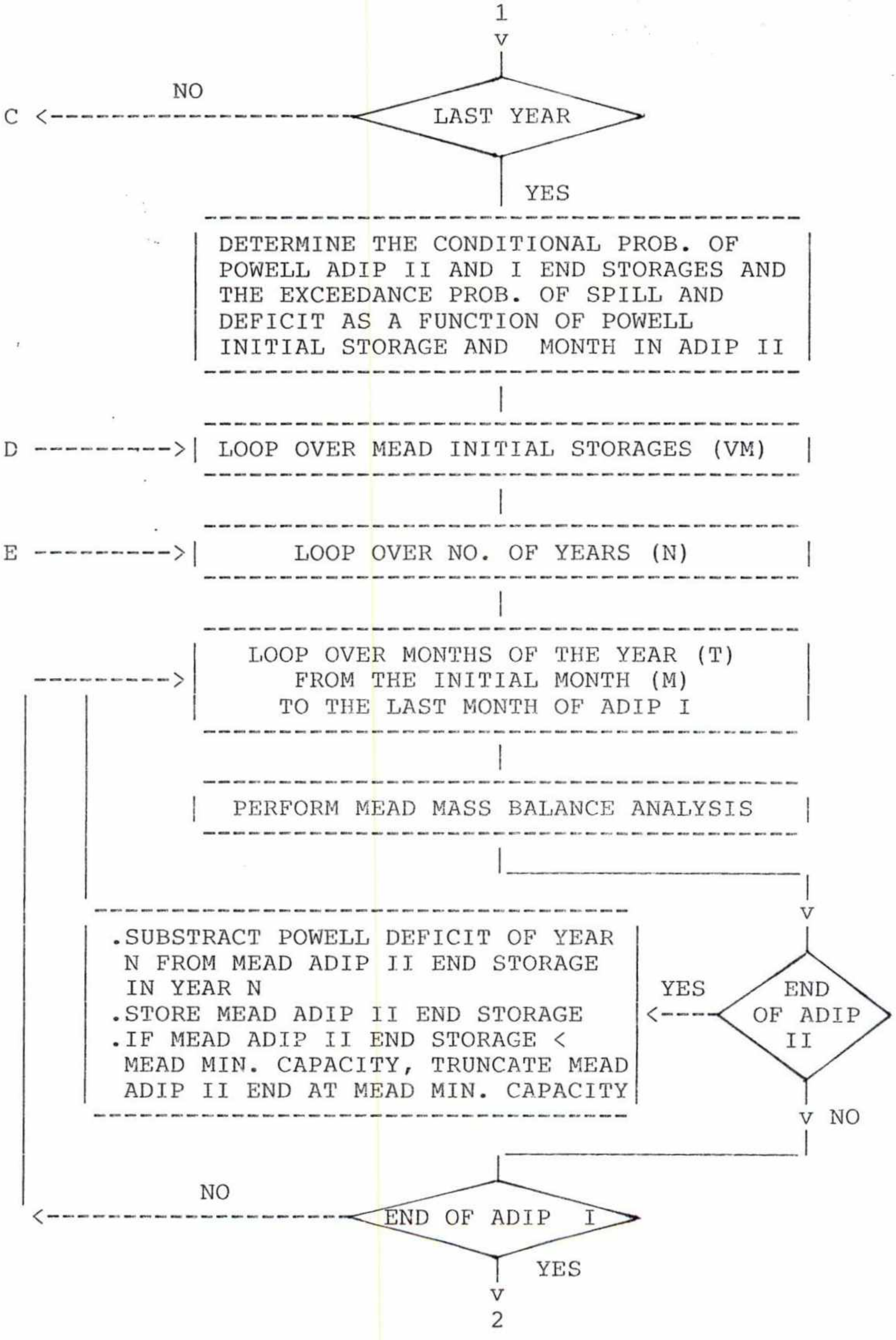


Figure 4.4(b) cont. Simulation Flow Chart for ADIP Type II

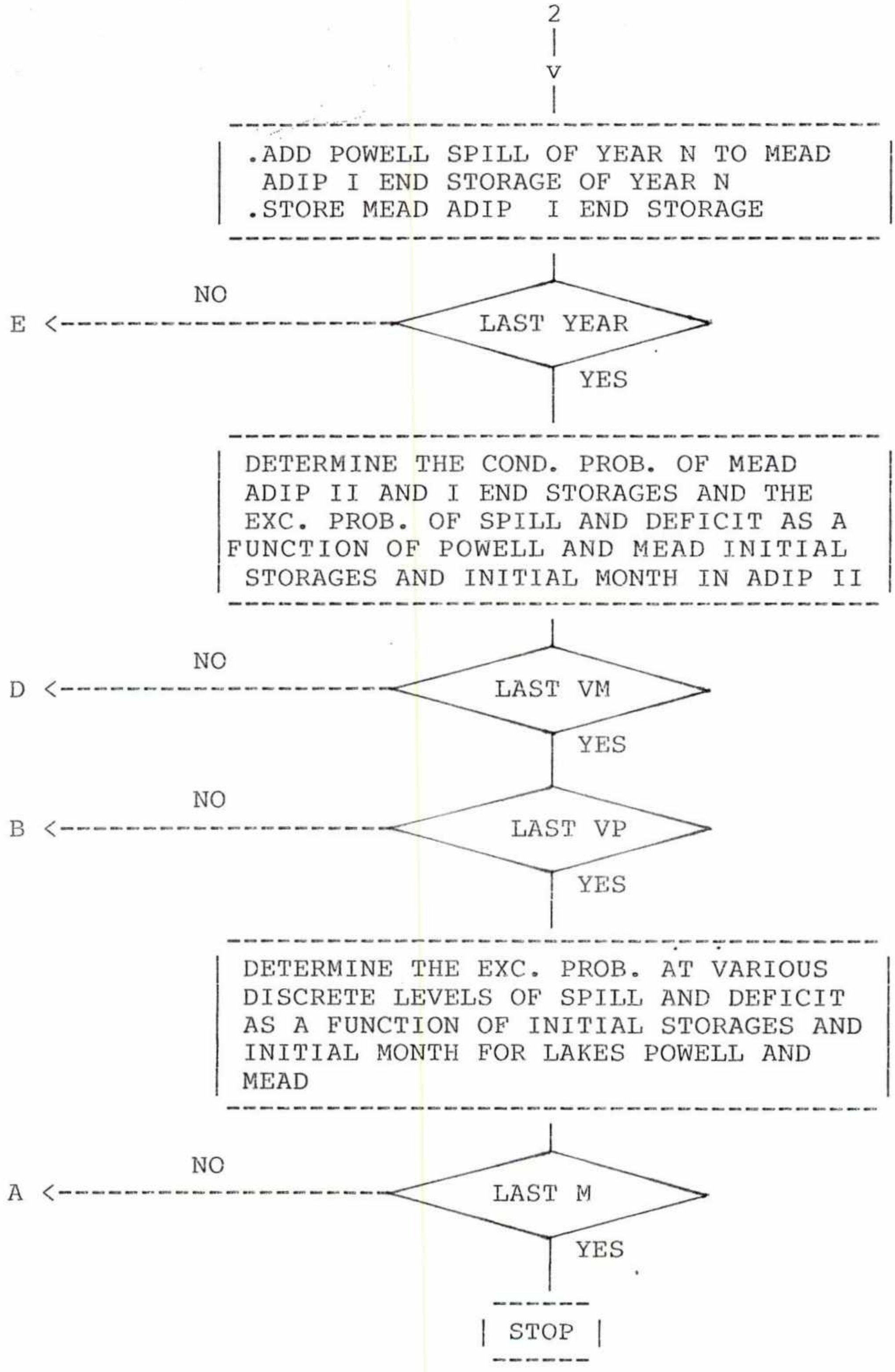


Figure 4.4(b) cont. Simulation Flow Chart for ADIP Type II

18.00 maf. Lastly Zone III is the zone of anticipated deficit when Lake Powell storage is between 5.57 to 10.00 maf. The storage zones of Lake Powell will give the general guidelines on when to make the additional or cutback release.

The exceedance probabilities of Mead spill and deficit depend not only on the Mead initial storage but the Powell initial storage also. Tables B1 to B12 indicate that when Powell initial storage is almost empty, the exceedance probability of Mead spill is almost insignificant even though the Mead initial storage is full or almost full. On the other hand, when the Powell storage is almost full, the exceedance probability of Mead deficit is insignificant even though the Mead initial storage is empty or almost empty. Regardless of the Powell initial storage, the exceedance probabilities of Mead spill and deficit are almost insignificant when the Mead initial storage is less than 22.00 and greater 14.00 maf, respectively. This leads to the conclusion that regardless of Powell initial storage, Mead storage in general can be divided into 3 zones similar to Lake Powell. The first is the zone of anticipated spill when Mead initial storage is between 22.00 to 29.05 maf. The second is the zone of anticipated no spill and no deficit when Mead initial storage is between 14.00 to 22.00 maf. The third is the zone of anticipated deficit when Mead initial storage is between 10.02 to 14.00 maf. The classification of the 3 zones in Lake Mead will give the general idea when the additional or cutback release should be considered.

May has the highest relative frequency of inflow first greater than or equal to the demand and it is considered as the beginning month of ADIP Type I as discussed in section 4.2. However, Table 4.1 indicates that the relative frequency of inflow first greater than or equal to the demand of April (27.4%) is only slightly less than that of May (29%). The sensitivity of changing the ADIP on the generated exceedance probabilities was made by assuming that April is the beginning month of ADIP Type I instead of May. By this assumption, ADIP Type I is a period from April to July and ADIP Type II is a period from August to March. The exceedance probabilities of spill at the end of ADIP Type I (July) and deficit at the end of ADIP Type II (March) were generated for the initial months of April and August.

The exceedance probabilities of spill using April as the beginning month of ADIP Type I are the same as those using May as the beginning month of ADIP Type I for both the initial months of April and August. This is true for both the exceedance probabilities of spill of Lakes Powell and Mead. This can be explained since the probability of spill is significant only when the initial storages are in the zone of anticipated spill. No matter the last month of ADIP Type II is April or May, the chance of deficit at the end of ADIP Type II is essentially zero when the initial storages in any month of the year are in the zone of anticipated spill. Therefore it is concluded that the generated exceedance probabilities of spill at the end of ADIP Type I are insensitive to the beginning month of ADIP Type I.

The exceedance probabilities of deficit is, on the other hand, will change according to the change of the beginning month of ADIP Type I. The generated exceedance probabilities of deficit for the case of April as the beginning month of ADIP Type I are compared to those for the case of May as the beginning month of ADIP Type I in Table 4.3. The exceedance probabilities of deficit are significant only when the initial storages are very low. First, consider August as the initial month. The exceedance probabilities of deficit at the end of ADIP Type II are generated based on a joint probability of monthly inflows of August to March when April is the beginning month of ADIP Type I and a joint probability of August to April inflows when May is the beginning month of ADIP Type I. The case where April is the beginning month of ADIP Type I gives slightly higher probabilities of deficit but gives slightly lower exceedance probabilities of deficit than the case where May is the beginning month of ADIP Type I. Second, when the initial month is April, the exceedance probabilities of deficit are generated based on a probability of April inflows as May being the beginning month month of ADIP Type I and a joint probability of April to March inflows as April being the beginning month of ADIP Type I. April as the beginning month of ADIP Type I gives

Table 4.3 The Exceedance Probabilities of Deficit When April and May Are The Beginning Months of ADIP Type I

(a) Lake Powell

Initial Month	Deficit (maf)	The Exceedance Probabilities of Deficit When The Beginning Month of ADIP Type I Is	
		May	April
		Initial Storage 5.57 maf	Initial Storage 5.57 maf
Apr.	0.0	0.210	0.273
	1.0	0.	0.155
	2.0	0.	0.072
	3.0	0.	0.026
Aug.	0.0	0.858	0.956
	1.0	0.525	0.661
	2.0	0.070	0.069
	3.0	0.	0.

(b) Lake Mead

Initial Month	Deficit (maf)	Powell Initial Storage (maf)	The Exceedance Probabilities of Deficit When The Initial Month of ADIP Type I Is	
			May	April
			Mead Initial Storage 10.02 maf	Mead Initial Storage 10.02 maf
Apr.	0.0	5.57	0.992	0.199
		8.00	0.990	0.024
		10.00	0.990	0.004
	1.0	5.57	0.	0.106
		8.00	0.	0.007
	2.0	5.57	0.	0.041
	3.0	5.57	0.	0.014
Aug.	0.0	5.57	0.621	0.664
	1.0	5.57	0.195	0.120
	3.0	5.57	0.009	0.

higher exceedance probabilities of deficit than the case where May is the beginning month of ADIP Type I. However the difference between the exceedance probabilities of deficit between these two cases are not substantial considering that the exceedance probabilities of significant deficit are very small even though the initial storages are at the minimum level. Besides the situation where the storages are at the minimum level has never occurred before in operations of Lakes Powell and Mead. Using May or April as the beginning month of ADIP Type I should not make much different in using the generated exceedance probabilities in evaluating release decisions.

4.4 Illustration of The Use of The ADIP Concept to Set Up The Operational Plan For Lakes Powell and Mead

4.4.1 Introduction

The method presented in this study can be used to set up the operational plan for a series of two reservoirs based on the anticipation of the future operational failures (spill and deficit), the trade off analysis between benefits and risk of operational failures or the criteria on the probability and magnitude of future operational failures. The plan will be made for a short term operation which is useful for a period of less than a year depending on how long the current ADIP is. The plan should be made at the beginning month of the current ADIP. It will provide a release plan for each month starting from the first to the last month of the current ADIP. The operational plan will be updated at the beginning of each month based on the new information on the inflow and demand during the previous month.

Based on the ADIP concept, there are two planning periods within a year. The plan will be made for either ADIP Type I or Type II. The main purpose of the operational plan for ADIP Type I is to manage the spill by increasing the release over the target release when high probability of spill is expected. The benefits in term of reducing the probability of spilling and increasing the hydropower production and downstream water supply and the adverse effectin terms of increasing the probability of not having enough water in the subsequent ADIP Type II will be assessed and traded off in order to decide how much additional release should be made. On the other hand, the main purpose of operation in ADIP Type II is to manage the deficit by trying to cut back the release from the target release when high probability of future deficit is anticipated. By doing so, the deficit still takes place. However the cutback plan is more favorable to the water users since it is known in advance that water availability is reduced and thus planning can proceed accordingly. Besides the cutback plan will distribute the deficit more evenly throughout the current ADIP than without the plan, the degree of damage to the users will be less than having only one or two big deficits.

This part of the study will illustrate how the method developed in this study can be used in setting up the short term operational plan and how to update the plan monthly. The illustration will include different ways to set up the operational plan with different levels of available information including the future failure probability criteria and the forecast of inflow.

4.4.2 Illustration No. 1

In this illustration, it is assumed that the future failure probability criteria and the forecast of inflow are not available. Given the initial storage contents of Lakes Powell and Mead at the beginning of the first month of ADIP Type I (May), the release plan for each month of ADIP Type I (May to July) will be determined based on trade offs between the benefits and risk associated with the release plan. In order to make decisions on the release plan, different release alternatives and the benefits and risks associated with them will be analyzed. The benefits and risks associated with each plan will be presented to the decision maker. However for sake of illustration, the author is assumed to be the decision maker to choose the most preferable release plan. At the beginning of each month in ADIP Type I, the release plan will be updated based on the new initial storage contents in Lakes Powell and Mead. The updating procedure during ADIP Type I is similar to the procedure for setting up the release plan at the beginning of the first month of ADIP Type I. The procedure for setting and updating the release plan of Lakes Powell and Mead for ADIP Type II is similar to that of ADIP Type I.

4.4.2.1 Determination of The Operating Plan for ADIP Type I

Based on the pre-selected operating rule, meeting the target releases for Lakes Powell and Mead whenever possible (the assumed Powell and Mead target releases are shown in Table 4.4), the future operational failure (spill or deficit) probability for Lake Powell can be obtained from Figures B1 to B12 of Appendix B and that for Lake Mead can be obtained from Tables B1 to B12 of Appendix B. Assume that the storage contents at the beginning of May of Lakes Powell and Mead are 22.78 and 24.59 maf, respectively. These numbers are the actual storage contents of Lakes Powell and Mead at the beginning of May 1983. The purpose of using these numbers is to make the result compatible with the May 1983 to April 1984 actual operation. According to the given initial storages, the exceedance probabilities of various levels of spill at the end of ADIP Type I (July) and deficit at the end of ADIP Type II (April) for Lake Powell are obtained from Figures B1(a) and B1(b) and those for Lake Mead are obtained from Tables B1(a) and B1(b) respectively. Those probabilities are shown in Table 4.5.

Table 4.5 indicates that if the target release is to be met exactly, there is high probability of spill from Lake Powell but no probability of deficit in both lakes. In addition, flood control has high priority in the operation

Table 4.4 The Monthly Target Releases for Lakes Powell and Mead[1]

Month	Monthly Target Releases, maf.	
	Lake Powell [2]	Lake Mead [3]
May	0.551	0.789
Jun.	0.585	0.724
Jul.	1.045	0.686
Aug.	1.012	0.635
Sep.	0.609	0.563
Oct.	0.568	0.541
Nov.	0.560	0.519
Dec.	0.856	0.552
Jan.	0.889	0.403
Feb.	0.527	0.610
Mar.	0.510	0.802
Apr.	0.518	0.818

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[1] This is the assumed target releases for Lakes Powell and Mead for the purpose of this study only.

[2] Powell minimum objective release

[3] To meet the Lower Basin depletion schedule and Mexican delivery schedule

of Lakes Powell and Mead. One might think about making additional releases to reduce the probability of spill and at the same time more benefits from hydropower and water supply are obtained. The adverse effect of the additional release will be in form of increasing the probability of deficit in the subsequent ADIP Type II particularly when the inflow during the current ADIP Type I is not as high as anticipated.

Analysis of The Additional Release from Lake Powell

One might try different levels of the additional release from Lake Powell, for example 1.00 , 2.00 , and 3.00 maf and see how each level of the additional release effects the exceedance probabilities of spill and deficit of both lakes.

Assuming that the additional releases from Lake Powell take place at the beginning of May, this will immediately decrease Powell storage and increase Mead storage at the beginning of May by the additional release volumes. The new initial storages of Lakes Powell and Mead are:

Alternatives	Additional Release (maf)	Powell (maf)	Mead (maf)
1	1.00	21.78	25.59
2	2.00	20.78	26.59
3	3.00	19.78	27.59

Table 4.5 The Exceedance Probabilities of Spill and Deficit for Lakes Powell and Mead When The Initial Month Is May[1]

Lake Powell (p = 22.78 maf)				Lake Mead (m = 24.59 maf)			
s maf	$P_p[S \geq s]$	d maf	$P_p[D \geq d]$	s maf	$P_{p,m}[S \geq s]$	d maf	$P_{p,m}[D \geq d]$
0.	0.51	0.	0.	0.	0.13	0.	0.
1.00	0.40	1.00	0.	1.00	0.08	1.00	0.
2.00	0.30	2.00	0.	2.00	0.05	2.00	0.
3.00	0.21	3.00	0.	3.00	0.04	3.00	0.

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[1] $P_{22.78}[S \geq s]$ is the probability of Powell spill [S] greater than or equal to s when the Powell initial storage at the beginning of May is 22.78 maf.

$P_{22.78,24.59}[S \geq s]$ is the probability of Mead spill [S] greater than or equal to s when the Powell and Mead storages at the beginning of May are 22.78 and 24.59 maf respectively.

$P_{22.78}[D \geq d]$ and $P_{22.78,24.59}[D \geq d]$ have similar meaning to $P_{22.78}[S \geq s]$ and $P_{22.78,24.59}[D \geq d]$ respectively except D means deficit.

With these new initial storages, the new exceedance probabilities of spill and deficit for Lake Powell are obtained from Figures B1(a) and B1(b) of Appendix B and those for Lake Mead are obtained from Tables B1(a) and B1(b). The new exceedance probabilities are shown in Tables 4.6(a) , 4.6(b) and 4.6(c) for the additional release alternatives 1, 2 and 3 respectively.

The benefits in term of the additional release for water supply and hydropower production and the risks in term of the probability and magnitude of spill and deficit from both lakes associated with the four alternatives (Alternative 4 is the " Do Nothing " alternative or " release according to the target release ") are presented in Tables 4.6(a), 4.6(b), 4.6(c) and 4.5 respectively. This information will be useful for the decision maker to make the release decision based on the objectives of the operation, the present benefits to be obtained and the potential future risk (spill or deficit).

Since the priority of the operation of Lakes Powell and Mead are flood control, water supply, hydropower and recreation, the operator may like to have as small probability of spill as possible, particularly for a very high magnitude of spill. For the purpose of flood control only, Alternative 3 is preferable. More benefits from hydropower production will be obtained from making additional release as long as the total release does not exceed the power plant capacity, although the value of

Table 4.6 The Exceedance Probabilities of Spill and Deficit for Lakes Powell and Mead for 3 Additional Release Alternatives When The Initial Month Is May

(a) Alternative 1 - 1.00 maf Powell additional release

Lake Powell (p = 21.78 maf)				Lake Mead (m = 25.59 maf)			
s maf	$P_p[S \geq s]$	d maf	$P_p[D \geq d]$	s maf	$P_{p,m}[S \geq s]$	d maf	$P_{p,m}[D \geq d]$
0.	0.36	0.	0.	0.	0.10	0.	0.
1.00	0.27	1.00	0.	1.00	0.05	1.00	0.
2.00	0.19	2.00	0.	2.00	0.03	2.00	0.
3.00	0.12	3.00	0.	3.00	0.02	3.00	0.

(b) Alternative 2 - 2.00 maf Powell additional release

Lake Powell (p = 20.78 maf)				Lake Mead (m = 26.59 maf)			
s maf	$P_p[S \geq s]$	d maf	$P_p[D \geq d]$	s maf	$P_{p,m}[S \geq s]$	d maf	$P_{p,m}[D \geq d]$
0.	0.25	0.	0.	0.	0.10	0.	0.
1.00	0.19	1.00	0.	1.00	0.06	1.00	0.
2.00	0.13	2.00	0.	2.00	0.04	2.00	0.
3.00	0.08	3.00	0.	3.00	0.02	3.00	0.

Table 4.6(cont.) The Exceedance Probabilities of Spill and and Deficit for Lakes Powell and Mead for 3 Additional Release Alternatives When The Initial Month is May

(c) Alternative 3 - 3.00 maf Powell additional release

Lake Powell (p = 19.78 maf)				Lake Mead (m = 27.59 maf)			
s maf	$P_p[S \geq s]$	d maf	$P_p[D \geq d]$	s maf	$P_{p,m}[S \geq s]$	d maf	$P_{p,m}[D \geq d]$
0.	0.15	0.	0.	0.	0.09	0.	0.
1.00	0.12	1.00	0.	1.00	0.06	1.00	0.
2.00	0.08	2.00	0.	2.00	0.03	2.00	0.
3.00	0.04	3.00	0.	3.00	0.02	3.00	0.

additional release is less than the target release. The maximum desirable release of Lake Powell as estimated from the 6 out of 8 generators operated at full capacity is approximately 15.50 maf/year or on the average of 1.30 maf/month or 3.90 maf for ADIP Type I (May to July). The total target release from Lake Powell during ADIP Type I is 2.18 maf. When considers only the benefits of hydropower production purpose, Alternative 2 (2.00 maf additional release) is prefered. The additional release will benefit to water uses downstream as long as it does not create flooding. The additional release today may cause more an adverse effect in using Lake Powell for recreational purposes in the future, however this effect will not be mentioned in this study. Ignoring the recreational purpose, the choice will be on either Alternative 2 or 3. It is noted that the probability of deficit in both lakes are essentially zero for all the alternatives.

Other information such as the snow pack survey or the forecast of incoming flow may be useful for decision makers to decide whether to choose Alternative 2 or 3. Suppose the decision maker decides to choose Alternative 3 based on trade offs between the reduction in risk of flooding and the loss of benefit in hydropower production (the release in excess of the maximum desirbale release capacity will not favor the hydropower production). The details on how to make use of the forecast will be shown in Illustration No.3.

Adjustment of The Evaporation and Bank Storage Effects-on The 3.00 maf Additional Release

It was assumed previously that the 3.00 maf additional release from Lake Powell takes place at the beginning of May. This assumption was made just to facilitate the use of the apriori generated exceedance probabilities in assessing the effect of additional releases since those exceedance probabilities were generated based on the operating rule of meeting the target release whenever possible. Once the additional release was made, the actual release will differ from the target release which was used in generating the exceedance probabilities. The apriori generated exceedance probabilities will not be useful any more. Therefore it has to be assumed that the whole additional release takes place immediately at the beginning of the current month. By this assumption, the additional release will effect only the initial storage of the reservoirs, but not the release policy.

Actually it might not be the case that the whole additional release takes place at the beginning of May because of limits on the release capacity. The operator might like to distribute the 3.00 maf additional release evenly or unevenly over the current ADIP Type I. The distribution of the 3.00 maf additional release is not the subject of this study. It is therefore simply assumed that the 3.00 maf additional release from Lake Powell is distributed uniformly over the ADIP Type I (May to July). Based on this assumption, the effects of evaporation and bank storages need to be adjusted if they are not minor.

According to Section 3.6, the adjustment on the Powell additional release can be done by Equation 3.8 as follows:

$$X'_u = X_u - (E^b_u - E^c_u) + CB_u \cdot X_u$$

where

$$(E^b_u - E^c_u) = 0.5(E^a_u - E^c_u) \text{ and}$$

E^a_u = 0.24 maf (from Figure 3.9 when Powell storage at the beginning of May is 22.78 maf)

E^c_u = 0.22 maf (from Figure 3.9 when Powell storage at the beginning of May is 19.78 maf)

$CB_u = 0.08$

X_u = 3.00 maf

$$X'_u = 3.00 - 0.5(0.24 - 0.22) + 0.08*3.00$$
$$= 3.23 \text{ maf/ ADIP, Type I (May to July)}$$

Since the Powell additional release is 3.23 maf and will take place uniformly during ADIP Type I instead of 3.00 maf taking place at the beginning of May, this will increase the magnitude of Mead spill at the end of ADIP Type I presented in Table 4.6(c) by ΔS_1. The ΔS_1 can be approximated by Equation 3.9 as follows:

$$\Delta S_1 = (X'_u - X_u) + (E^c_1 - E^b_1) - CB_1.X_u$$

where

$$(E^c_1 - E^b_1) = 0.5(E^c_1 - E^a_1) \text{ and}$$

E^c_1 and E^a_1 are 0.32 and 0.30 maf as obtained from Figure 3.11 when Mead storages at the beginning of May are 27.59 and 24.59 maf, respectively.

$CB_1 = 0.065$

$$\Delta S_1 = (3.23 - 3.00) + 0.5(0.32 - 0.30) - 0.065*3.00$$
$$= 0.045 \text{ maf. (too small and negligible)}$$

Analysis of The Additional Release from Lake Mead

Although the probability of spill at the end of ADIP Type I of Lake Mead as appeared in Table 4.6(c) is not very high, only 9 percent, one might like to try making some additional release from Lake Mead. The reasons are : (1) the probability that a deficit will take place in the near future (during the subsequent ADIP Type II) is essentially zero ; (2) more additional benefit from hydropower and water supply will be obtained from making the additional release ; (3) the 3.00 maf additional release from Lake Powell will increase the Lake Mead storage content and the adverse effect on using Lake Mead for recreation purpose should be small ; (4) reducing the probability of flooding downstream of Lake Mead although it is not high. Three alternatives including 1.00 , 2.00 and 3.00 maf additional releases are analyzed. Assuming additional releases from Lake Mead take place at the beginning of May, the effect of these three alternatives (Alternative 1 - 1.00 maf, Alternative 2 - 2.00 maf, Alternative 3 - 3.00 maf) and Alternative 4 (Do Nothing alternative) on the future probabilities of spill and deficit for Lake Mead can be assessed by the exceedance probabilities in Tables B1(a) and B1(b) of Appendix B as shown in Table 4.7.

The exceedance probabilities of spill from Lake Mead at the end of ADIP Type I for all four alternatives are small and are very close to each other. Therefore it is difficult to use those probabilities to justify which of the

Table 4.7 The Exceedance Probabilities of Spill and Deficit of Lake Mead for The Three Proposed Alternatives and The Target Release Alternative When The Initial Month Is May

Alter-natives	New Mead Initial Storage (m) in maf	$P_{19.78,m}[S \geq s]$				$P_{19.78,m}[D \geq d]$
		s in maf				d in maf
		0.	1.00	2.00	3.00	0
1	26.59	0.06	0.03	0.02	0.01	0.
2	25.59	0.03	0.02	0.01	0.01	0.
3	24.59	0.02	0.01	0.01	0.01	0.
4	27.59	0.09	0.06	0.03	0.02	0.

four alternatives should be chosen. To minimize the probability of flooding downstream of Lake Mead which is the prime objective of the operation, Alternative 3 is prefered. The 3.00 maf additional release plus the target release during ADIP Type I gives the total release of 5.20 maf which exceeds the maximum desirable release of Lake Mead 13.80 maf/year or on the average of 3.45 maf for ADIP type I. This maximum desirable release is dictated by the power plant capacity of Davis Dam downstream of Lake Mead. Some hydropower benefit will be lost from bypassing the Davis Dam power plant by the amount of 1.75 maf during May to July. When considering the hydropower benefits against the risk of flood control, the decision maker might be interested in Alternative 2 in which the lost of water for hydropower is smaller (only 0.75 maf) but the probability of flooding increases very slightly.

Alternatives 1 and 4 might be considered if the decision maker believed that there will be a long period of low flow (many years) and as much water as possible should be stored in Lake Mead for future benefits of water supply, hydropower and recreation. However since this study was focused only on developing the seasonal operating plan, only the information about near future (less than a year) is provided. For short term planning, Alternatives 1 and 4 do not give full benefits (release less than the maximum desirable release) and have higher future risk of spilling, they are considered inferior to Alternatives 2 and 3.

One of the objectives in the operation of Lakes Powell and Mead is to balance the contents of Lakes Powell and Mead by the end of September so long as storage levels in the upper basin are kept above the levels determined by the Secretary of the Interior to satisfy the Section 602(a) of Public Law 90-537. Based on this operational objective, the decision maker might choose Alternative 3 so that the 3.00 maf additional release from Lake Powell will not accumulate in Lake Mead and has to be discharged by the end of

September to balance the storage contents of Lakes Powell and Mead.

Based on trade-offs between the loss of hydropower production and the risk of flooding and the objective to balance the contents between Lakes Powell and Mead, it is probable that Alternative 3 would be selected.

Adjustment of The Evaporation and Bank Storage Effects on The 3.00 Maf Additional Release from Lake Mead

Similarly to the adjustment of the additional release from Lake Powell, the 3.00 maf additional release from Lake Mead can be adjusted by Equation 3.18 as follows:

$$X'_1 = X_1 - (E^{b'}_1 - E^{c'}_1) + CB_1 . X_1$$

where

$(E^{b'}_1 - E^{c'}_1) = 0.5(E^a_1 - E^{c'}_1)$ and

E^a_1 and $E^{c'}_1$ are 0.30 and 0.27 maf which are obtained from Figure 3.11 when Mead storages at the beginning of May are 24.59 and 21.59 maf respectively,

$CB_1 = 0.065$

$$X'_1 = 3.00 - 0.5(0.30 - 0.27) + 0.065*3.00$$
$$= 3.18 \text{ maf/ ADIP Type I (May to July)}$$

Given that the initial storages of Lakes Powell and Mead at the beginning of May are 22.78 and 24.59 maf respectively, it is decided to have 3.23 and 3.18 maf additional release from Lakes Powell and Mead respectively based on trade-offs between the benefits and risks associated with the additional release in accordance with the operational objective. Assuming that these additional releases uniformly take place over ADIP Type I, the release plan which includes the target and additional releases for ADIP Type I (May to July) formulated by the ADIP-based method is presented in Table 4.8. Note that Lake Powell releases are 1.51 maf in excess of the Powell maximum desirable level and Lake Mead releases are 1.93 maf in excess of the Mead maximum desirable release level during ADIP Type I. These amounts of water represent a loss for hydropower production in order to keep the chance of flooding at the desirable level.

4.4.2.2 Determination of The Operating Plan for ADIP Type II

The method to set up the operating plan for ADIP Type II for Lakes Powell and Mead is similar to the one for ADIP Type I illustrated previously. Although the method is similar, the prime consideration is different. In general the main consideration in ADIP Type I is to manage the spill but that of ADIP Type II is to manage the deficit. Given that the storage contents at the beginning of August (the first month of ADIP Type II) for Lakes Powell and Mead are 25.90 and 26.80 maf respectively (these numbers are the actual storage contents of Lakes Powell and Mead at the

Table 4.8 The Monthly Release Plan for Lake Powell and Mead for May to July When Lakes Powell and Mead Storages at The Beginning of May Are 22.78 and 24.59 Maf Respectively.

Lake		May	Jun.	Jul.
	Target Release, maf	0.55	0.59	1.05
	Additional Release, maf	1.08	1.08	1.08
Powell	Total Release, maf	1.63	1.66	2.12
	Probability of Spill	15 %		
	Probability of Deficit	0 %		
	Target Release, maf	0.79	0.72	0.69
	Additional Release, maf	1.06	1.06	1.06
Mead	Total Release, maf	1.85	1.78	1.75
	Probability of Spill	2 %		
	Probability of Deficit	0 %		

beginning of August 1983), the exccedance probabilities of deficit at the end of April and spill at the end of July for Lake Powell are obtained from Figures B4(b) and B4(a) of Appendix B and those for Lake Mead are obtained from

Tables B4(b) and B4(a) of Appendix B. The exceedance probabilities are tabulated in Table 4.9.

Usually during ADIP Type II (a period where the demand exceeds the inflow), a deficit is expected. Table 4.9 indicates the opposite result, high probability of spill at the end of July in both lakes (73 and 55 percent probability of spill for Powell and Mead respectively) but essentially probability of deficit at the end of April. The reasons are: (1) at the beginning of August Lake Powell is full and Lake Mead is almost full ; (2) both lakes have such a tremendous storage capacity that the storage can never be depleted from the full level to the minimum level within a year ; (3) the mean of total annual inflows to Lakes Powell and Mead (15.90 maf) is greater than the total depletion schedule of 1985 (11.20 maf - USBR estimate) which is used in this study. This explains why the probability of deficit at the end of April is essentially zero. With this situation, the operating plan for ADIP Type II is to manage the spill similar to that for ADIP Type I illustrated before, and the planning period will be extended to the end of July (the end of subsequent ADIP Type I) instead of April (the end of ADIP Type II).

Analysis of The Additional Release Plan for Lake Powell During ADIP Type II Plus ADIP Type I

Five additional release alternatives for Lake Powell are proposed. Those include 4.00 , 5.00 , 6.00 and 7.00 maf additional release during ADIP Type II plus ADIP Type I for

Table 4.9 The Exceedance Probabilities of Deficit and Spill for Lakes Powell and Mead When The Initial Month Is August

Lake Powell (p = 25.90 maf)				Lake Mead (m = 26.80 maf)			
s maf	$P_p[S \geq s]$	d maf	$P_p[D \geq d]$	s maf	$P_{p,m}[S \geq s]$	d maf	$P_{p,m}[D \geq d]$
0.	0.73	0.	0.	0.	0.55	0.	0.
1.00	0.63	1.00	0.	1.00	0.45	1.00	0.
2.00	0.54	2.00	0.	2.00	0.36	2.00	0.
3.00	0.44	3.00	0.	3.00	0.29	3.00	0.

Alternatives 1 , 2 , 3 and 4 respectively. Alternative 5 is " Do Nothing ". Assuming that the additional releases take place at the beginning of August, the new Powell initial storages are 21.90 , 20.90 , 19.90 and 18.90 maf and the new Mead initial storages are 30.80 , 31.80 , 32.80 and 33.80 maf corresponding to Alternatives 1 , 2 , 3 and 4. It is noted that the new Mead surrogate storage contents exceed Lake Mead total capacity (29.05 maf) when assuming immediate 4.00 to 7.00 maf additional releases from Lake Powell. This indicates that the additional release from Lake Mead is needed without any further consideration.

The exceedance probabilities of spill at the end of July for Lakes Powell and Mead for the first 4 alternatives are obtained from Figure B4(a) and Table B4(a) of Appendix B as shown in Table 4.10. Note that the probabilities of deficit at the end of April for both lakes are essentially zero.

Based on the priority of the objectives of the operation and the benefits and the risks associated with each additional release alternative, the decision maker might choose Alternative 3 or 4 if the flood control is more important than other objectives. The choice between Alternatives 3 and 4 will be decided by trade offs between the increase in the amount of additional release and the small reduction in the risk of flooding. It is noted that the economic value of the additional release is not as high as that of the target release.

If the hydropower and water supply objectives are important and the economic value of the additional release is far less than that of the target release, the decision maker might be interested in taking more risk of spilling to reduce the amount of additional release. Alternative 1 or 2 might be the choice. The " Do Nothing " alternative (Alternative 5) is very risky because the probability of a significant spill is very high (44 percent probability of spill greater than or equal to 3.00 maf which will take place during the current time to the end of subsequent ADIP Type I). Note that the additional release alternatives of

Table 4.10 The Exceedance Probabilities of Spill for Lakes Powell and Mead When The Initial Month Is August

(a) Alternative 1 - 4.00 maf Additional Release

Lake Powell		Lake Mead	
s (maf)	$P_{21,90}[S \geq s]$	d (maf)	$P_{21.90,30.80}[S \geq s]$
0.	0.26	0.	1.0
1.00	0.21	1.00	1.0
2.00	0.16	2.00	1.0
3.00	0.11	3.00	1.0

(b) Alternative 2 - 5.00 maf Additional Release

Lake Powell		Lake Mead	
s (maf)	$P_{20.90}[S \geq s]$	d (maf)	$P_{20.90,31.80}[S \geq s]$
0.	0.20	0.	1.0
1.00	0.16	1.00	1.0
2.00	0.12	2.00	1.0
3.00	0.08	3.00	1.0

Table4.10(cont) The Exceedance Probabilities of Spill for Lakes Powell and Mead When The Initial Month Is August

(c) Alternative 3 - 6.00 maf Additional Release

Lake Powell		Lake Mead	
s (maf)	$P_{19.90}[S\geq s]$	d (maf)	$P_{19.90,32.80}[S\geq s]$
0.	0.13	0.	1.0
1.00	0.11	1.00	1.0
2.00	0.08	2.00	1.0
3.00	0.05	3.00	1.0

(d) Alternative 4 - 7.00 maf Additional Release

Lake Powell		Lake Mead	
s (maf)	$P_{18.90}[S\geq s]$	d (maf)	$P_{18.90,33.80}[S\geq s]$
0.	0.11	0.	1.0
1.00	0.09	1.00	1.0
2.00	0.06	2.00	1.0
3.00	0.04	3.00	1.0

Lake Powell will result in spilling from Lake Mead unless the additional release from Lake Mead is made. The additional release from Lake Mead will be analyzed later.

The information about the future inflow and snowpack survey will be very useful for the decision maker to decide which of these choices is prefered. However at this moment it is assumed that those information are not available. Since flood control has high priority in the operation of Lakes Powell and Mead, it is assumed that Alternative 3 or 4 is prefered over Alternative 1 or 2. Finally Alternative 3 is chosen over 4 based on taking a slightly increased percent probability of spill, that is 1 more percent probability of spill 3.00 maf or more at the end of July, to reduce 1.00 maf additional release during ADIP Type II plus ADIP Type I. It is noted that the additional release has less value than the target release.

Adjustment of The Evaporation and Bank Storage Effect on The 6.00 Maf Additional Release from Lake Powell During ADIP Type II Plus ADIP Type I

It is more realistic to assume that the 6.00 maf additional release from Lake Powell takes place uniformly over the ADIP Type II plus ADIP Type I (August to July) instead of assuming that the 6.00 maf additional release immediately takes place at the beginning of August. If the evaporation and bank storage effects are not minor, the adjustment is needed. Equation 3.8 is used for adjusting the 6.00 maf additional release from Lake Powell as follows:

$$X'_u = X_u - (E^b_u - E^c_u) + CB_u.X_u$$

where

$(E^b_u - E^c_u) = 0.5(E^a_u - E^c_u)$ and

E^a_u and E^c_u are 0.54 and 0.45 maf obtained from Figure 3.10 when Powell storage contents at the beginning of August are 25.90 and 19.90 maf respectively,

$CB_u = 0.08$

$X_u = 6.00$ maf

$X'_u = 6.00 - 0.5(0.54 - 0.45) + 0.08*6.00$

$= 6.44$ maf/ ADIP Type II plus ADIP Type I.

Since the total evaporation from the beginning of August to the end of July is not available, that from the beginning of August to the end of April which is obtained from Figure 3.10 is used for approximating E^a_u and E^c_u in the above equation instead. Although the absolute value of the total evaporation from the beginning of August to the end of April are different from that of the total evaporation from the beginning of August to the end of July, the relative value of $E^a_u - E^c_u$ should not be much different when using the total evaporation from the beginning of August to the end of April instead of the other.

The 6.44 maf additional release from Lake Powell which takes place uniformly over ADIP Type II plus ADIP Type I instead of the 6.00 maf additional release taking place at the beginning of August will have an effect on the magnitude of Mead spill at the end of July. The magnitude of Mead spill at the end of July shown in Table 4.10(c) will be increased approximately by ΔS_1 which can be calculated by Equation 3.9 as follows:

$$\Delta S_1 = (X'_u - X_u) + (E^c_1 - E^b_1) - CB_1 . X_u$$

where

$(E^c_1 - E^b_1) = 0.5(E^c_1 - E^a_1)$ and

E^c_1 and E^a_1 are 0.76 and 0.73 maf obtained from Figure 3.12 when Mead storage contents at the beginning of August are 32.80 and 26.80 maf respectively,

$CB_1 = 0.065$

$X_u = 6.00$ maf

$X'_u = 6.44$ maf

$$\Delta S_1 = (6.44 - 6.00) + (0.76 - 0.73) - 0.065*6.00$$
$$= 0.060 \text{ maf (too small and negligible)}.$$

Note that the value of E^c_1 and E^b_1 used in the above equation are the total evaporation from the beginning of August to the end of April instead of that from the beginning of August to the end of July. The reason is the same as previously explained in the above paragraph.

Analysis of The Additional Release Plan for Lake Mead During ADIP Type II Plus I

The 6.00 maf additional release from Lake Powell at the beginning of August increases Mead storage content to 32.80 maf which exceeds the Mead maximum total capacity (29.05 maf) by 3.75 maf. Four additional release alternatives are proposed. They are :

Alternative 1 - 4.00 maf additional release
Alternative 2 - 5.00 maf additional release
Alternative 3 - 6.00 maf additional release
Alternative 4 - 7.00 maf additional release

Tables B4(a) and B4(b) of Appendix B are used for assessing the effect of each additional release alternative on the change in the exceedance probabilities of spill and deficit of Lake Mead. Table 4.11 shows the exceedance probabilities of Mead deficit at the end of April and Mead spill at the end of July for each of those four alternatives. It is noted that all the exceedance probabilities of Mead deficit at the end of ADIP Type II (April) are essentially zero.

The probability of Mead spill for Alternatives 2 to 4 are very close to each other which makes it difficult to make an additional release decision based on the probability of future spill only. Although Alternative 1 has high probability of spill, the probability of heavy spill (for example the spill of 3.00 maf or more) is not much different from Alternatives 2 to 4. However if flood control is the

Table 4.11 The Exceedance Probabilities of Spill and Deficit for Lake Mead for The Four Proposed Alternatives When The Initial Month Is August

Alter-natives	New Mead Initial Storage (m) in maf	$P_{19.90,m}[S \geq s]$				$P_{19.90,m}[D \geq d]$
		s in maf				d in maf
		0.	1.00	2.00	3.00	0.
1	28.80	0.54	0.14	0.08	0.05	0.
2	27.80	0.13	0.08	0.05	0.04	0.
3	26.80	0.09	0.06	0.04	0.03	0.
4	25.80	0.06	0.04	0.02	0.02	0.

prime objective and one wants to minimize the probability of flooding, Alternative 4 is the choice. If hydropower objective is the most important and the additional release has much less value than the target release, one might like Alternative 1 , 2 or 3 over Alternative 4. Trade-offs between the decrease in the probability of flooding and the loss of benefits in hydropower production should be done based on the decision maker's risk-benefit preference. It is expected that the water supply benefits are always obtained from making additional release as long as the plan is made early enough and water users downstream are informed.

However the operational objective to balance the storage contents of Lakes Powell and Mead by the end of water year (September) may favor Alternative 3 (6.00 maf) because Lake Powell will release 6.00 maf of water in addition to the target release during ADIP Type II plus ADIP Type I to Lake Mead. Let 's assume that Alternative 3 (6.00 maf additional release) is the decision.

Adjustment of The Effects of Evaporation and Bank Storage on The 6.00 Maf Additional Release from Lake Mead During ADIP Type II Plus ADIP Type I

Similar to the previous adjustment, Equation 3.18 is used for adjusting the 6.00 maf additional release from Lake Mead as Follows:

$$X'_1 = X_1 - (E^{b'}_1 - E^{c'}_1) + CB_1 . X_1$$

where

$(E^{b'}_1 - E^{c'}_1) = 0.5(E^a_1 - E^{c'}_1)$ and

E^a_1 and $E^{c'}_1$ are 0.73 and 0.63 maf obtained from Figure 3.12 when Mead storage contents at the beginning of August are 26.80 and 20.80 maf respectively,

$CB_1 = 0.065$

$X_1 = 6.00$ maf

$$X'_1 = 6.00 - 0.5(0.73 - 0.63) + 0.065*6.00$$

$$= 6.34 \text{ maf/ ADIP Type II plus ADIP Type I.}$$

Also the value of total evaporation from the beginning of August to the end of April obtained from Figure 3.12 was usedin the above equation instead of the total evaporation from the beginning of August to the end of July since the latter is not available.

Given that the initial storage contents of Lakes Powell and Mead at the beginning of August are 25.90 and 26.80 maf respectively, the release plan for ADIP Type II plus ADIP Type I (August to July) formulated by the ADIP-based method based on the assumption that the additional release is uniformly distributed over the planning period is presented in Table 4.12.

Recall that the real purpose of the analysis in this section is to determine an operating plan for ADIP Type II (August to April) only. The period of analysis had to be extended beyond the end of ADIP Type II to the end of subsequent ADIP Type I because the exceedance probability of deficit at the end of ADIP Type II is essentially zero which is useless information upon which to base a decision and the exceedance probability of spill at the end of subsequent ADIP Type I is high. Although the analysis covered ADIP Type II plus ADIP Type I, only the operating plan for ADIP Type II is needed. This is because the plan for the next ADIP Type I will be studied again at the end of the current ADIP Type II or the beginning of the next ADIP Type I. The

Table 4.12 The Monthly Release Plan for Lakes Powell and Mead for August to July When Lakes Powell and Mead Storages at The Beginning of August Are 25.90 and 26.80 maf Respectively

Lake	Release in maf	Aug.	Sep.	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.
Powell	Target release	1.01	0.61	0.57	0.56	0.86	0.89	0.53	0.51	0.52
	Additional release	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54	0.54
	Total release	1.55	1.15	1.11	1.10	1.40	1.43	1.07	1.05	1.06
	Probability of spill	13 %								
	Probability of deficit	0 %								
Mead	Target release	0.64	0.56	0.54	0.52	0.55	0.40	0.61	0.80	0.82
	Additional release	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53
	Total release	1.17	1.09	1.07	1.05	1.08	0.93	1.14	1.33	1.35
	Probability of spill	9 %								
	Probability of deficit	0 %								

new information obtained during the current ADIP Type II will make the operating plan for the next ADIP Type I determined at the beginning of next ADIP Type I be more accurate and efficient than that determined at the beginning of the current ADIP Type II.

4.4.2.3 Comparison of The ADIP-Based Operating Plan with The May 1983 to April 1984 USBR Operating Plan and Actual Operation

Based on the ADIP-based release plans in Tables 4.8 and 4.12 and the actual inflow to Lake Powell and sideflow to Lake Mead, the mass balance analysis for Lakes Powell and Mead is performed as shown in Appendix C. The storage policies of Lakes Powell and Mead for ADIP Type I and II are presented in Table 4.13.

The ADIP-based release plans for Lakes Powell and Mead are compared to the May 1983 - April 1984 USBR operating plan and the actual operation (obtained from the operational plan of the Colorado River Storage Project, Water Year 1983 - 1984 Annual Operating Plan, USBR) in Figures 4.5 and 4.6. The storage policies are compared similarly in Figures 4.7 and 4.8.

During ADIP Type I, the ADIP-based method gives a little higher release from Lake Powell and gives on the average a little higher release from Lake Mead than the actual release during May to July 1983. This can be explained since at the beginning of ADIP Type I (May), there is high probability of spill from Lake Powell (the

Table 4.13 The ADIP-Based Storage Policies of Lakes Powell and Mead for ADIP Type I and ADIP Type II

ADIP Type	Month	Powell Storage(maf)		MeadStorage(maf)	
		At the beginning of month	At the end of month	At the beginning of month	At the end of month
I	May	22.78	23.79	24.59	24.51
	Jun.		25.90 (1.67)		25.93
	Jul.		25.90 (1.52)		27.79
II	Aug.	25.90	25.75	26.80	27.16
	Sep.		25.31		27.13
	Oct.		25.05		27.23
	Nov.		24.71		27.31
	Dec.		24.12		27.58
	Jan.		23.53		27.98
	Feb.		23.32		27.84
	Mar.		23.28		27.58
	Apr.		23.65		27.33

Note : The numbers in parenthesis are the spill during that month.

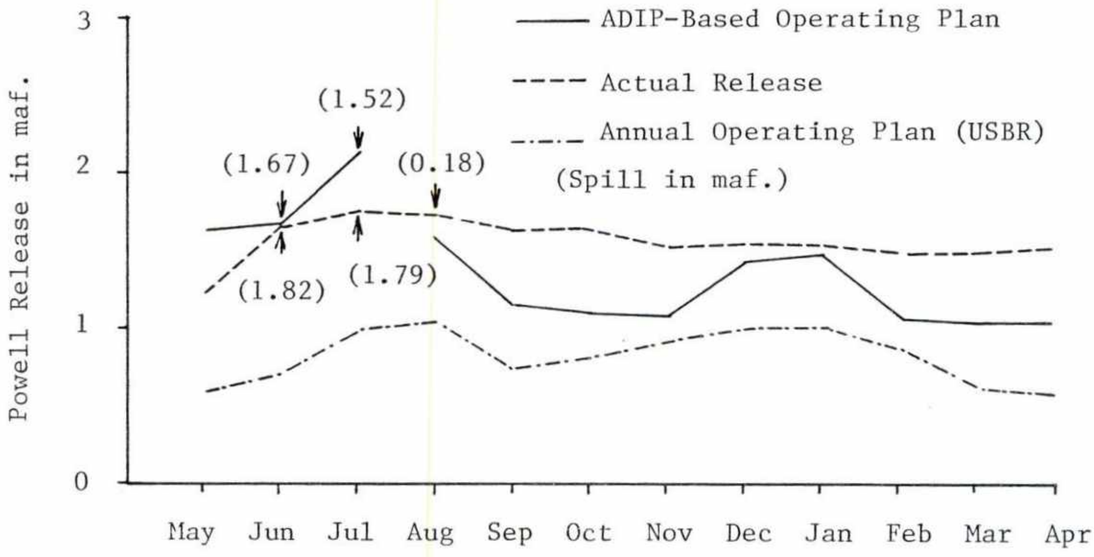

Figure 4.5 Powell Release Plans for Illustration No.1

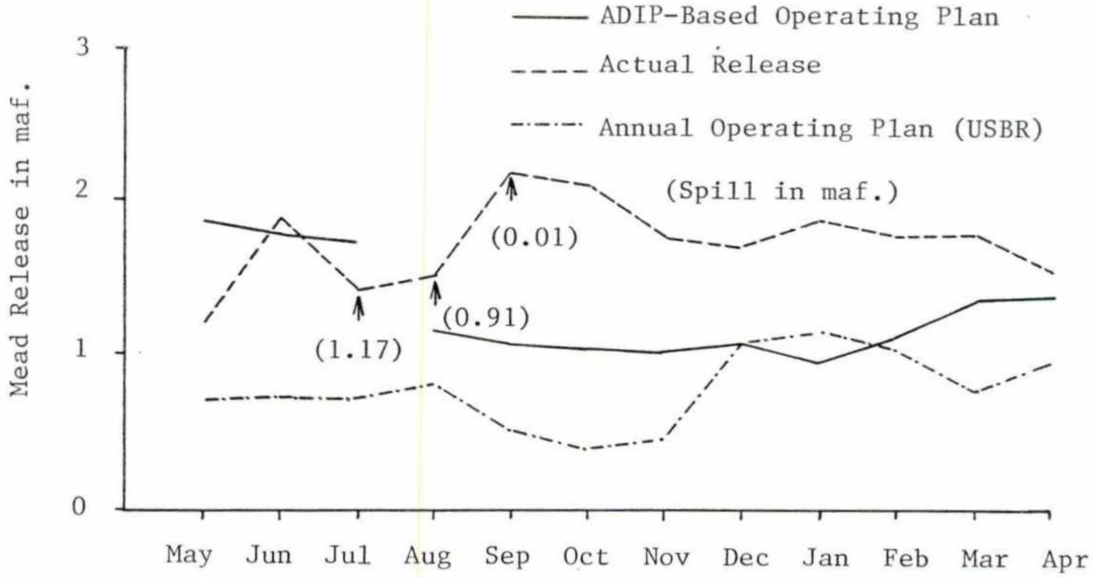

Figure 4.6 Mead Release Plans for Illustration No.1

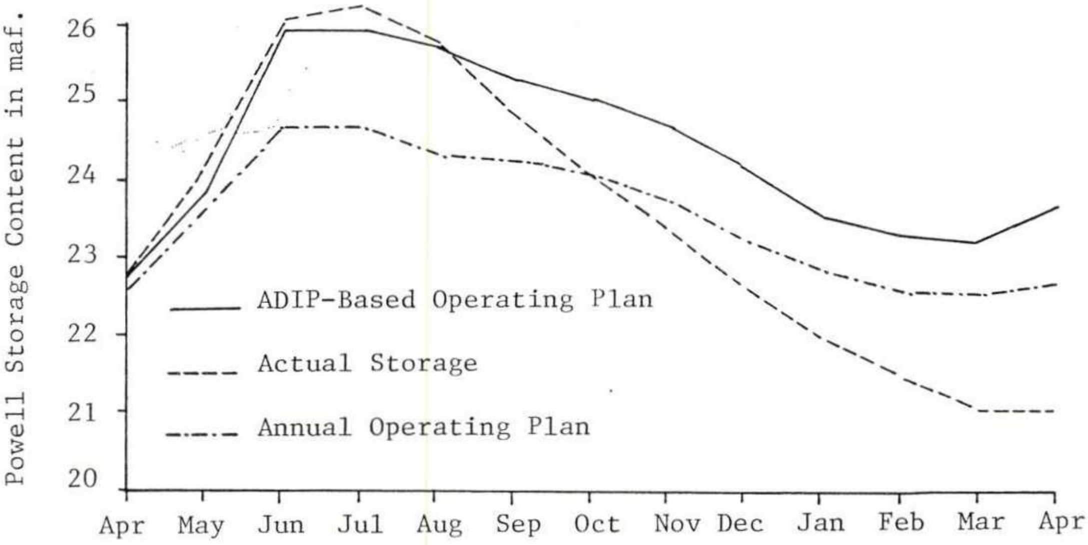

Figure 4.7 Powell Storage Policies for Illustration No.1

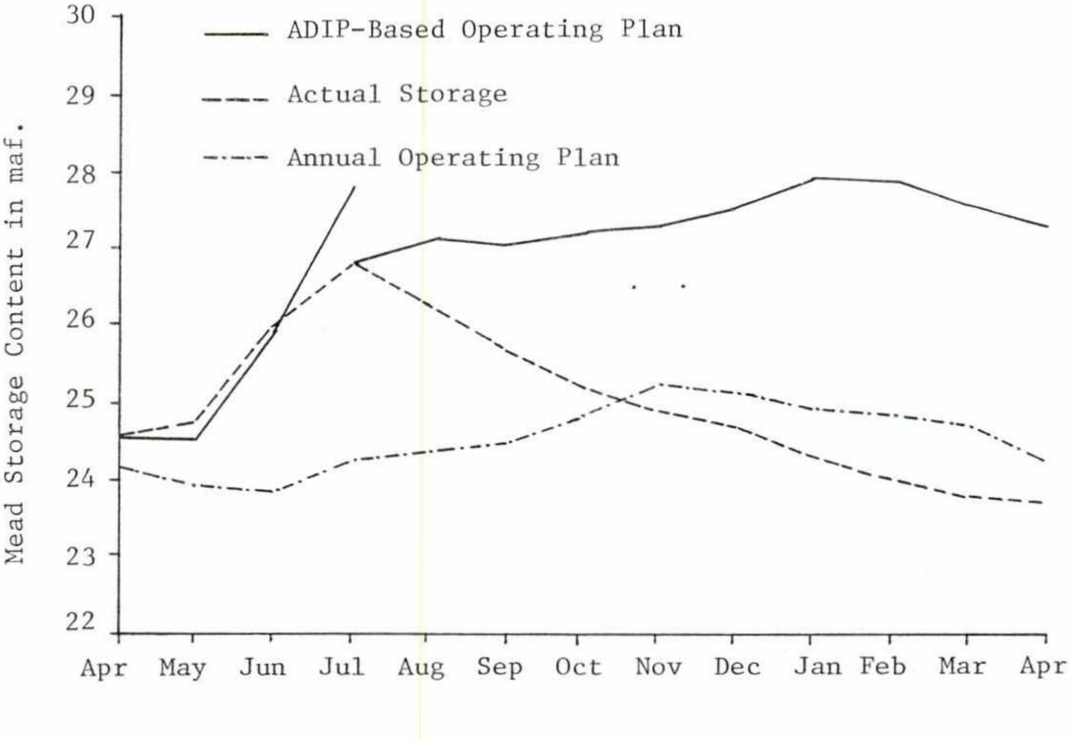

Figure 4.8 Mead Storage Policies for Illustration No.1

probability of Powell spill is about 50 percent) if the target release is to be maintained. Trade-offs between the risk of flooding at the end of July and the loss of benefit from hydropower production and water supply associated with the additional release (since the release in excess of the maximum desirable release will not favor the hydropower production) dictate that 3.23 maf additional release from Lake Powell should be made during May to July. Although this action does not make any change in Mead spill probability, about 3.18 maf additional release from Lake Mead during May to July is dictated based on the operational objective of balancing the storage content of Lakes Powell and Mead. Based on the ADIP-based release plan, there is 15 percent probability that a spill might take place during May to July. The ADIP-based release plan is simulated with the actual inflow during May 1983 to April 1984 to see how well the ADIP-based release plan works. The simulation indicates that 1.67 and 1.52 maf spill from Lake Powell will take place in June and July respectively while there is no spill from Lake Mead. The actual spills were 1.82 , 1.79 and 0.18 maf in June , July and August for Lake Powell and 1.17 , 0.91 and 0.01 maf in July, August and September for Lake Mead respectively. Although the ADIP-based release plan during ADIP Type I gives a smaller spill, the difference is small. The ADIP-based storages during ADIP Type I do not show any big differences from the actual storages in both Lakes Powell and Mead.

During ADIP Type II (August to April), the ADIP-based release plans of both Lakes Powell and Mead dictate much lower release than the actual release. This is because at the end of ADIP Type I (May) the spill took place and the storages in both Lakes Powell and Mead were full. The flood control regulation of the Colorado River system required that at least 5.35 maf of empty space must be available by January 1st. This results in very high actual release during ADIP Type II. The ADIP-based method, on the other hand, has the knowledge of the exceedance probability of spill at the end of subsequent ADIP Type I which shows that if about 4.80 maf additional releases are made from Lakes Powell and Mead, respectively, during ADIP Type II (or about 6.44 and 6.34 maf additional releases during August to July for Lakes Powell and Mead ,respectively), they will lower the probability of spill from Powell and Mead to about 13 and 9 percent respectively. This decision is made based on trade-offs between the risk of flooding and the loss of benefit from hydropower production and water supply since the additional release is less value than the target release. The storages in Figures 4.7 and 4.8 reflect the release policies, that is the actual storages are much lower than the ADIP-based storages.

The ADIP-based method used in this illustration decides the release policy at the beginning of ADIP Type I (May) or ADIP Type II (August) based on the entire stochastic variability of inflow between the beginning of ADIP to the end of ADIP and requires judgement on how to trade risk against benefit. There is high probability that the actual operation which used full current information will deviate from the ADIP-based release plan.

It is noted that in general the USBR operating plan gives lower releases and storages than the ADIP-based operating plan and tha actual operation. This is because the forecast of inflow to Lake Powell estimated for making the USBR plan is much lower than the actual inflow to Lake Powell. The reason to compare the USBR operating plan with the other two is to show that the plan can be much different from the actual operation under the unexpected high flow even though it is produced by the very practically acceptable method which is used by the USBR in making the annual operating plan.

Actually the ADIP-based operating plan can be updated at the beginning of each month based on the inflow during the previous month and the new reservoir storage content at the beginning of the month. The monthly updating procedure will be mentioned in the next illustration.

4.4.3 Illustration No. 2

The future operational failure (spill and deficit) probability criteria will be used to decide the levels of the additional or cutback release in this illustration. Given the initial storage content at the beginning of the month , the exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II can be obtained. If the exceedance probability of spill exceeds the future spill probability criteria, the additional release is required to reduce the exceedance probability of spill below the spill probability criteria. Similarly, if the exceedance probability of deficit exceeds the future deficit probability criteria, the cutback release is required to reduce the exceedance probability of deficit below the deficit probability criteria.

Ballestero(1981) used the maximum steady state spill probability and deficit probability as the criteria, which when violated, prompted an increase or decrease of releases, respectively. The spill and deficit probabilities depend on the initial storage and time of the year. He showed by the failure probability history plot through five years of operation that ignoring the first peak in the plot, due to the influence of the large initial condition, the other peaks have nearly constant level. However the length of time to attain the steady state levels is a function of reservoir size (assuming stationary inputs and outputs), many years may be required for large reservoirs and possibly only one season for very small reservoirs with minimal over year storage.

He pointed out the fact that if the reservoir were to be regulated in a totally inflexible manner, the probability criteria could be set at unity: no matter what the future operational failure probability is , no deviation will be made from the set operation policy. Setting operational failure criteria at any probability less than unity introduces a degree of flexibility.

For this study, the storage capacities of Lakes Powell and Mead are tremendous relative to the annual inflows and demands, it will require a long period of time (many years) to reach the steady state failure probability if it exists at all. A more simple way to derive the future operational failure probability criteria from the actual operational history is introduced in this study. The exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II as the function of initial storage and initial month can be used to anticipate the future probabilities of spill and deficit once the initial storage is known. These generated exceedance probabilities can also be used to tell what was the probability of spill and deficit in making release decision in the past. For example, from the historical operation, the Powell storage content at the beginning of May 1983 was 22.78 maf. The actual release between May to July was 4.64 maf. The target release during that period was 2.18 maf. Then the additional release during May to July was 2.46 maf. Assuming that 2.46 maf. Powell additional release takes place at the beginning of May, the Powell new initial storage was 20.33 maf. Figure B1(a) of Appendix B shows that the probability of Powell spill at the end of July was 0.20. Similarly the probabilities of spill and deficit in the past decisions can be determined.

The probabilities of spill and deficit in each month decision for the past April 1981 to April 1985 operation of Lakes Powell and Mead were studied as shown in Appendix D. The decision on the probabilities of spill and deficit during the April 1981 to April 1985 operation varied considerably. The probability of spill was varied from 0. to 0.44 for Lake Powell and 0. to 0.04 for Lake mead. All the probabilities of deficit were essentially zero in the past four year operation. On the average, the probabilities of spill from Lakes Powell and Mead were controlled within 0.13 and 0.01 percent, respectively. These probabilities of spill will be used as the future spill probability criteria for Lakes Powell and Mead in this study.

4.4.3.1 Illustration Procedure

To illustrate how to use the operational failure (spill and deficit) probability criteria for making a release decision for Lakes Powell and Mead, the following procedure is to follows:

For ADIP Type I (May to July)

1. Read the exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II for the given initial storages of Lakes Powell and Mead at the beginning of the current month, starting from the first month of ADIP Type I.

2. Check if the exceedance probabilities exceed the spill and deficit probability criteria.

3. Make an additional release (if the exceedance probability of spill exceeds the criteria) to decrease the probability of spill below the operational failure probability criteria, be careful that the additional release during ADIP Type I will not increase the exceedance probability of deficit at the end of ADIP Type II above the probability criteria.

4. Adjust for the effects of evaporation and bank storage on the additional release.

5. Distribute the additional release uniformly over ADIP Type I.

6. Operate Lakes Powell and Mead according to the target release and additional release schedules.

7. The storage contents at the end of the current month will be used as the storage contents at the beginning of next month. The procedure is then repeated from steps 1 to 6 until the last month of ADIP Type I.

For ADIP Type II (August to July)

The procedure is similar to 7 step procedure for ADIP Type I given previously when the storages at the beginning of ADIP Type II are given, except when the exceedance probability of deficit at the end of ADIP Type II exceeds the deficit probability criteria, the target release schedule is cutback to reduce the probability of deficit below the probability criteria. The cutback release is assumed uniformly distributed over ADIP Type II. The operation of Lakes Powell and Mead is assumed to follow the target release and cutback release schedules exactly. The storage contents at the end of the first month will be used as the storage contents at the beginning of the second month. The release decision making procedure is repeated until the last month of ADIP Type II.

However, as shown in Illustration No. 1, the exceedance probability of deficit at the end of ADIP Type II are all essentially zero, the cutback release during ADIP Type II is not needed. Furthermore the exceedance probability of spill at the end of subsequent ADIP Type I is very significant. The type of decision for ADIP Type II for Lakes Powell and Mead, therefore, has to change from the conventional (theoretical) way. The additional release for ADIP Type II plus ADIP Type I is to be decided to reduce the probability of spill at the end of subsequent ADIP Type I below the spill probability criteria. The additional release is assumed uniformly distributed over the period of ADIP Type II plus ADIP Type I. This procedure for making a release decision will be repeated at the beginning of each month in ADIP Type II.

Note that the procedure given above utilizes all the current information and allows the release schedule made at the beginning of ADIP to be updated at the beginning of each month based on the inflow in the previous month and new state of the system. This will help make a better release decision for real time operations.

4.4.3.2 Determination of The Operating Plan for ADIP Type I for Lakes Powell and Mead

Given that the storage contents at the beginning of May for Lakes Powell and Mead are 22.78 and 24.59 maf respectively, the ADIP-based method is used to determine the release decision for Lakes Powell and Mead for ADIP Type I (May to July). As explained in the illustration procedure, the exceedance probability of spill for Lakes Powell and Mead is obtained from Figure B1(a) and Table B1(b) respectively, and that of deficit for Lakes Powell and Mead is obtained from Figure B1(b) and Table B1(b) based on the given storage contents of Lakes Powell and Mead. The exceedance probability of spill from both lakes for the initial month of May is presented in Table 4.14. Since the probability of spill, P[spill$\geq$0], at the end of ADIP Type I (July) for both lakes exceeds the spill probability criteria, i.e. 0.13 for Lake Powell and 0.01 for Lake Mead. The 3.28 maf additional release from Lake Powell and 3.79 maf additional release from Lake Mead are proposed to reduce the probability of spill in both lakes below the probability criteria limit. Assuming that the evaporation and bank storage have minor effects (actually the effects are about 8 percent as shown in Illustration No. 1), it makes no difference whether the 3.28 and 3.79 maf additional releases take place at the beginning of May or uniformly over the ADIP Type I (May to July). However it is assumed that the 3.28 and 3.79 maf additional releases take place uniformly

Table 4.14 The Effect of Additional Release in ADIP Type I on The Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)			
May			22.78	24.59	0.	0.51	0.13
					1.00	0.40	0.08
					2.00	0.30	0.05
					3.00	0.21	0.04
	3.28 (1.09)	3.79 (1.27)	19.50	24.08	0.	0.13	0.01
					1.00	0.10	0.00
					2.00	0.07	0.00
					3.00	0.04	0.00
Jun.			23.77	24.34	0.	0.51	0.06
					1.00	0.37	0.03
					2.00	0.23	0.01
					3.00	0.14	0.01
	2.27 (1.14)	2.45 (1.23)	21.50	24.16	0.	0.13	0.01
					1.00	0.11	0.01
					2.00	0.07	0.00
					3.00	0.03	0.00
Jul.			25.90	25.59	0.	0.55	0.02
					1.00	0.18	0.01
					2.00	0.06	0.00
					3.00	0.01	0.00
	1.60 (1.60)	1.06 (1.06)	24.30	26.13	0.	0.13	0.01
					1.00	0.05	0.00
					2.00	0.01	0.00
					3.00	0.00	0.00

Note: The number in parenthesis is the monthly release.

over ADIP Type I. The May additional releases for Lakes Powell and Mead are 1.09 and 1.27 maf respectively.

The May mass balance is performed in Appendix C to determine the May end storages for Lakes Powell and Mead based on the target releases (Table 4.4), the additional releases (Table 4.14), the actual inflow to Lake Powell and side flow to Lake Mead. The May end storages are then used as the beginning of June storages, and the release decision making procedure is repeated until the last month of ADIP Type I (July). The exceedance probability of spill from Lakes Powell and Mead based on the storages at the beginning of each month of ADIP Type I are shown in Table 4.14 and the effects of additional releases on the exceedance probability of spill from both lakes are shown in the same table. It is noted that all the exceedance probabilities of deficit for both lakes are essentially zero and they are not shown.

The storage, release and spill characteristics of Lakes Powell and Mead for ADIP Type I (May to July) dictated by the ADIP-based operation with the operational failure probability criteria are presented in Table 4.16.

4.4.3.3 Determination of The Operating Plan for ADIP Type II for Lakes Powell and Mead

The storage contents at the end of ADIP Type I are 25.90 maf for Lake Powell and 27.44 maf for Lake Mead will be used as the initial storage contents for the ADIP-based operation during ADIP Type II. With known initial storages at the beginning of August, the exceedance probabilities of deficit at the end of ADIP Type II for Lakes Powell and Mead are obtained from Figure B4(b) and Table B4(b) respectively and those of spill at the end of the subsequent ADIP Type I for Lakes Powell and Mead are obtained from Figure B4(a) and Table B4(a) respectively. Those exceedance probabilities are shown in Table 4.15. Since the exceedance probabilities of deficit at the end of ADIP Type II are all zero but those of spill at the end of the subsequent ADIP Type I are significant, the operation objective will be to manage the spill at the end of the subsequent ADIP Type I instead of to manage the deficit at the end of ADIP Type II. The planning period then becomes the period of ADIP Type II plus ADIP Type I.

Table 4.15 indicates that, in August, the probabilities of Powell and Mead spill at the end of the subsequent ADIP Type I are higher than the spill probability criteria, that is 0.13 for Lake Powell and 0.01 for Lake Mead. In order to reduce the exceedance probabilities of spill below the probability criteria, the 5.90 and 11.34 maf additional releases are to be made from Lakes Powell and Mead respectively. Assuming that the evaporation and bank storage effects are minor, actually the effects are about 8 percent, it makes no difference whether the 5.90 and 11.34 maf additional releases take place at the beginning of August or any time between August to July (the end of the subsequent ADIP Type I). Assuming that the 5.90 and 11.34 maf additional releases take place uniformly over the ADIP

Table 4.15 The Effect of Additional Release in ADIP Type II on The Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)			
Aug.			25.90	27.44	0.	0.73	0.61
					1.00	0.64	0.50
					2.00	0.54	0.41
					3.00	0.44	0.33
	5.90	11.34	20.00	22.00	0.	0.13	0.01
	(0.49)	(0.95)			1.00	0.11	0.01
					2.00	0.08	0.01
					3.00	0.05	0.01
Sep.			25.79	27.36	0.	0.78	0.60
					1.00	0.68	0.50
					2.00	0.57	0.40
					3.00	0.47	0.32
	5.79	11.16	20.00	22.00	0.	0.13	0.01
	(0.53)	(1.01)			1.00	0.11	0.01
					2.00	0.08	0.01
					3.00	0.05	0.01
Oct.			25.36	26.87	0.	0.74	0.52
					1.00	0.63	0.42
					2.00	0.52	0.33
					3.00	0.43	0.26
	5.36	9.92	20.00	22.31	0.	0.13	0.01
	(0.54)	(0.99)			1.00	0.11	0.01
					2.00	0.08	0.01
					3.00	0.05	0.01

Table 4.15(cont.) The Effect of Additional Release in ADIP TypeII on The Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)			
Nov			25.10	26.53	0.	0.71	0.46
					1.00	0.60	0.37
					2.00	0.50	0.29
					3.00	0.40	0.22
	5.10	9.27	20.00	22.36	0.	0.13	0.01
	(0.57)	(1.03)			1.00	0.11	0.01
					2.00	0.08	0.01
					3.00	0.05	0.01
Dec.			24.73	26.17	0.	0.68	0.39
					1.00	0.58	0.31
					2.00	0.47	0.24
					3.00	0.37	0.17
	4.73	8.53	20.00	22.37	0.	0.13	0.01
	(0.59)	(1.07)			1.00	0.11	0.01
					2.00	0.08	0.01
					3.00	0.05	0.01
Jan.			24.09	25.99	0.	0.66	0.31
					1.00	0.54	0.24
					2.00	0.43	0.18
					3.00	0.34	0.13
	4.59	8.15	19.50	22.43	0.	0.13	0.01
	(0.66)	(1.16)			1.00	0.11	0.01
					2.00	0.08	0.01
					3.00	0.05	0.01

Table 4.15(cont.) The Effect of Additional Release in ADIP TypeII on The Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)			
Feb.			23.39	25.90	0.	0.62	0.25
					1.00	0.50	0.19
					2.00	0.40	0.14
					3.00	0.31	0.09
	4.39 (0.73)	7.68 (1.28)	19.00	22.62	0.	0.13	0.01
					1.00	0.10	0.01
					2.00	0.07	0.01
					3.00	0.05	0.01
Mar.			23.00	25.25	0.	0.58	0.20
					1.00	0.47	0.14
					2.00	0.36	0.10
					3.00	0.28	0.07
	4.30 (0.86)	6.73 (1.35)	18.70	22.81	0.	0.13	0.01
					1.00	0.10	0.01
					2.00	0.07	0.01
					3.00	0.04	0.01
Apr.			22.66	24.53	0.	0.53	0.13
					1.00	0.42	0.09
					2.00	0.33	0.06
					3.00	0.24	0.04
	3.66 (0.91)	5.62 (1.41)	19.00	22.57	0.	0.13	0.01
					1.00	0.10	0.01
					2.00	0.07	0.01
					3.00	0.05	0.01

Note: The number in parenthesis is the monthly release.

Type II plus ADIP Type I, the August additional releases are 0.49 maf for Lake Powell and 0.95 maf for Lake Mead.

Assume the Lakes Powell and Mead operation for August follows the target release and additional release schedules exactly. The end of August storages which will be used as the initial storages for September are determined from August mass balance of Lakes Powell and Mead based on the actual inflows as shown in Appendix C. The additional release decisions of September to April are made similarly to that of August and they are shown in Table 4.15.

The release and storage characteristics of Lakes Powell and Mead during ADIP Type I dictated by the ADIP-based operation with the operational failure probability criteria are presented in Table 4.16.

4.4.3.4 Comparison of The ADIP-Based Operation with The Failure Probability Criteria with The May 1983 - April 1984 Operating Plan and Actual Operation

The ADIP-based operation with the operational failure probability criteria gives the storage and release characteristics of Lakes Powell and Mead as shown in Table 4.16. Note that these characteristics are based on the actual inflow to Lake Powell and side flow to Lake Mead during May 1983 to April 1984. The release characteristics of Lakes Powell and Mead derived in this illustration are plotted against the actual release and the release of the USBR annual operating plan of the same time period in

Table 4.16 The Storage and Release Characteristics of Lakes Powell and Mead

Month	Powell					Mead				
	Release, maf.				Storage at the beginning of the month	Release, maf.				Storage at the beginning of the month
	Target	Additional	Total	Spill		Target	Additional	Total	Spill	
May	0.55	1.09	1.65		22.78	0.79	1.27	2.05		24.59
Jun.	0.59	1.14	1.72	1.60	23.77	0.72	1.23	1.95		24.34
Jul.	1.05	1.60	2.65	0.99	25.90	0.69	1.06	1.75		25.59
Aug.	1.01	0.49	1.50		25.90	0.64	0.95	1.58		27.44
Sep.	0.61	0.53	1.14		25.79	0.56	1.01	1.58		27.36
Oct.	0.57	0.54	1.10		25.36	0.54	0.99	1.53		26.87
Nov.	0.56	0.57	1.13		25.10	0.52	1.03	1.55		26.53
Dec.	0.86	0.59	1.45		24.73	0.55	1.07	1.62		26.17
Jan.	0.89	0.66	1.55		24.09	0.40	1.16	1.57		25.99
Feb.	0.53	0.73	1.26		23.39	0.61	1.28	1.89		25.90
Mar.	0.51	0.86	1.37		23.00	0.80	1.35	2.15		25.25
Apr.	0.52	0.91	1.43		22.66	0.82	1.41	2.22		24.53
May					22.68					23.81

Figures 4.9 and 4.10. Similarly Lakes Powell and Mead storages charateristics are plotted against the actual storage and the USBR annual operating plan storage in Figures 4.11 and 4.12.

The ADIP-based release depends on an initial storage content, time of the year and the stochastic pattern of inflow. Given the storage contents of 22.78 and 24.59 maf at the beginning of May for Lakes Powell and Mead respectively, the exceedance probabilities indicate high probability of Powell spill at the end of ADIP Type I (51 %) but rather low probability of Mead spill at the end of ADIP Type I (13 %). The spill probability criteria (0.13 for Lake Powell and 0.01 for Lake Mead) dictates the large volume of additional release from Lakes Powell and Mead, that is 3.28 maf for Powell and 3.79 maf for Mead, between May to the end of ADIP Type I (July), since the period of ADIP Type I is short, only 3 months, and the additional releases have to be made within that time period. The actual inflow to Lake Powell during May to July 1983 was extremely high. It was about 56 percent of the total inflow to Lake Powell during May 1983 to April 1984. This increased the storage contents considerably in both lakes during May to July. The higher initial storage contents together with the shorter time to distribute the additional release result in the high intensity release during ADIP Type I, particulrly from Lake Powell, as appeared in Figures 4.9 and 4.10.

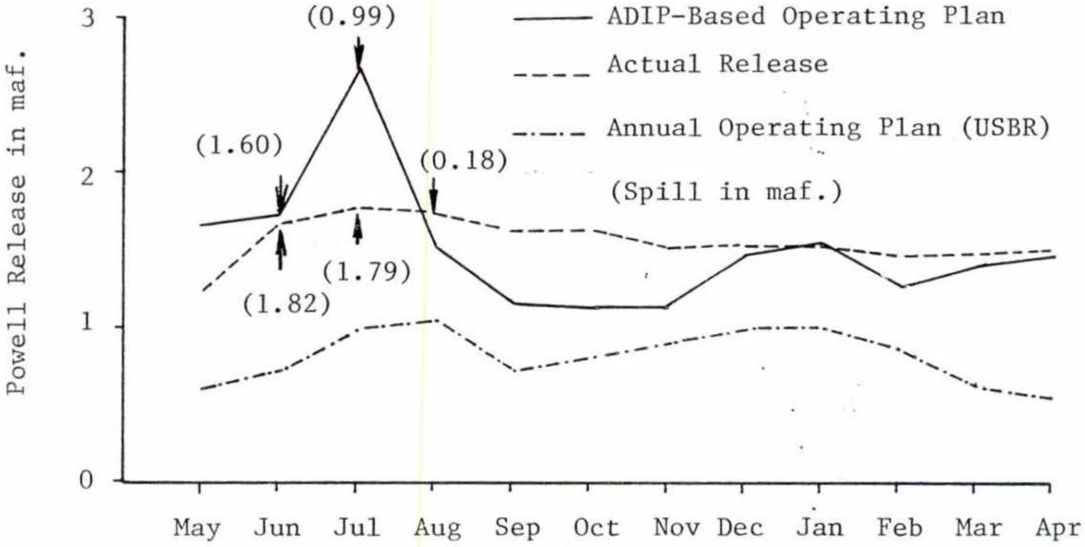

Figure 4.9 Powell Release Characteristics for Illustration No.2

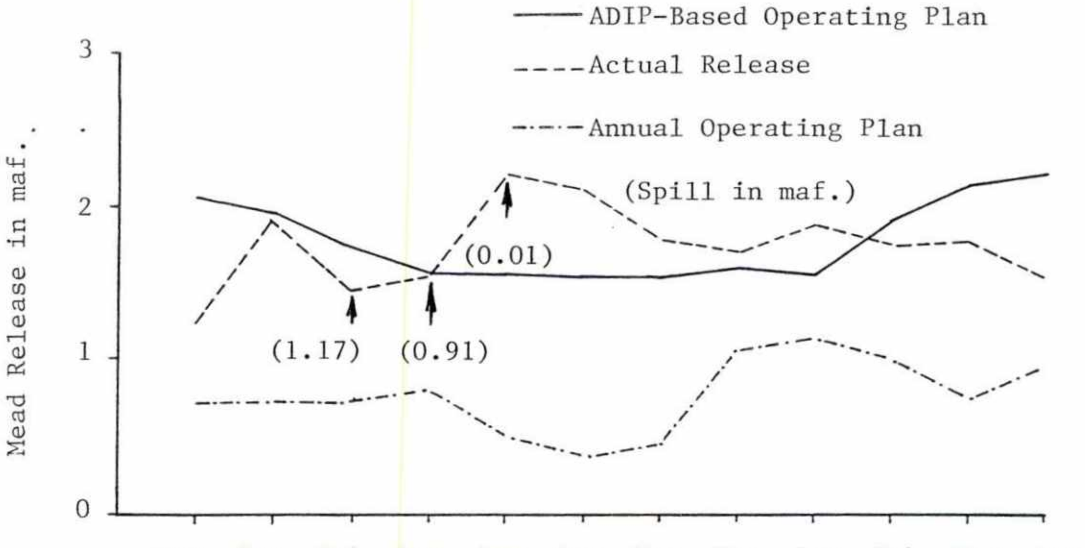

Figure 4.10 Mead Release Characteristics for Illustration No.2

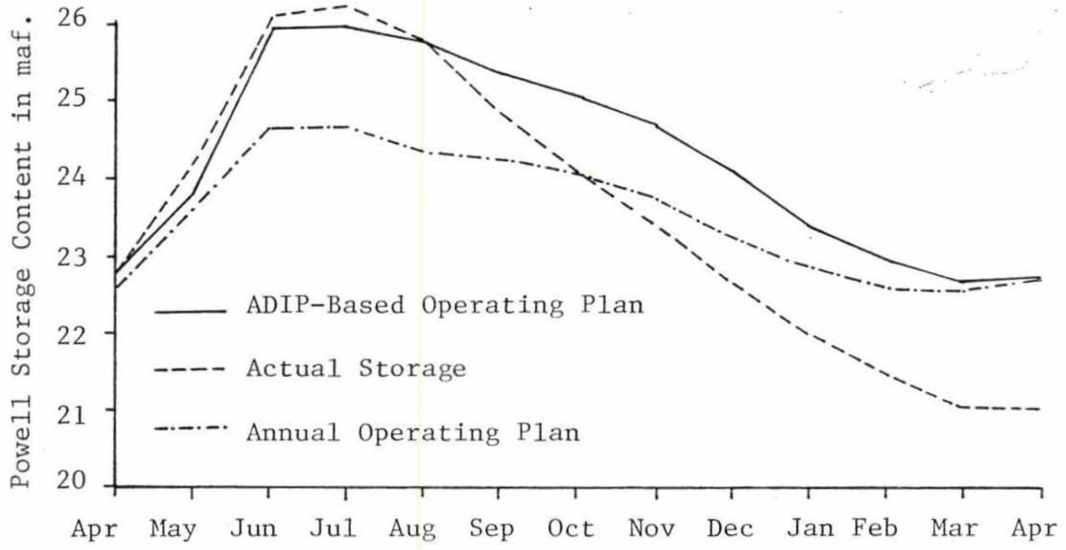

Figure 4.11 Powell Storage Characteristics for Illustration No.2

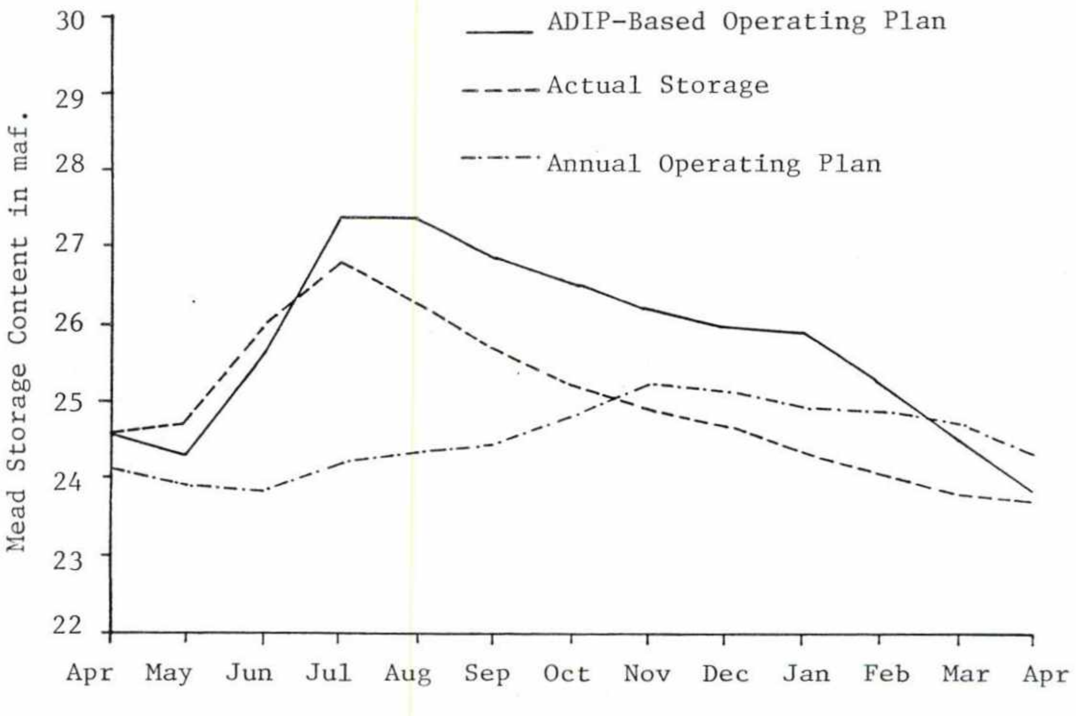

Figure 4.12 Mead Storage Characteristics for Illustration No.2

At the beginning of ADIP Type II, since there is longer time to distribute the additional releases, the releases drop considerably compared to the release in the ADIP Type I. However the releases start increasing during the last few months of ADIP Type II when the time for distributing the additional release becomes shorter and the probability of spill at the end of subsequent ADIP Type I increases. The actual releases during ADIP Type II as shown in Figures 4.9 and 4.10 are ,on the other hand, almost as high as that during ADIP Type I. This is because in the actual operation the reservoir storages were high at the end of ADIP Type I because of the very high inflow during May to July 1983, the flood control regulation of the Colorado River system required that a considerable amount of water be removed from the flood control zone.

According to the nature of the ADIP-based operation with the probability criteria and the assumption of uniform additional release, the ADIP-based operation gives a higher release during ADIP Type I but a smaller release during ADIP Type II when compared to the actual release of May 1983 to April 1984. However during the last few months of ADIP Type II, the ADIP-based operation gives high release particularly Mead release as shown in Figure 4.10. The release characteristics of Lake Powell produced by the ADIP-based method are more irregular than that given by the actual operation because of the nature of the ADIP-based operation explained in the previous paragraph (release a lot of water if the probability of spill is high and the time to distribute the additional release is short) and the variation of inflow to Lake Powell during the selected 12-month operation. The opposite result is shown for the case of Lake Mead in Figure 4.10, the release characteristics produced by the ADIP-based method are rather smooth. This can be explained from the point that the inflow to Lake Mead has less variation than that to Lake Powell and the probability of spill from Lake Mead depends on the combination of Powell and Mead storage contents, not only Lake Mead storage. Also the sensitivity of Mead probability of spill to Mead storage itself is less than that of Powell probability of spill to Powell storage.

It is noted that the ADIP-based method gives less unintentional spill than the actual operation. This is because the spill probability criteria is chosen such that a small chance of spill (13 % for Powell and 1 % for Mead) is allowed.

The storage characteristics of Lakes Powell and Mead are presented in Figures 4.11 and 4.12. They reflect the release characteristics, for example the storages produced by the ADIP-based operation of both lakes during ADIP Type II are higher than those of the actual operation because the releases of the ADIP-based operation are smaller.

The storage and release characteristics of the USBR annual operating plan were plotted in Figures 4.9 to 4.12 for the purpose of comparison that the USBR annual operating plan could be far different from the actual operation when the forecast of inflow was not correct.

4.4.4 Illustration No. 3

This part of study will illustrate how to use the forecast of inflow to update the apriori generated exceedance probabilities of future operational failures (spill and deficit) based on the method presented in Section 3.7. The exceedance probabilities of spill and deficit before and after making the additional release based on the future failure probability criteria, 0.13 for Powell spill and 0.01 for Mead spill, as shown in Illustration No.2 will be updated according to the forecast of inflow to Lake Powell. The updated exceedance probabilities will be used for evaluating how good the additional release plan is without the forecast.

According to the actual operation of the Colorado River Storage Project, the forecast of April - July natural inflow to Lake Powell will first be available in January and it will be updated every month. This forecast is used for determining the operating plan for Lakes Powell and Mead. If the forecasted inflow is close to what will actually happen, it will be useful for developing a good operational plan. If the forecast is wrong, it will give a wrong operating plan. The later case is worse than developing the operational plan without the forecast. The April - July forecast of inflow to Lake Powell during 1958 - 1983 made by the USBR is shown in Table 4.17. On the average, the

Table 4.17 April - July Forecast of Inflow to Lake Powell
(Units are in maf.)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Actual Apr.-Jul.
1958	12.90	11.80	12.10	11.00	10.60	9.70	9.90
Dif	3.00	1.90	2.20	1.10	0.70	-0.20	
1959	5.70	5.10	6.10	5.10	4.90	4.50	4.05
Dif	1.65	1.05	2.05	1.05	0.85	0.45	
1960	8.50	8.40	9.20	7.40	6.80	6.50	6.05
Dif	2.45	2.35	3.15	1.35	0.75	0.45	
1961	8.10	6.60	5.80	5.20	5.00	4.80	3.70
Dif	4.40	2.90	2.10	1.50	1.30	1.10	
1962	8.00	8.10	10.20	10.40	10.10	9.80	10.65
Dif	-2.65	-2.55	-0.45	-0.25	-0.55	-0.85	
1963	6.70	7.10	6.60	4.50	4.00	3.00	3.30
Dif	3.40	3.80	3.30	1.20	0.70	-0.30	
1964	6.50	5.70	4.70	4.70	5.10	5.10	5.55
Dif	0.95	0.15	-0.85	-0.85	-0.45	-0.45	
1965	9.00	9.60	9.00	10.80	11.00	11.00	11.67
Dif	-2.67	-2.07	-2.67	-0.87	-0.67	-0.67	
1966	9.30	7.90	7.00	4.50	3.50	3.90	4.67
Dif	4.63	3.23	2.33	-0.17	-1.17	-0.77	
1967	10.00	9.90	8.80	6.30	5.10	5.70	6.05
Dif	3.95	3.85	2.75	0.25	-0.95	-0.35	
1968	7.70	6.70	7.00	6.90	7.30	7.30	7.23
Dif	0.47	-0.53	-0.23	-0.33	0.07	0.07	
1969	7.00	8.80	9.00	9.00	8.50	7.40	8.15
Dif	-1.15	0.65	0.85	0.85	0.35	-0.75	
1970	9.20	8.50	6.70	7.50	7.60	7.00	8.25
Dif	0.95	0.25	-1.55	-0.75	-0.65	-1.25	
1971	8.50	7.60	7.60	7.50	7.50	7.50	8.35
Dif	0.15	-0.75	-0.75	-0.85	-0.85	-0.85	
1972	10.00	9.30	8.30	6.40	6.10	5.70	5.50
Dif	4.45	3.75	2.75	0.85	0.55	0.15	
1973	9.50	9.00	8.40	9.00	9.00	10.00	11.35
Dif	-1.85	-2.35	-2.95	-2.35	-2.35	-1.35	
1974	7.00	9.00	9.00	8.00	8.40	7.60	7.05
Dif	-0.05	1.95	1.95	0.95	1.35	0.55	
1975	7.00	7.80	8.00	9.80	10.50	10.50	10.40
Dif	-3.40	-2.60	-2.40	-0.60	0.10	0.10	
1976	7.50	6.80	7.90	7.60	7.40	7.40	5.30
Dif	2.20	1.50	2.60	2.30	2.10	2.10	
1977	5.00	5.00	2.20	2.20	2.20	1.80	1.10
Dif	3.90	3.90	1.10	1.10	1.10	0.70	
1978	7.50	9.00	9.50	10.80	10.80	11.00	9.00
Dif	-1.50	0.	0.50	1.80	1.80	2.00	
1979	8.40	10.50	11.50	11.70	11.30	11.70	10.90
Dif	-2.50	-0.40	0.60	0.80	0.40	0.80	

Table 4.17(cont.) April- July Forecast of Inflow to Lake Powell (Units are in maf.)

Year	Jan.	Feb.	Mar.	Apr.	May	Jun.	Actual Apr.-Jul.
1980	6.00	8.35	10.00	10.80	10.80	11.40	10.80
Dif	-4.80	-2.45	-0.80	0.	0.	0.60	
1981	5.70	4.50	3.00	3.20	2.80	2.80	3.00
Dif	2.70	1.50	0.	0.20	-0.20	-0.20	
1982	8.00	8.80	8.20	8.70	8.70	8.70	8.20
Dif	-0.20	0.60	0.	0.50	0.50	0.50	
1983	7.80	7.10	6.70	7.90	8.10	9.10	14.50
Dif	-6.70	-7.40	-7.80	-6.60	-6.40	-5.40	
Tot	206.50	206.95	202.50	196.90	193.10	190.90	194.72
Ave	7.92	7.96	7.79	7.57	7.43	7.34	7.49
Stdv	1.68	1.73	2.28	2.60	2.72	2.86	3.24
Sdif	11.78	12.23	7.78	2.18	-1.62	-3.82	
Avdf	0.45	0.47	0.30	0.08	-0.06	-0.15	
Stder	3.08	2.65	2.47	1.71	1.63	1.38	

Tot = Total of that month from 1958 to 1983
Ave = Average of total over 26 years
Stdv = Standard deviation
Dif = Difference of actual value and forecast value
Sdif = Sum of the differences of that month from 1958 thru 1983
Avdf = Average of the differences
Stder = Standard deviation of errors for each from 1958 thru 1983

1958 - 79 values are for runoff at Grand Canyon (USBR forecast).
1980 - 83 values are Colorado River Forecast Service (NWS-RFC) for runoff upstream of Lake Powell.

forecast in Table 4.17 is slightly over-estimates the actual value. This results in a conservative plan for flood control. However the 1983 forecast was about 50 percent lower than the actual value, the result was the flooding downstream of Lakes Powell and Mead. The total estimated damages were roughly $ 80.0 million dollars, Holburt(1984).

The analysis in this part of the study will illustrate the effects of incorporating a right forecast and a wrong forecast of inflow in making the ADIP-based operating plan. The actual inflow to Lake Powell during May 1983 to April 1984 as shown in Table 4.18 will be used for representing the correct forecast during that period. The actual 1983 forecast of inflow to Lake Powell is assumed to represent the wrong forecast, about 50 percent less than the actual April - July inflow to Lake Powell.

4.4.4.1 THe Case When The Forecast Is Correct

The ADIP-based method has two different planing periods, ADIP Type I and ADIP Type II. Given the initial condition such as the reservoir storage content at the beginning of ADIP Type I, the future operational failure (spill/deficit) characteristics at the end of ADIP Type I and those at the end of subsequent ADIP Type II can be obtained from the apriori generated exceedance probabilities of an operational failure (spill/deficit). The future operational failure characteristics together with the operational objectives and the judgement can be used to formulate the operating plan for ADIP Type I. Similarly the

Table 4.18 The Actual Regulated Inflow to Lake Powell in maf. (Source: The Operational Plan for Colorado River Storage Project of 1983 - 1984, USBR, Denver, Colorado)

Month	1983	1984
Jan.	0.70	0.82
Feb.	0.66	0.88
Mar.	1.13	1.05
Apr.	1.10	1.50
May	2.78	4.77
Jun.	5.70	4.85
Jul.	3.73	2.42
Aug.	1.48	1.40
Sep.	0.75	0.88
Oct.	0.90	1.01
Nov.	0.78	0.93
Dec.	0.81	0.83

operating plan for ADIP Type II can be developed based on the initial storage at the beginning of ADIP Type II.

The forecast of inflow from now to the end of ADIP Type I will help predict the spill characteristics at the end of ADIP Type I more accurately. Similarly the forecast of inflow from now to the end of ADIP Type II will help predict the deficit characteristics at the end of ADIP Type II more accurately. The more accurate prediction of the future operational failure characteristics will result in a better operating plan.

Determination of The Operating Plan for ADIP Type I for Lake Powell and Mead

The same initial condition as used in Illustration No.2 is used in here, that is the storage at the beginning of May (the beginning month of ADIP Type I) is 22.78 maf for Lake Powell and 24.59 maf for Lake Mead. The exceedance probability of spill at the end of July and that of deficit at the end of April are obtained from Figures B1(a) and B1(b) for Lake Powell and from Tables B1(a) and B1(b) for Lake Mead.

Although the actual forecast of April - July inflow to Lake Powell is first made in January, only the forecast available at the beginning of May will be used according to the planning period , ADIP type I (May to July) and ADIP Type II (August to April), of the ADIP-based method. Given the forecast of May - July inflow to Lake Powell available at the beginning of May is 12.21 maf (this is the actual May - July inflow in 1983 obtained from Table 4.18). This forecasted inflow is in the upper quartile since it is greater than the maximum value of the upper quartile of the cumulative monthly inflow from May to July obtained from Table 4.19, which is equal to 11.52 maf. The forecasted inflow from August to April is 8.97 maf. (also this is the actual August 1983 to April 1984 obtained from Table 4.18) which is in the upper quartile too. The minimum value of the upper quartile of August to April inflow to Lake Powell is 6.34 maf.

Table 4.19 The Quartiles of Cumulative Monthly Inflow to Lake Powell from The Current Month to The End of The Current ADIP[1]

ADIP Type	Month	Inflow in maf.			
		Upper Quartile	Second Quartile	Third Quartile	Lower Quartile
		>	> to ≤	> to ≤	≤
I	May	11.44	9.06-11.44	7.07-9.06	7.07
	Jun.	7.71	6.05- 7.71	4.52-6.05	4.52
	Jul.	2.68	2.02- 2.68	1.48-2.02	1.47
II	Aug.	6.34	5.45- 6.34	4.68-5.45	4.68
	Sep.	5.11	4.39- 5.11	3.81-4.39	3.81
	Oct.	4.39	3.75- 4.39	3.25-3.75	3.25
	Nov.	3.76	3.23- 3.76	2.78-3.23	2.78
	Dec.	3.23	2.77- 3.23	2.34-2.77	2.34
	Jan.	2.86	2.43- 2.86	1.99-2.43	1.99
	Feb.	2.54	2.09- 2.54	1.69-2.09	1.69
	Mar.	2.15	1.70- 2.15	1.33-1.70	1.33
	Apr.	1.44	1.07- 1.44	0.81-1.07	0.81

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[1] This table is obtained from the frequency distribution analysis of 500 years of the generated inflows at Lees Ferry. The frequency is calculated from n/(N+1)).

Based on the method of adjusting the exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II in Section 3.7, the apriori generated exceedance probabilities have to be adjusted according to the forecast of inflow. Since the forecasts of May to July inflow and August to April inflow are in the upper quartiles, the exceedance probability of spill at the end of ADIP Type I can be adjusted by Equation 3.29:

$$P'[S \geq s] = P[S \geq s]*4$$

and that of deficit at the end of ADIP Type II can be adjusted by Equation 3.33:

$$P'[D \geq d] = \{P[D \geq d] - 0.75\}*4$$

Given the May initial storages of Lakes Powell and Mead, the exceedance probabilities of spill of both lakes before and after adjusted are presented in Table 4.20. Note that the exceedance probabilities of deficit of both Lakes Powell and Mead are essentially zero and are not shown in Table 4.20. The adjusted exceedance probabilities of spill indicate that about 2.56 maf will spill from Lake Powell by the end of July and there is a probability of 0.16 that the spill from Lake Mead will be greater than or equal to 3.00 maf. Based on these adjusted exceedance probabilities of spill , it is decided that the additional releases from Lakes Powell and Mead are 3.28 and 3.79 maf respectively, which are the same as the additional releases for ADIP Type

Table 4.20 The Effect of Additional Releases in ADIP Type I on The Adjusted Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S\geq s]$	$P'_p[S\geq s]$	$P_{p,m}[S\geq s]$	$P'_{p,m}[S\geq s]$
	Powell	Mead	Powell (p)	Mead (m)					
May			22.78	24.59	0.	0.51	-	0.13	0.52
					1.00	0.40	-	0.08	0.32
					2.00	0.30	-	0.05	0.20
					2.56*	0.25	1.00		
					3.00	0.21	0.84	0.04	0.16
	3.28 (1.09) **	3.79 (1.27) **	19.50	24.08	0.	0.13	0.52	0.01	0.04
					1.00	0.10	0.40	0.007	0.03
					2.00	0.07	0.28	0.006	0.02
					3.00	0.04	0.16	0.005	0.02
Jun.			23.77	24.34	0.	0.51	-	0.06	0.24
					1.00	0.37	-	0.03	0.12
					1.86*	0.25	1.00		
					2.00	0.23	0.92	0.01	0.04
					3.00	0.14	0.56	0.008	0.03
	2.27 (1.14) **	2.45 (1.23) **	21.50	24.16	0.	0.13	0.52	0.01	0.04
					1.00	0.11	0.44	0.006	0.02
					2.00	0.07	0.28	0.004	0.02
					3.00	0.03	0.12	0.002	0.01

Table 4.20(cont.) The Effect of Additional Releases in ADIP Type I on The Adjusted Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P'_p[S \geq s]$	$P_{p,m}[S \geq s]$	$P'_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)					
Jul.			25.90	25.59	0.	0.55	–	0.02	0.08
					0.81*	0.25	1.00		
					1.00	0.18	0.72	0.005	0.02
					2.00	0.06	0.24	0.003	0.01
					3.00	0.01	0.04	0.	0.
	1.60 (1.60) **	1.06 (1.06) **	24.30	26.13	0.	0.13	0.52	0.01	0.04
					1.00	0.05	0.20	0.002	0.01
					2.00	0.01	0.04	0.001	0.
					3.00	0.00	0.00	0.	0.

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* Determined by interpolation

** The numbers in parenthesis are the additional release for that month.

I decided in May as shown in Table 4.14 of Illustration No.2. Assuming that 3.28 and 3.79 maf additional releases from Lakes Powell and Mead take place at the beginning of May, the new initial storages for Powell and Mead are 19.50 and 24.08 maf respectively. According to the new initial storages, the adjusted exceedance probabilities in Table 4.20 indicate that the probabilities of spill at the end of ADIP Type I, when considering the forecast of May to July inflow, are 0.52 for Lake Powell and 0.04 for Lake Mead. If this adjusted exceedance probability of spill from Lake Powell is too high, more additional release should be made to reduce that probability to an acceptable level. For sake of illustration, it is assumed that 0.52 probability of spill from Lake Powell and 0.04 probability of spill from Lake Mead are acceptable.

When uses 0.52 adjusted probability of spill from Lake Powell and 0.04 adjusted probability of spill from Lake Mead as the future spill probability criteria, the additional release decisions in this illustration are the same as those in Table 4.14 of Illustration No.2. However the adjusted exceedance probabilities in here give more accurate prediction of the future operational failure characteristics as long as the forecast of inflow is not much deviated from the realization. The mass balance of May is performed according to the target and additional releases and the actual inflows to determine the storages at the end of May for Lakes Powell and Mead. The storages at the end of May will be used as the initial storages for June.

The forecast of June - July inflow is 9.43 maf and the July inflow is 3.73 maf. Both are in the upper quartile. The exceedance probabilities of spill in both lakes will be adjusted by multiplying the apriori generated exceedance probabilties of spill of less than or equal to 0.25 by 4. The exceedance probabilities of spill from both Lakes Powell and Mead before and after adjusted and the additional release decisions for June and July are presented in Table 4.20.

Since the future failure probability criteria used in this illustration is equivalent to the one used in Illustration No. 2, the storage, release and spill characteristics of Lakes Powell and Mead for ADIP Type I (May to July) dictated by the ADIP-based method with the failure probability criteria and utilizing the forecast of inflow are the same as those in Table 4.16 of Illustration No. 2. However the predicted future characteristics of spill (in term of the adjusted exceedance probabilities of spill) in Table 4.20 are more accurate and concise than those in Table 4.14 as long as the forecast of inflow is close to the realization.

Determination of The Operating Plan for ADIP Type II for Lakes Powell and Mead

The storage contents at the end of ADIP Type I for Lakes Powell and Mead are 25.90 and 27.44 maf respectively, which will be used as the initial storage contents at the beginning of ADIP Type II for the ADIP-based operation with the forecast of inflow. The future failure (spill/deficit) probability criteria which will be used in here are 0.52 adjusted probability of spill from Lake Powell and 0.04 adjusted probability of spill from Lake Mead. Since this spill probability criteria are equivalent to those used in Illustration No. 2, that is 0.13 apriori generated probability of Powell spill and 0.01 apriori generated probability of Mead spill, the additional release decisions during ADIP Type II will be the same as those in Table 4.15 of Illustration No. 2. However the apriori generated exceedance probabilities of spill from both Lakes will be adjusted based on the forecast of inflow. As mentioned in Illustration No. 1 and No. 2, the exceedance probabilities of deficit at the end of ADIP Type II are essentially zero and cannot be used to base the release decision, the decision period then has to be extended to the end of subsequent ADIP Type I.

Assume that the forecast is correct and the actual inflow to Lake Powell in Table 4.18 is used to represent the forecast. The forecasts of cumulative monthly inflow to Lake Powell from

August to July is 21.01 maf,
September to July is 19.52 maf,
October to July is 18.77 maf,
November to July is 17.87 maf,

December to July is 17.09 maf,
January to July is 16.28 maf,
February to July is 15.46 maf,
March to July is 14.59 maf,
April to July is 13.54 maf.

When comparing the forecast of cumulative inflow from the month in ADIP Type II to the end of subsequent ADIP Type I to the corresponding quartiles of inflow in Table 4.19, it indicates that all the forecasts are in the upper quartile. Equations 3.29 and 3.33 in Section 3.7 will be used for adjusting the apriori generated exceedance probabilities of spill and deficit respectively. Table 4.21 shows the adjusted exceedance probabilities of spill from both Lakes Powell and Mead.

The release and storage characteristics of Lakes Powell and Mead during ADIP Type II (August to April) are the same as those in Table 4.16 of Illustration No. 2.

4.4.4.2 The Case When The Forecast Is Not Correct

The actual April - July inflow forecast of 1983 was about 50 percent under-estimate the actual inflow to Lake Powell of that time period, as seen in Table 4.17. It will be used for an illustration of how a bad forecast results in a worse operating plan. Practically the Colorado River Storage Project makes the first April - July inflow forecast in January. The forecast is updated every month since then. The forecast of inflow is made for the period of high flow, April to July. It covers the entire period of ADIP Type I.

Table 4.21 The Effect of Additional Releases in ADIP Type II on The Adjusted Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S\geq s]$	$P'_p[S\geq s]$	$P_{p,m}[S\geq s]$	$P'_{p,m}[S\geq s]$
	Powell	Mead	Powell (p)	Mead (m)					
Aug.			25.90	27.44	0.	0.73	-	0.61	-
					1.00	0.64	-	0.50	-
					2.00	0.54	-	0.41	-
					3.00	0.44	-	0.33	-
					>3.00		1.00		1.00
	5.90 (0.49) **	11.34 (0.95) **	20.00	22.00	0.	0.13	0.52	0.01	0.04
					1.00	0.11	0.44	0.009	0.04
					2.00	0.08	0.32	0.008	0.03
					3.00	0.05	0.20	0.006	0.02
Sep.			25.79	27.36	0.	0.78	-	0.60	-
					1.00	0.68	-	0.50	-
					2.00	0.57	-	0.40	-
					3.00	0.47	-	0.32	-
					>3.00		1.00		1.00
	5.79 (0.53) **	11.16 (1.01) **	20.00	22.00	0.	0.13	0.52	0.01	0.04
					1.00	0.11	0.44	0.008	0.03
					2.00	0.08	0.32	0.008	0.03
					3.00	0.05	0.20	0.006	0.02

Table 4.21(cont.) The Effect of Additional Releases in ADIP Type II on The Adjusted Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P'_p[S \geq s]$	$P_{p,m}[S \geq s]$	$P'_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)					
Oct.			25.36	26.87	0.	0.74	-	0.52	-
					1.00	0.63	-	0.42	-
					2.00	0.52	-	0.33	-
					3.00	0.43	-	0.26	-
					>3.00		1.00		1.00
	5.36 (0.54) **	9.92 (0.99) **	20.00	22.31	0.	0.13	0.52	0.01	0.04
					1.00	0.11	0.44	0.009	0.04
					2.00	0.08	0.32	0.008	0.03
					3.00	0.05	0.20	0.007	0.03
Nov.			25.10	26.53	0.	0.71	-	0.46	-
					1.00	0.60	-	0.37	-
					2.00	0.50	-	0.29	-
					2.57*			0.25	1.00
					3.00	0.40	-	0.22	0.88
					>3.00		1.00		
	5.10 (0.57) **	9.27 (1.03) **	20.00	22.36	0.	0.13	0.52	0.01	0.04
					1.00	0.11	0.44	0.009	0.04
					2.00	0.08	0.32	0.007	0.03
					3.00	0.05	0.20	0.006	0.02

Table 4.21(cont.) The Effect of Additional Releases in ADIP Type II on The Adjusted Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P'_p[S \geq s]$	$P_{p,m}[S \geq s]$	$P'_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)					
Dec.			24.73	26.17	0.	0.68	-	0.39	-
					1.00	0.58	-	0.31	-
					1.86*			0.25	1.00
					2.00	0.47	-	0.24	0.96
					3.00	0.37	-	0.17	0.68
					>3.00		1.00		
	4.73 (0.59) **	8.53 (1.07) **	20.00	22.36	0.	0.13	0.52	0.01	0.04
					1.00	0.11	0.44	0.009	0.03
					2.00	0.08	0.32	0.007	0.03
					3.00	0.05	0.20	0.006	0.02
Jan.			24.09	25.99	0.	0.66	-	0.31	-
					0.86*			0.25	1.00
					1.00	0.54	-	0.24	0.96
					2.00	0.43	-	0.18	0.72
					3.00	0.34	-	0.13	0.52
					>3.00		1.00		
	4.59 (0.66) **	8.15 (1.16) **	19.50	22.43	0.	0.13	0.52	0.01	0.04
					1.00	0.11	0.44	0.009	0.04
					2.00	0.08	0.32	0.007	0.03
					3.00	0.05	0.20	0.006	0.02

Table 4.21(cont.) The Effect of Additional Releases in ADIP Type II on The Adjusted Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P'_p[S \geq s]$	$P_{p,m}[S \geq s]$	$P'_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)					
Feb.			23.39	25.90	0.	0.62	-	0.25	1.00
					1.00	0.50	-	0.19	0.76
					2.00	0.40	-	0.14	0.56
					3.00	0.31	-	0.09	0.36
					>3.00		1.00		
	4.39 (0.73) **	7.68 (1.28) **	19.50	22.62	0.	0.13	0.52	0.01	0.04
					1.00	0.10	0.40	0.009	0.04
					2.00	0.07	0.28	0.006	0.02
					3.00	0.05	0.20	0.005	0.02
Mar.			23.00	25.25	0.	0.58	-	0.20	0.80
					1.00	0.47	-	0.14	0.56
					2.00	0.36	-	0.10	0.40
					3.00	0.28	-	0.07	0.28
					>3.00		1.00		
	4.30 (0.86) **	6.73 (1.35) **	18.70	22.82	0.	0.13	0.52	0.01	0.04
					1.00	0.10	0.40	0.009	0.04
					2.00	0.07	0.28	0.006	0.02
					3.00	0.04	0.16	0.005	0.02

Table 4.21(cont.) The Effect of Additional Releases in ADIP Type II on The Adjusted Exceedance Probability of Spill at The End of ADIP Type I

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P'_p[S \geq s]$	$P_{p,m}[S \geq s]$	$P'_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)					
Apr.			22.66	24.53	0.	0.53	-	0.13	0.52
					1.00	0.42	-	0.09	0.36
					2.00	0.33	-	0.06	0.24
					2.89*	0.25	1.00		
					3.00	0.24	0.96	0.04	0.16
	3.66 (0.91) **	5.62 (1.41) **	19.00	22.57	0.	0.13	0.52	0.01	0.04
					1.00	0.10	0.40	0.009	0.04
					2.00	0.07	0.28	0.005	0.02
					3.00	0.05	0.20	0.005	0.02

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* Determined by interpolation

** The numbers in parenthesis are the additional release for that month.

According to the ADIP-based method, actually the forecast of May to July inflow obtained at the beginning of May, June and July should be used instead, since ADIP Type I is the period from May to July. The April - July forecasts in May, June and July obtained from Table 4.17 are 8.10, 9.10 and 14.50 maf respectively. These available forecasts of inflow will be recalculated based on actual historical inflow of 1983 obtained from Table 4.18 to represent the May to July, June to July and July inflow forecasts. There is no available forecast of inflow during ADIP Type II. Therefore, the illustration of how to incorporate the forecast of inflow into the ADIP-based method for setting up the operating plan will be done for ADIP Type I only.

Determination of The Operating Plan for ADIP Type I for Lakes Powell and Mead

For this illustration, the storage contents at the beginning of May are 22.78 and 24.59 maf for Lakes Powell and Mead respectively, which are the same as those used in Illustration No.2. The exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II are obtained from Figures B1(a) and B1(b) for Lake Powell and from Tables B1(a) and B1(b) for Lake Mead. The exceedance probabilities are the same as those in Table 4.5. Since the April - July forecast of inflow in May 1983 was 8.10 maf and the actual inflow of April 1983 was 1.10 maf, the May - July inflow forecast was 7.01 maf. This May - July inflow forecast was classified into the lower quartile, less than 7.07 maf. The apriori generated exceedance probability of spill will be adjusted by Equation 3.32:

$$P'[S\geq s] = \{P[S\geq s] - 0.75\}*4$$

which whenever the adjusted exceedance probability of spill, $P'[S\geq s]$, is less than 0., it will assume zero value. Similarly that of deficit will be adjusted by Equation 3.36:

$$P'[D\geq d] = P[D\geq d]*4$$

Since all the exceedance probabilities of deficit are essentially zero, and all those exceedance probabilities of spill are less than 0.75, the adjusted exceedance probabilities of spill and deficit of both lakes Powell and Mead are essentially zero. The release decision at the beginning of May is to meet the target release in Table 4.4, that is 0.55 and 0.79 maf for Lakes Powell and Mead respectively. No additional release is needed.

The mass balance analysis in Appendix C indicates that the end of May storage contents of Lakes Powell and Mead are 24.79 and 24.50 maf respectively. These numbers will be used as the June initial storage contents. With the June initial storages, the exceedance probabilities of spill and deficit for Lake Powell are obtained from Figures B2(a) and B2(b) and those for Lake Mead are obtained from Tables B2(a) and B2(b) as shown in Table 4.22. Note that the exceedance

Table 4.22 The Apriori Generated Exceedance Probability and The Adjusteded Exceedance Probability of Spill at The End of ADIP Type I for Lakes Powell and Mead

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P'_p[S \geq s]$	$P_{p,m}[S \geq s]$	$P'_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)					
May			22.78	24.59	0.	0.51	0.	0.13	0.
					1.00	0.40	0.	0.08	0.
					2.00	0.30	0.	0.05	0.
					3.00	0.20	0.	0.04	0.
	0.	0.	22.78	24.59	0.	0.51	0.	0.13	0.
					1.00	0.40	0.	0.08	0.
					2.00	0.30	0.	0.05	0.
					3.00	0.20	0.	0.04	0.
Jun.			24.79	24.50	0.	0.68	0.72	0.12	0.
					1.00	0.53	0.12	0.07	0.
					1.20*	0.50	0.		
					2.00	0.38	-	0.04	0.
					3.00	0.29	-	0.02	0.
	0.39 (0.19) **	0.	24.40	24.88	0.	0.63	0.52	0.12	0.
					0.81*	0.50	0.		
					1.00	0.47	-	0.07	0.
					2.00	0.31	-	0.04	0.
					3.00	0.22	-	0.02	0.

Table 4.22(cont.) The Apriori Generated Exceedance Probability and The Adjusted Exceedance Probability of Spill at The End of ADIP Type I for Lakes Powell and Mead

Month	Additional Release Through The End of ADIP I (maf)		Initial Storage (maf)		s (maf)	$P_p[S \geq s]$	$P'_p[S \geq s]$	$P_{p,m}[S \geq s]$	$P'_{p,m}[S \geq s]$
	Powell	Mead	Powell (p)	Mead (m)					
Jul.			25.90	27.92	0.	0.55	-	0.23	0.92
					1.00	0.18	0.72	0.07	0.28
					2.00	0.06	0.24	0.02	0.08
					3.00	0.02	0.08	0.006	0.02
	1.60 (1.60) **	3.39 (3.39) **	24.30	26.13	0.	0.13	0.52	0.01	0.04
					1.00	0.05	0.20	0.002	0.01
					2.00	0.01	0.04	0.001	0.
					3.00	0.00	0.00	0.	0.

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* Determined by interpolation

** The numbers in parenthesis are the additional release for that month.

probabilities of deficit are all essentially zero and are not shown in Table 4.22.

Since the April - July forecast of inflow in June 1983 was 9.10 maf and the actual inflows of April and May 1983 were 1.10 and 2.78 maf respectively, the estimated June - July forecast was 5.22 maf. The forecast of June - July inflow was in the third quartile, between 4.52 and 6.05 maf. The exceedance probabilities of spill obtained from Figure B2(a) and Table B2(a) will be adjusted by Equation 3.31:

$$P'[S \geq s] = \{P[S \geq s] - 0.50\}*4$$

Table 4.22 indicates that the adjusted probability of Powell spill is 0.72 which exceeds the spill probability criteria of Lake Powell. The 0.39 maf additional release from Lake Powell is decided to reduce the adjusted probability of Powell spill below the probability criteria limit of 0.52. Since the adjusted probability of Mead spill is zero, no additional release from Lake Mead is needed. Assume a uniform additional release from Lake Powell, the additional release in June is equal to 0.19 maf. The mass balance for Lakes Powell and Mead performed in Appendix C shows that the storages at the end of June are 25.90 and 27.92 maf for Powell and Mead respectively. The mass balance analysis also indicates that 3.63 maf of water would spill from Lake Powell in June.

With the July initial storages of 25.90 and 27.92 maf for Powell and Mead respectively, the exceedance probabilities of spill and deficit for Lake Powell are obtained from Figures B3(a) and B3(b) of Appendix B and those for Lake Mead are obtained from Tables B3(a) and B3(b) as shown in Table 4.22. Since all the exceedance probabilities of deficit are essentially zero, they are not shown.

The April - July forecast of inflow in July 1983 was 14.50 maf. The actual inflows of April, May and June 1983 were 1.10, 2.78 and 5.70 maf respectively. The estimated July forecast of inflow to Lake Powell was 4.93 maf. The forecasted inflow to Lake Powell for July was in the upper quartile, greater than 2.65 maf. The apriori generated exceedance probability of spill will be adjusted by Equation 3.29:

$$P'[S \geq s] = P[S \geq s]*4$$

The adjusted exceedance probabilities of spill from Lakes Powell and Mead at the end of July are shown in Table 4.22. Since the adjusted spill probability criteria are 0.52 and 0.04 for Lakes Powell and Mead respectively, the additional release from Lake Powell is 1.60 maf and that from Lake Mead is 3.39 maf.

The mass balance analysis of July in Appendix C indicates that the end of July storage contents for Lakes Powell and Mead are 25.90 and 27.58 maf respectively and 0.99 maf of water is spilled from Lake Powell.

Based on the actual forecast of April - July inflow to Lake Powell in 1983 and the actual inflow during May to July 1983, the ADIP-based method with the future failure probability criteria (0.52 for the adjusted probability of spill from Lake Powell and 0.04 for Lake Mead) gives the storage, release and spill characteristics for Lakes Powell and Mead as shown in Table 4.23.

Since in the actual operation of Lakes Powell and Mead, the forecast of inflow is made available only for a period of high inflow April - July which covers only for ADIP Type I, the illustration of how to incorporate the forecast of inflow into the ADIP-based method for setting up the operating plan is therefore made for ADIP Type I only.

4.4.4.3 Comparison of The Release and Storage Characteristics of Lakes Powell and Mead Derived from The Cases of Correct Forecast and Incorrect Forecast

The release and storage characteristics of Lakes Powell and Mead derived from the ADIP-based method with the future failure probability criteria and assumed correct forecast of inflow are presented in Table 4.16 and those with the same future failure probability criteria but assumed incorrect forecast of inflow are shown in Table 4.23. The comparison of the release characteristics of Lakes Powell and Mead of both cases is shown in Figures 4.13 and 4.14 and that of the storage characteristics is shown in Figures 4.15 and 4.16.

Table 4.23 The Storage, Release and Spill Characteristics of Lakes Powell and Mead During ADIP Type I for Illustration No.3

Month	Powell					Mead				
	Release, maf.				Storage at the beginning of the month	Release, maf.				Storage at the beginning of the month
	Target	Additional	Total	Spill		Target	Additional	Total	Spill	
May	0.55	-	0.55	-	22.78	0.79	-	0.79	-	24.59
Jun.	0.59	0.19	0.78	3.63	24.79	0.72	-	0.72	-	24.50
Jul.	1.05	1.60	2.65	0.99	25.90	0.69	3.39	4.08	-	27.92
Aug.					25902					27582

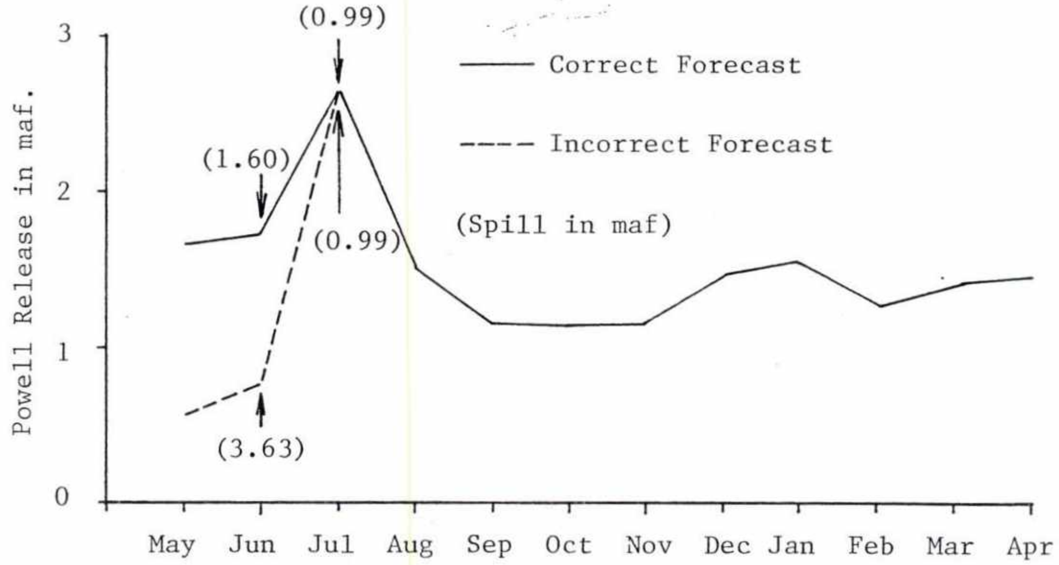

Figure 4.13 Powell Release Characteristics for Illustration No.3

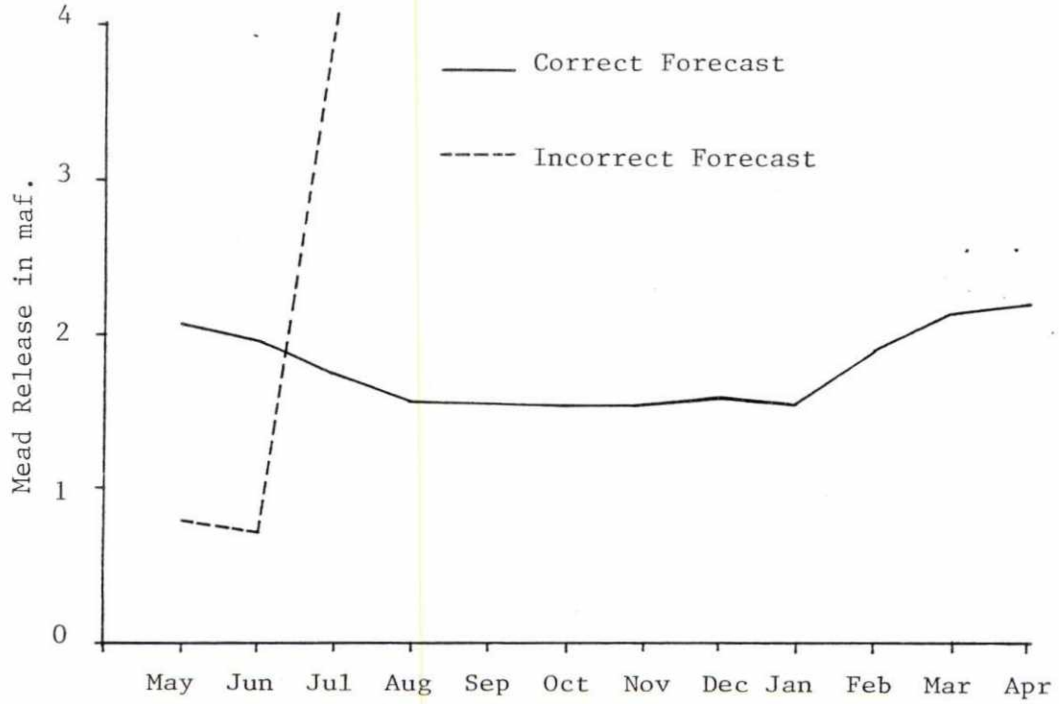

Figure 4.14 Mead Release Characteristics for Illustration No.3

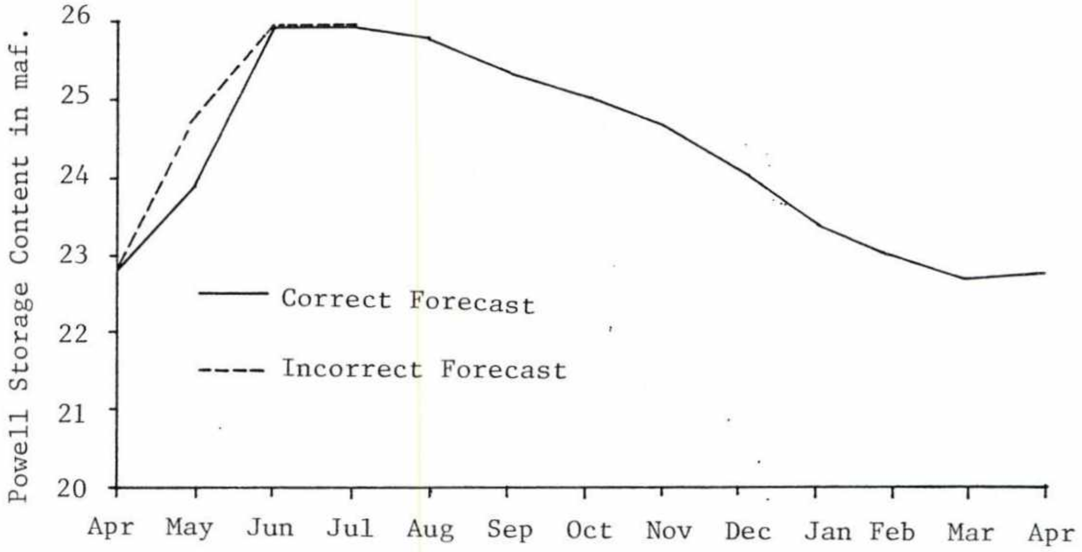

Figure 4.15 Powell Storage Characteristics for Illustration No.3

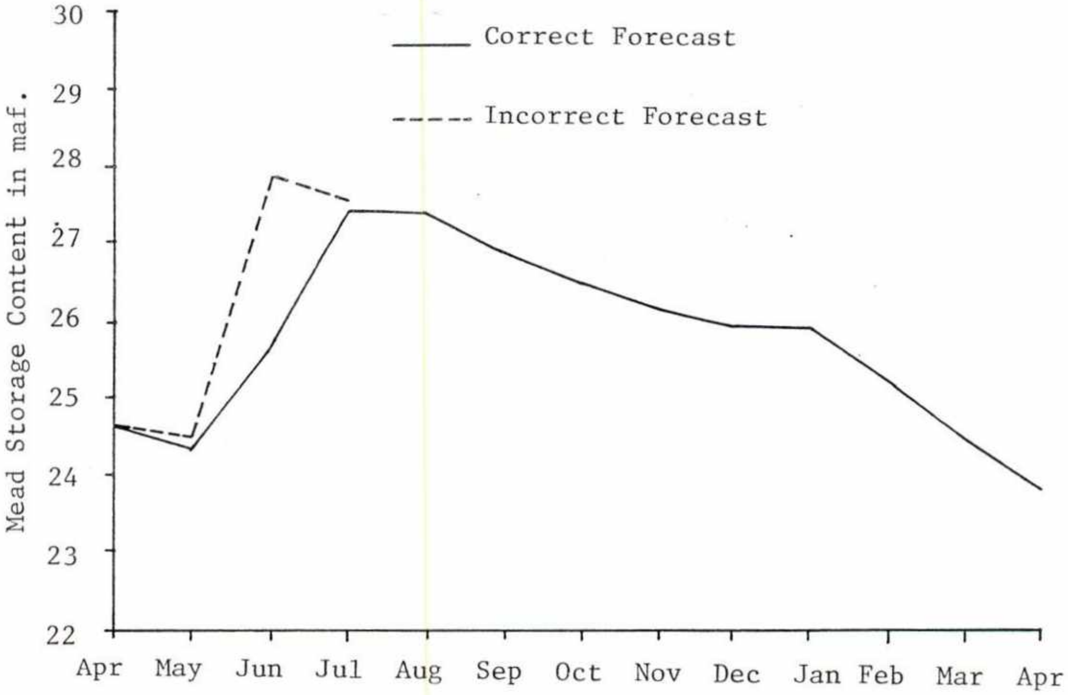

Figure 4.16 Mead Storage Characteristics for Illustration No.3

The release characteristics in Figures 4.13 and 4.14 reflect clearly the influence of the forecast of inflow. The 1983 April - July forecast of inflow to Powell was considerably low from the beginning. The ADIP-based method dictates no additional release from both lakes in May and only 0.19 maf additional release from Powell in June due to the expectation of a low flow. The unsual high flow during June results in a heavy spill from Lake Powell in June. With the high storage contents in both Lakes Powell and Mead at the end of June and the forecast of high inflow in July, the ADIP-based method suggested the large amount of additional releases from both lakes, particularly from Lake Mead.

The storage characteristics of Lakes Powell and Mead in Figures 4.15 and 4.16 show higher storages contents in June for the case of incorrect forecast than the other because the releases during the beginning of ADIP Type Iare lower due to the under-estimated forecast.

The incorporation of forecast into the ADIP concept has both advantages and disadvantages. If the forecast is close to the realization, the forecast will provide more concise exceedance probabilities of future operational failures which the decision to update the pre-selected operating rule can be made more efficiently. However if the forecast is far away from the realization, the wrong decision to update the pre-selected operating rule will be made. This becomes a question of trading off between the reliability of forecast and the reduction of the very unlikely future events.

CHAPTER V

SUMMARY, CONCLUSIONS AND SUGGESTIONS

5.1 Summary and Conclusions

This study presented the method for applying the concept called " Anticipated Decision Influence Period " or simply " ADIP " to a system of two large reservoirs in series. The study involved the method to identify the ADIP of two large reservoirs in series, the method to generate the exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of ADIP Type II as a function of the initial storages and initial month and finally the method for evaluating and updating the release decisions for a series of two reservoirs. Lakes Powell and Mead, a series of the two most important reservoirs of the Colorado River system were chosen as the case study to demonstrate the methodology developed in this study.

5.1.1 Identification of ADIP and Its Result

In identification of the ADIP of a series of two reservoirs (Lakes Powell and Mead), it was assumed that the two reservoirs in series can be represented by a single equivalent reservoir since the intervening flow is small compared to the inflow to the upper reservoir and the objective in operation of the upper reservoir is to meet the downstream demand. Considering the aggregated inflow and the aggregated target demand of a series of two reservoirs, the ADIP of the single equivalent reservoir can be identified according to the criteria given in Section 3.2.3.

The ADIP identified by the method mentioned above was sensitive to the stochastic nature of inflow and the characteristics of target demands. Using the 500 years of synthetically generated inflows and the 1985 USBR-estimated depletion schedule, ADIP Type I and II of Lakes Powell and Mead were the periods between May to July and August to April respectively. May which was the most probable beginning month of ADIP Type I had a relative frequency of 29 percent and August which was the most probable beginning month of ADIP Type II had a relative frequency of 35 percent. These percentages indicated that the reliability of the ADIP of Lakes Powell and Mead identified by this method was low. Scott(1983), in his study, using the same criteria in identifying ADIP reported that

> " The frequencies, using the 500 year record, with which May and December were the ending months, marked by the criteria of a transition between inflows and demands discussed previously, were 0.79 and 0.81 for the ADIP Type I and the ADIP Type II ends, respectively. "

This indicates that the reliability of ADIP identified by the method and criteria used in this study depends on the stochastic nature of inflows and the characteristics of target demands. Besides for a fixed set of stochastic of inflows, a change in target demand will change the ADIP accordingly.

Whenever the actual beginning months of ADIP Type I and II are not May and August, for a specific trace of inflow, the apriori generated exceedance probabilities of spill and deficit based on the expectation that ADIP Type I is May to July and ADIP Type II is August to April will under-estimate the magnitudes of spill and deficit. Although they are under-estimated, they are still useful for evaluating and updating the release decision. They give the direction on how to increase or decrease the release over or below the pre-selected target release. The updated release plan is by no mean better off than the target release since the risk of operational failures is controlled by decision makers.

5.1.2 Generation of The Exceedance Probabilities of Spill and Deficit

After the ADIP of Lakes Powell and Mead was identified, a Monte Carlo method was used for determining the exceedance probabilities of spill at the end of ADIP Type I and deficit at the end of ADIP type II. The exceedance probabilities of spill and deficit were conditioned on the initial storages and initial month of the year. Five hundred years of monthly inflow to Lake Powell and intervening flow between Lakes Powell and Mead were synthetically generated for Monte Carlo simulation.

The ADIP concept is a two stage decision making process. The operating rule is first selected. The consequences of using that selected operating rule are analyzed and displayed. The alternatives are designed and evaluated. Finally the second stage decision is made based on the known or partially known consequences of the first decision and the designed alternatives. The apriori generated exceedance probabilities of spill and deficit are the tool for displaying the consequences of using the pre-selected operating rule and evaluating the alternative release policies in terms of the probability of future operational failure (spill/deficit).

In this study, a simple operating rule for Lakes Powell and Mead was selected. The operating rule was simply to meet the minimum objective release of Lake Powell and the projected demands downstream of Lake Mead whenever possible. This simple operating rule was selected instead of the very complicated operating rule which includes the flood control regulations, the objective for balancing the storages in a series of reservoirs, the rule for maintaining the minimum pool etc., because this was only the tentative decision. As a matter of fact, the generated exceedance probabilities of spill and deficit would be used for displaying the consequences of using the pre-selected operating rule (in terms of risk) and for evaluating the alternative release policies. If the complicated operating rule which includes the flood control regulations, the rule for maintaining the minimum pool etc., was used instead, the probabilties of spill and deficit would be at the minimum level and would not be significant enough for evaluating any alternative release policies.

As discussed in the previous Section 5.1.1 , the reliability of the ADIP was low due to the hydrology and characteristics of the target demand. Whenever the actual ADIP of any particular inflow trace in those 500 inflow traces was not the same as the expected ADIP, the spill and deficit determined from that trace would be under-estimated no matter whether the actual ADIP was longer or shorter than the expected ADIP. Therefore the reliability of the exceedance probabilities of spill and deficit depended on the reliability of the expected ADIP.

The apriori generated exceedance probabilties of spill and deficit for Lake Powell as shown in Figures B1 to B12 of Appendix B and for Lake Mead as shown in Tables B1 to B12 of Appendix B indicated that the storage capacity of those lakes are very large. When the storages of those lakes are full or almost full, the chance of deficit at the end of ADIP Type II is essentially zero. On the other hand, when those reservoirs are empty or almost empty, the chance of spill at the end of ADIP Type I is essentially zero. Because of this fact, the storage content of those reservoirs can be divided into 3 zones: Zone I or the top zone is the zone of anticipated spill, Zone II or the middle zone is the zone of anticipated no spill and no deficit and

Zone III is the zone of anticipated deficit. Figures B1 to B12 indicated that for Lake Powell, Zone I is the storage between 18.00 to 25.90 maf, Zone II is the storage between 10.00 to 18.00 maf and Zone III is the storage between 5.57 to 10.00 maf. The storage zones of Lake Mead depend on the available storage of Lake Powell. Table B1 to B12 indicated that when Powell storage is almost empty, the chance of Mead spill is almost insignificant even though the Mead storage is full or almost full. On the other hand, when Powell storage is almost full, the chance of Mead deficit is almost insignificant even though the Mead storage is empty or almost empty. Regardless of the Powell storage, the probabilities of Mead spill and deficit are almost insignificant when the Mead storage is less than 22.00 maf and greater than 14.00 maf, respectively. For Lake Mead , Zone I is between 22.00 to 29.05 maf, Zone II is between 14.00 to 22.00 maf and Zone III is between 10.02 to 14.00 maf. These storage zones will give the general guidelines about when to make the additional or cutback release.

It is noted that since the target demand (11.2 maf/year) is less than the average inflows (15.9 maf/year) and the large storage capacities of Lakes Powell and Mead, the generated exceedance probabilities of deficit for both lakes were almost negligible. There exists the chance of deficit only when the storages of Lakes Powell and Mead are very low, less than 10.00 maf for Lake Powell and less than 14.00 maf for Lake Mead (regardless of Lake Powell storage).

The storages of Lakes Powell and Mead will have very little chance to be that low since the Powell and Mead current storages are almost full and the current projected depletion schedule is less than the average flow. Because of this fact, a deficit is of little concern. The major concern in operations of Lakes Powell and Mead is to manage the spill. Although the operation is in ADIP Type II, the operating plan will be to increase the release (making the additional release) over the schedule to prevent the spill in the subsequent ADIP Type I instead of to cutback the release to prevent the deficit in the current ADIP Type II since the chance of deficit in the current ADIP Type II is almost zero.

5.1.3 Evaluating and Updating Procedure

According to the ADIP concept, there are two different periods in the reservoir operation planning. They are the period of anticipated spill (ADIP Type I) and the period of anticipated deficit (ADIP Type II), which are the seasonal characteristics of a reservoir. At the beginning of ADIP Type I, with the known initial storage, the exceedance probability of spill at the end of ADIP Type I and that of deficit at the end of the subsequent ADIP Type II are obtained. This information indicates the performance of pre-selected operating rule. If the exceedance probabilities indicate high probability of significant spill during ADIP Type I but little if any chance of deficit during ADIP Type II, the additional release should be made to prevent the spill. The additional release is the total amount of water to be released from now to the end of ADIP Type I in excess of the target release. This study does not address how to distribute the additional release over the ADIP Type I optimally. It was only assumed in this study that the additional release is uniformly distributed over the ADIP Type I. At the beginning of each month, the new initial storage is known, the new exceedance probabilities of spill and deficit are obtained. The additional release made at the beginning of ADIP Type I or in the previous month can be updated accordingly.

Since the exceedance probabilties of spill and deficit were generated by Monte Carlo simulation according to the pre-specified target release, when additional or cutback release is made, the actual release will be different from the pre-specified target release. The apriori generated exceedance probabilites of spill and deficit will not be useful for predicting future operational failures. To overcome this problem, it was assumed that the additional or cutback release takes place immediately at the beginning of the current month and has an immediate effect on the initial storage. Based on this assumption, the release during the rest of the ADIP will follow the target release exactly. Although the actual additional or cutback release may not take place immediately at the beginning of the current month as assumed, this assumption is still acceptable if the evaporation and bank storage effects are minor. If it is not the case, the effects of evaporation and bank storage on the additional or cutback release have to be considered.

The procedure to update the release of two reservoirs in series is to consider the upper reservoir first according to the method mentioned above. After deciding to make additional or cutback release from the upper reservoir, the effect of the additional or cutbak release from the upper reservoir on the lower reservoir has to be evaluated. If that decision results in high probability of spill or deficit in the lower reservoir, the lower reservoir target release will have to be updated by making additional or cutback release similar to the upper reservoir.

Two methods for making the decision on the additional or cutback release were used in this study. The first method used the future failure probability criteria and the second method used the trade-off analysis between the benefits and risks associated with the additional or cutback release.

The future failure probability criteria can be derived from the long term experience in operating the reservoir system and the preference of the decision maker. Based on the operation of Lakes Powell and Mead during April 1981 to 1985, on the average, the probability of spill from Lake Powell was 0.13 and the probability of spill from Lake Mead was 0.01. The probability of deficit from both lakes approached zero. These probabilities were used as the future spill/deficit probability criteria. Whenever the probabilities of spill and deficit of Lakes Powell and Mead obtained from the apriori generated exceedance probability exceeded the the future spill/deficit probability criteria, the additional/cutback release was required to bring the anticipated probability of spill/deficit down below the probability criteria. This method to update the target release is quite simple, although the derivation of the future spill/deficit probability criteria is rather subsective.

Trade-offs between benefits and risks associated with additional and cutback release alternatives need no pre-decision like the first method. However this method requires the decision maker's knowledge and full cooperation. If the apriori generated exceedance probabilities indicate that to follow the pre-specified target release, there is high risk of spill or deficit, alternatives (additional/cutback release) are designed. The apriori generated exceedance probability can be used to assess the effect of each alternative in term of benefits and risks. Finally the consequences of each alternative in terms of the benefits and risks associated with them are compared to the " Do Nothing " alternative (to follow the pre-specified target release). The decision maker then decides based on the benefits to be obtained and risks to be taken whether to follow the pre-selected operating rule or to increase or decrease the release.

The second method has some advantage because the decision maker has full information about the consequences of the pre-specified operating rule and alternatives before making the decision, while the first method needs apriori decisions on the future spill/deficit probability criteria which the decision maker may not know.

The ADIP concept is based on the anticipation of future operational failures (spill and deficit) due to the use of the pre-selected operating rule. The probability distribution of operational failures are generated based on the pre-selected operating rule and the stochastic nature of inflows. This probability distribution of operational failures gives a general idea of all possible future failures of the system. Although this information is useful, it is not concise. The decision has to be made from all of the future failure possibilities which is difficult. The forecast of inflow will eliminate a large number of very small probability events.

In this study, the forecast of inflow was used in conjunction with the ADIP concept. The incorporation of forecasts into the ADIP concept helps eliminate very small probability events of future operational failures. The forecast of inflow from the current time to the end of the current ADIP is first identified as to whether it falls into the upper, second ,third or lower quartiles. Based on the assumption that the upper quartile of inflow produces the upper quartile of spill and deficit, the second quartile of inflow produces the second quartile of spill and deficit and so on. Once the quartile of inflow is identified, the quartile of spill and deficit are identified correspondingly. The exceedance probabilities of spill and deficit will be adjusted such that the probability of that quartile of spill and deficit is equal to 1.00 . This is based on the assumption that the forecasted inflow becomes a realization. Note that based on this assumption, the probability of other quartiles of spill and deficit is assumed to be zero.

The incorporation of forecast into the ADIP concept has both advantages and disadvantages. If the forecast is close to the realization, the forecast will help provide the more concise probability of future operational failures and the decision to update the pre-selected operating rule can be done more efficiently and correctly. However, if the forecast is far from a realization, the wrong decision to update the pre-selected operating rule will be made. This becomes a question of trade offs between the reliability of forecast and the reduction of the very unlikely future events.

5.1.4 The Illustration Results

Three illustrations were made in this study to show different ways to set up the ADIP-based operational plan. The first illustration showed how to design the release alternatives and to assess those alternatives in term of the change in the probability of operational failures (spill and deficit) at the end of the anticipated time of failures and finally to trade-off benefits and risks associated with each alternative before making the decision. The second illustration showed how to use the future operational failure probability criteria. The last (third) illustration showed how to incorporate the forecast of inflow into the ADIP concept. The illustrations were done for a period of one year using the actual inflow data during May 1983 to April 1984 and the actual storages for Lakes Powell and Mead at the beginning of May 1983.

Comparing the ADIP-based release policies to the actual release, it was shown in both Illustration No.1 and No.2 that the releases of the ADIP-based method were higher than the actual release during ADIP Type I but the ADIP-based releases were lower than the actual release during ADIP Type II. This was true for both Lakes Powell and Mead releases. This can be explained from the point that the ADIP-based operation has foreseen the future in a probabilistic sense. That knowledge about the future probability of operational failures then dictates the release policy such that if the probabilistic future indicates a high chance of spill ,the future release plan will be increased from the target release to prevent the spill and flooding, on the other hand if the probabilistic future indicates a high chance of deficit, the future release will be reduced from the target release. According to the case study of Lakes Powell and Mead, the ADIP-based operation foresaw that the chance of spill by the end of July particularly from Lake Powell was high, it then dictated high releases. The actual operation, on the other hand, depended partly on the inflow forecast which indicated that the future inflow was normal. There was no need to increase the release much more than the target. That was why the ADIP-based releases were higher than the actual releases during the ADIP Type I.

During ADIP type II, the result was opposite. After the high flow caused flooding in June and July, the flood control regulation required high release so that Lake Mead and the upper reservoirs could provide at least 5.35 maf. of the flood control space on January 1st. Although the ADIP-based operation foresaw that the chance of spill at the end of subsequent ADIP Type I was high, the time of anticipated spill was far away into the future. There was no hurry to increase the release far above the target release.

The purpose of this study was not to conclude that the ADIP-based operation was better or worse than the actual operation. The deviation of the ADIP-based operation from the actual operation of May 1983 to April 1984 was totally because the logic of the ADIP-based method was different from the actual operation. It was noted that under the unenexpected high inflow, the actual operation was much different from the USBR annual operating plan.

Illustration No. 3 showed how to incorporate the inflow forecast into the ADIP concept. Based on the method of incorporating the inflow forecast used in this study and the actual forecast of April - July 1983 inflow to Lake Powell by USBR, which was about 50 percent low particularly at the beginning (January to May), the ADIP-based operation with the forecast dictated almost no additional release in May and June due to the expected low flow. Since the actual June inflow was much higher than the forecast, the spill took place in Lake Powell in June. The high storage contents in both lakes by the end of June or the beginning of July together with the forecast of high inflow then dictated the large amount of additional releases from both lakes in July. The incorporation of inflow forecast into the ADIP concept has both advantages and disadvantages. The advantage is that if the forecast is correct, it will give a better idea about the future operational failures of the reservoir system. If it is wrong, the ADIP-based tends to provide a worse release policy than without the forecast. As mentioned before the decision to include the forecast of inflow into the ADIP concept should be made based on trading off between the reliability of the forecast and the level of exclusion of the very unlikely future events.

The result of this study indicated that more benefits can be extracted from the system of Lakes Powell and Mead in terms of increasing the target releases as clearly seen from the high exceedance probability of spill from both lakes but essentially zero exceedance probability of deficit. This indicated that the target releases (demands) are still smaller than the yield of the system. Increasing the use of water from the system will not only increase benefit from hydropower production and water supply but will reduce the chance and magnitude of flooding downstream.

5.1.5 Final Remarks

The ADIP concept is a very useful tool for decision makers in evaluating and updating the release decision based on the fact that the present benefit and future risk associated with any release decision are not independent. The present benefit to be obtained should be traded against the future risk according to the decision maker preferences in making the release decision. However, in applying the ADIP concept to a series ot two large reservoirs, Lakes Powell and Mead, the reliability of the ADIP was very low. Consequently it resulted in low reliability of the generated exceedance probabilities of spill and deficit. The reliability of the ADIP and exceedance probabilities of spill and deficit highly depends on the hydrology and the characteristics of demands. Besides because of the tremendous carry over storage capacity of Lakes Powell and Mead, the storages were divided into 3 zones; zone of anticipated spill, zone of anticipated no spill and no deficit and zone of anticipated deficit.

When the storage is in the zone of anticipated spill, the chance of spill at the end of ADIP Type I is high but the chance of deficit at the end of ADIP Type II is approaching zero. Increasing the release over the target release will reducing the chance of spill but will not effect the chance of deficit. Making the additional release will not only benefits more for hydropower and water supply but will reduce the future risk of flooding also. For a certain range, making an additional release will have no negative impact over the ADIP. Based on this fact, the release decision is quite obvious, that is the release will be as high as the maximum release for hydropower production or the release is limited by the operational objectives other than hydropower, water supply and flood control. The apriori generated exceedance probabilities of spill and deficit are not very useful for the decision makers to base their release decision.

As shown in Illustration No.1, usually the release decision for Lake Powell was to release as high as the maximum desirable release. Only when releasing at the maximum desirable release, the chance of spill at the end of ADIP Type I is still high (decided by the decision maker), the trade offs analysis between the reduction in the chance of spill at the end of ADIP Type I and the loss of benefit from releasing in excess of the maximum desirable release was done according to the decision maker preference in making the release decision. The release decision for Lake Mead was on the other hand dictated by the objective of balancing Lakes Powell and Mead storages instead of trading off the benefit and risk associated with the release decision.

It is therefore concluded that when applying the ADIP to a series of two large reservoirs, Lakes Powell and Mead, the ADIP concept is not as useful for evaluating and updating the release decision as it is supposed to be as shown in Illutration No.1. The release decision was dictated by the maximum release capacity and the objective of balancing the storages between Lakes Powell and Mead instead of trading off benefit against risk associated with the release decision.

However if the decision maker has the pre-decision in mind about the future operational failure probability criteria, the ADIP concept is still apply to a series of two large reservoirs as shown in Illustration No.2 provided that the hydrology of the reservoir system gives a very reliable ADIP and exceedance probabilities of spill and deficit, which is not the case of Lakes Powell and Mead.

5.2 Suggestion for Further Research

In applying the ADIP concept to a series of two reservoirs, many problems were identified. Answers to those problems will contribute considerably to the ADIP concept. The writer suggests that the following areas be investigated further.

5.2.1 Criteria for Identifing ADIP

The criteria for identifying the ADIP used in this study gave very low reliability of Lakes Powell and Mead 's

ADIP. The reliability is very highly dependent on the stochastic variation of inflow and the characteristics of target demand. A study should be conducted to identify that what kinds of inflow distributions and characteristics of target demand would not work well with the ADIP definition criteria.

5.2.2 Classification of Reservoir for Application of ADIP Concept

The future operational failure characteristics of a reservoir depend on the inflow, the target demand, and the size of reservoir. For a very small reservoir, the spill and deficit may take place alternately each year. The ADIP concept was originally designed for this type of reservoir. For a large reservoir, the operational failure characteristics of the reservoir depend on the chracteristics of inflow and demand. If on the average the inflow is greater than the demand, the major failure will be a spill. A deficit rarely takes place. On the other hand, if the inflow is, on the average, less than the demand, the major failure will be a deficit. If the average inflow is close to the target demand, the spill and deficit will rarely occur. For the last case, the generated exceedance probability of operational failures (spill and deficit) will not be significant enough for evaluating the release decision. A study should be done to classify reservoirs into small or large and for a large reservoir what is its failure characteristics (spill or deficit) based on the characteristics of inflow, demand and the size of reservoir.

5.2.3 Application of the ADIP Concept to A System of More Than Two Reservoirs in Series

To apply the ADIP concept to a system of more than two reservoirs in series it will be too time consuming if the Monte Carlo method is used for generating the exceedance probabilites of spill and deficit . Besides the generated exceedance probabilities of spill and deficit of the lower reservoirs depend not only on its initial storage and operating rule but also depend on the initial storages and the operating rules of the upper reservoirs. Using the generated exceedance probabilities of spill and deficit to evaluate the release decision of more than two reservoirs in series can be time consuming. Other alternatives should be studied for a case of more than two reservoirs in series.

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APPENDIX A

INFLOWS - DEMANDS AND RESERVOIR CHARACTERISTICS OF LAKES POWELL AND MEAD

A.1 Historical Inflows

The inflow and the intervening flow used in this study are obtained from the hydrology data base of the Colorado River Simulation System (CRSS). Actually these flows are the calculated natural flows; natural is defined as historical data adjusted for human development. This adjustment is made to estimate what the flows would be without present development on the river. The data for this data base were developed from historical streamflow records, climatological records, cropped acreages, calculated evaporation from reservoirs and the recorded diversion and return flows.

The natural flow at Lees Ferry, Figure A1, is adjusted by the effect of the upper basin storages before it is used to represent the inflow to Lake Powell in this study. The adjustment is made simply by adding the term " ADJUST " in Powell mass balance equation in Subroutine POWST. The "ADJUST " is actually the change in the total upper basin storage volume above Lake Powell, or

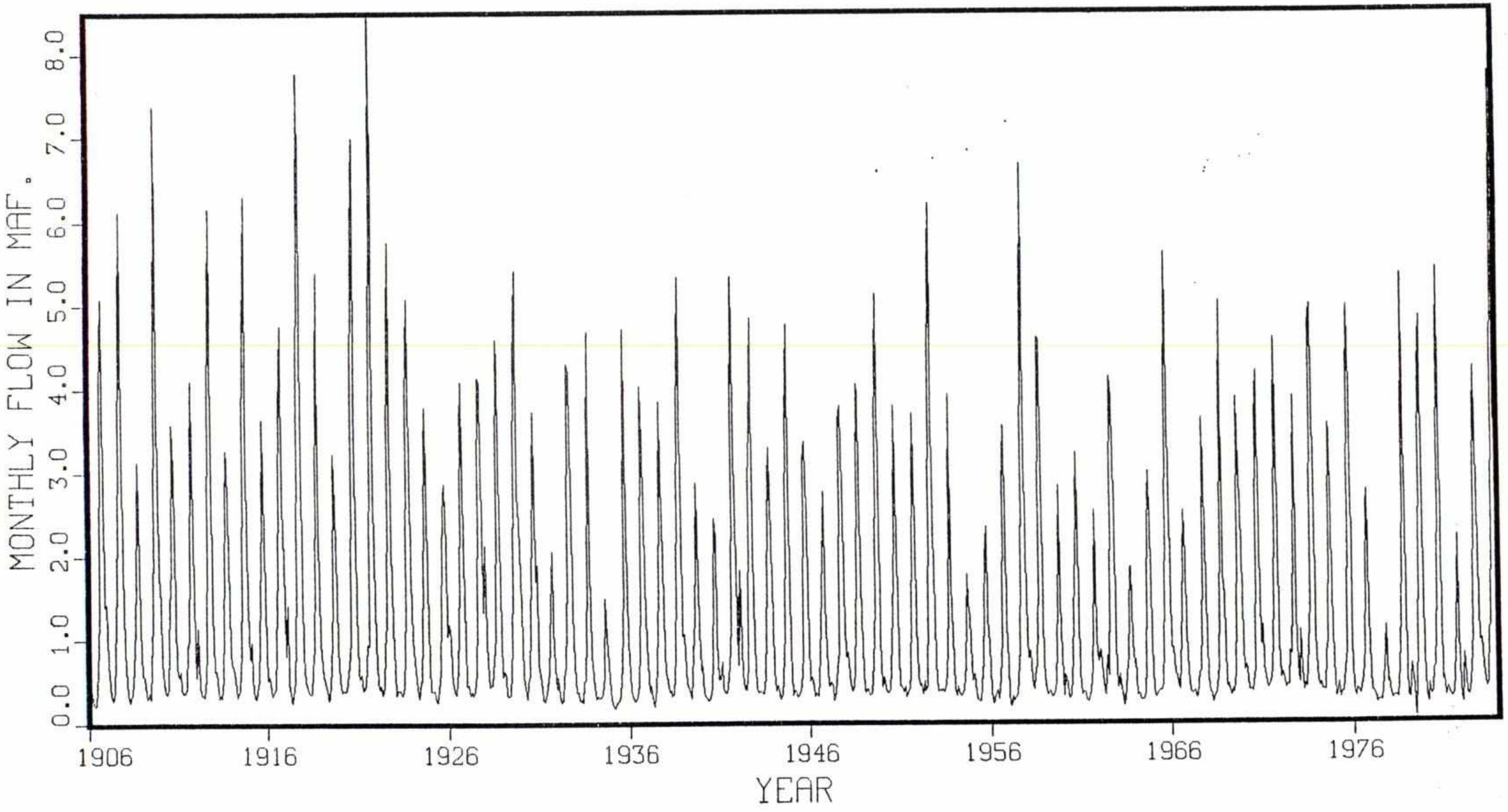

Figure A1 Natural Flow At Lees Ferry During 1906 to 1983

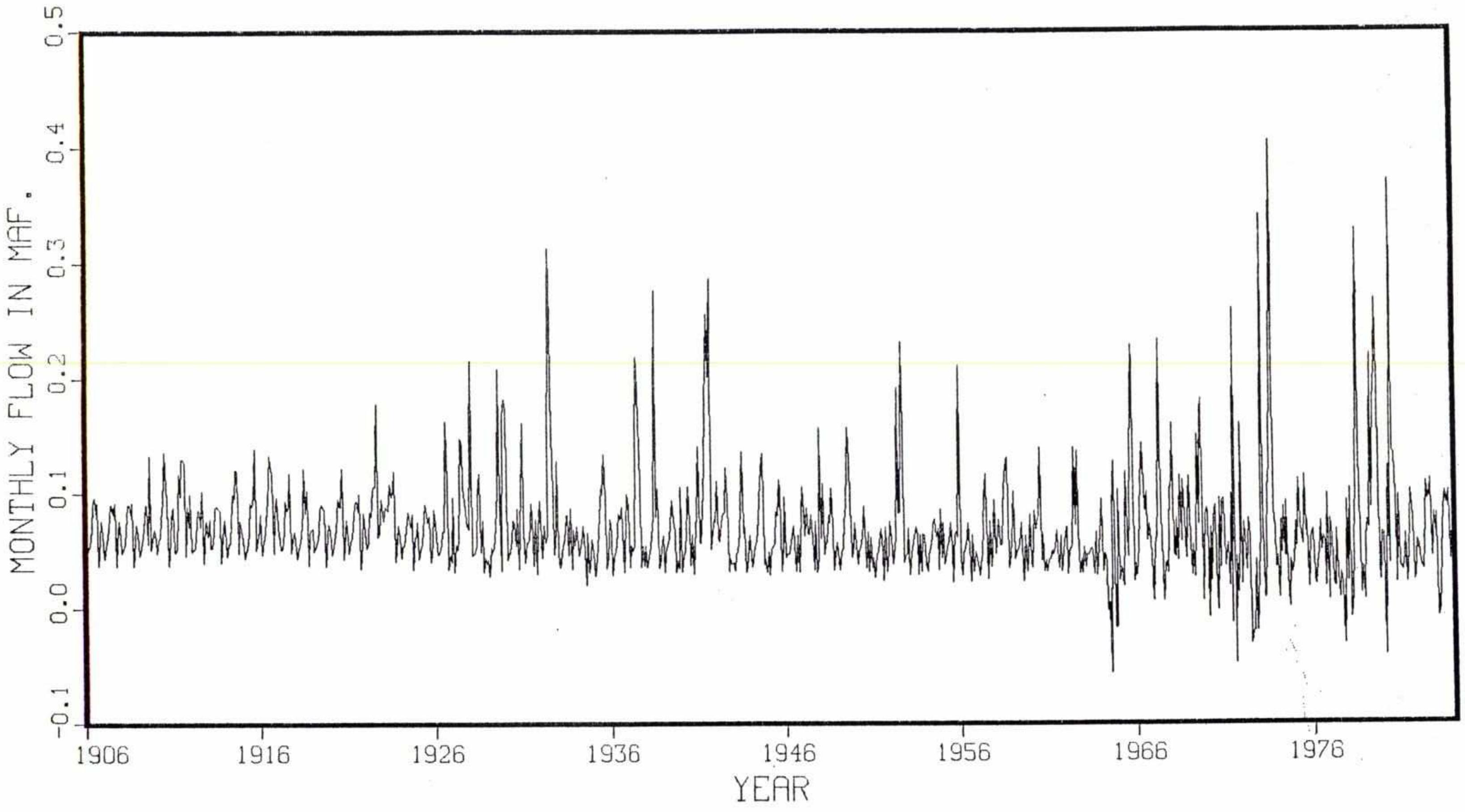

Figure A2 Intervening Flow Between Lakes Powell and Mead During 1906 to 1983 calculated by multiplying the annual target demands in Table A1 by the monthly distribution coefficients in Table A2.

The reservoir characteristics including the maximum and minimum storage capacities and the maximum desirable releases are shown in Table A3.

The monthly evaporation rates of Powell and Mead are shown in Table A4.

Table A1 The Annual Target Demands (maf)
(USBR estimate depletion schedule)

Year	Upper Basin	Lower Basin	Southern Nevada	Mexican Delivery
1985	3.496	6.127	.110	1.515
1986	3.510	6.568		1.515
1987	3.524	6.948		1.515
1988	3.538	7.343		1.515
1989	3.551	7.353		1.515
1990	4.035	7.378	.151	1.515
1991	4.044	7.385		1.515
1992	4.052	7.394		1.515
1993	4.060	7.401		1.515
1994	4.069	7.401		1.515
1995	4.084	7.412	.186	1.515
1996	4.093	7.420		1.515
1997	4.102	7.428		1.515
1998	4.110	7.436		1.515
1999	4.118	7.444		1.515
2000			.213	

Source: USBR, Denver, Colorado

Table A2 The Monthly Distribution Coefficients of The Annual Target Demands and Powell Minimum Objective Release (USBR-estimate)

Month	Upper Basin	Lower Basin	Southern Nevada	Powell Min. Objective Release	Mexican Delivery
Oct.	0.01	0.0709	0.08	0.0690	0.07
Nov.	0.	0.0699	0.07	0.0680	0.06
Dec.	0.	0.0753	0.05	0.1040	0.06
Jan.	0.	0.0609	0.06	0.1080	0.02
Feb.	0.	0.0823	0.05	0.0640	0.07
Mar.	0.01	0.1136	0.07	0.0620	0.07
Apr.	0.06	0.1063	0.08	0.0629	0.11
May	0.23	0.1015	0.09	0.0670	0.11
Jun.	0.30	0.0885	0.11	0.0711	0.12
Jul.	0.22	0.0823	0.12	0.1270	0.12
Aug.	0.13	0.0764	0.12	0.1230	0.11
Sep.	0.04	0.0721	0.10	0.0740	0.08

Source: USBR, Denver, Colorado

Table A3 The Powell and Mead Characteristics

	Powell	Mead
Maximum Capacity in maf. (including dead storage)	25.902	29.054
Minimum Allowable Storage in maf (including dead storage)	5.574	10.024
Maximum Desirable Release in maf/year	15.500	13.800
Bank Storage Coefficient	0.08	0.065

Source : USBR, Denver, Colorado

Table A4 The Monthly Evaporation Rates (ft/month)

Month	Powell	Mead
Oct.	0.375	0.51
Nov.	0.312	0.51
Dec.	0.261	0.44
Jan.	0.198	0.36
Feb.	0.186	0.33
Mar.	0.233	0.37
Apr.	0.265	0.46
May	0.359	0.53
Jun.	0.411	0.64
Jul.	0.466	0.80
Aug.	0.478	0.85
Sep.	0.415	0.70

Source : USBR, Denver, Colorado

APPENDIX B

THE EXCEEDANCE PROBABILITIES OF FAILURES

The apriori generated exceedance probabilities of cumulative spill at the end of ADIP Type I and that of cumulative deficit at the end of ADIP Type II as a function of initial storage and initial month for Lake Powell are presented in Figures B1(a) to B12(a) and B1(b) to B12(b), respectively. Those exceedance probabilities for Lake Mead are presented in Tables B1(a,b) to B12(a,b).

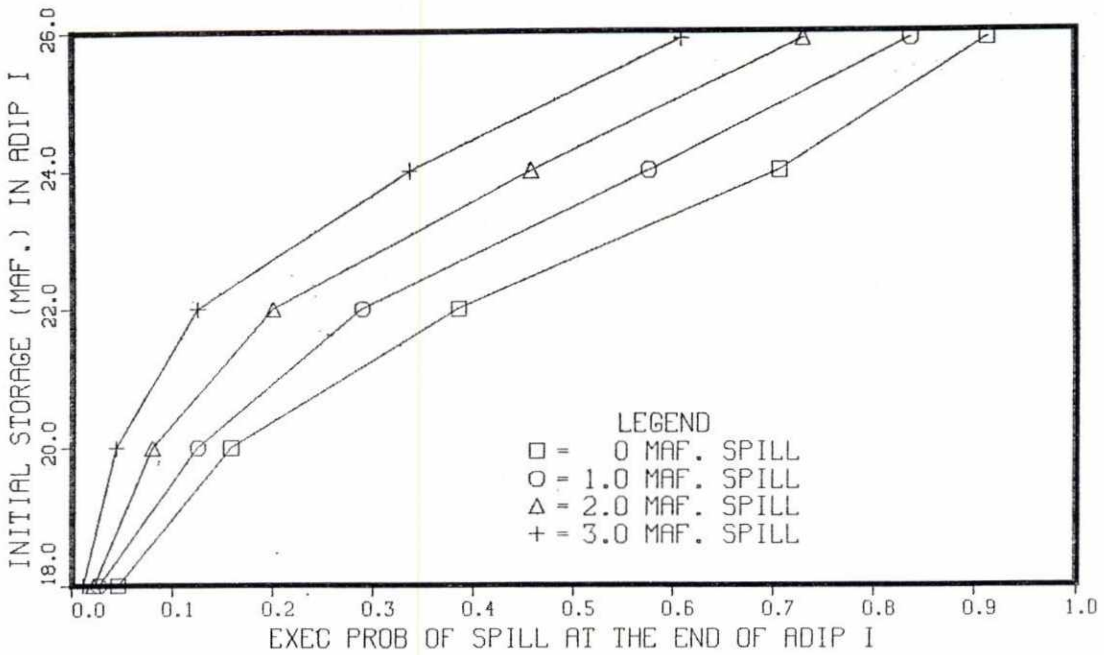

Fig. B1(a) Exec. Prob. of Powell Spill As A Function of Initial Storage in May

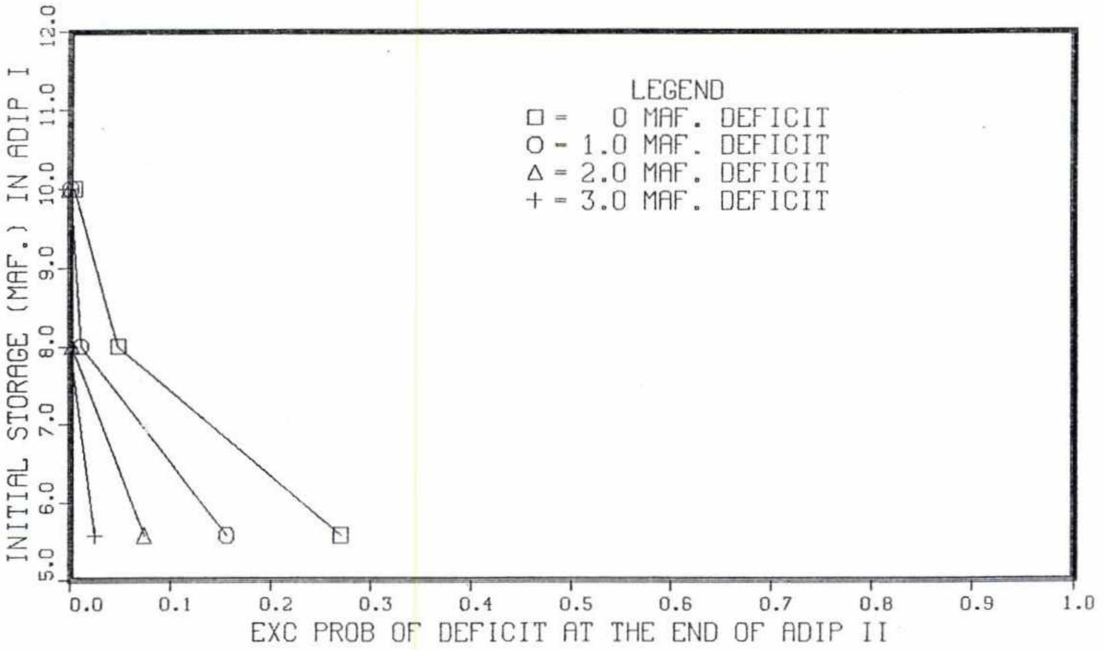

Fig. B1(b) Exec. Prob. of Powell Deficit As A Function of Initial Storage in May

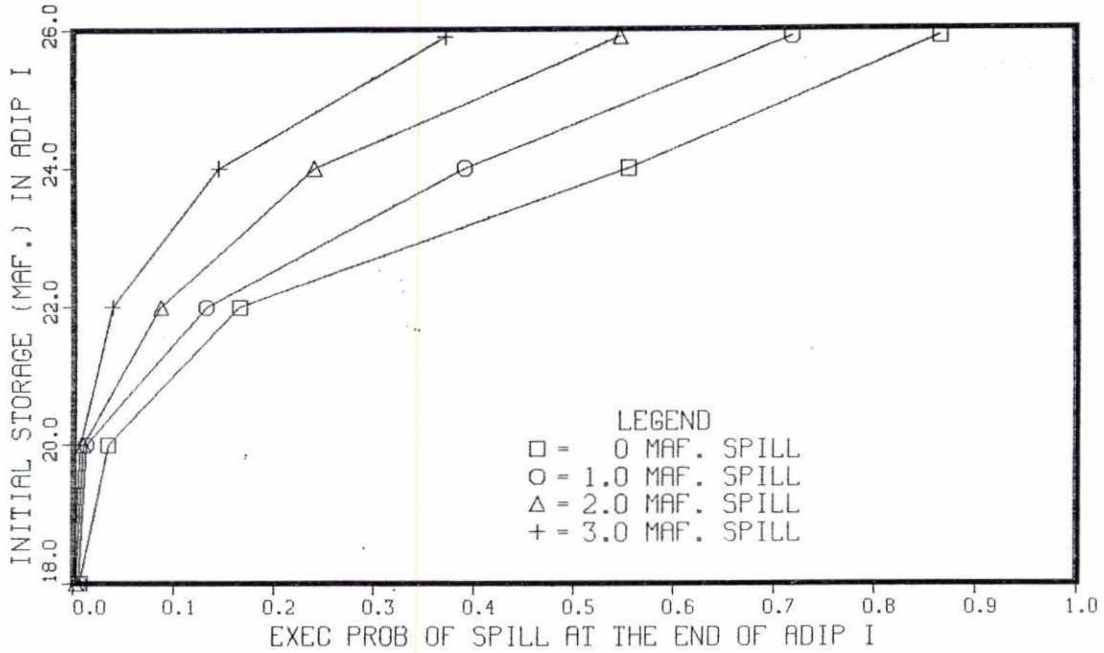

Fig. B2(a) Exec. Prob. of Powell Spill As A Function of Initial Storage in June

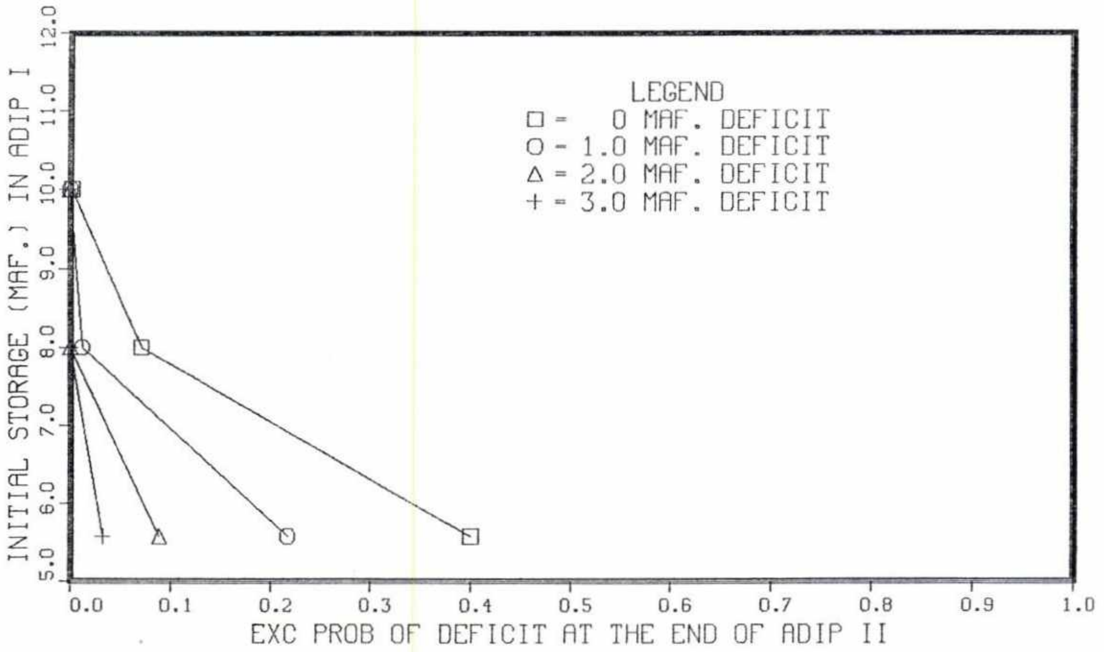

Fig. B2(b) Exec. Prob. of Powell Deficit As A Function of Initial Storage in June

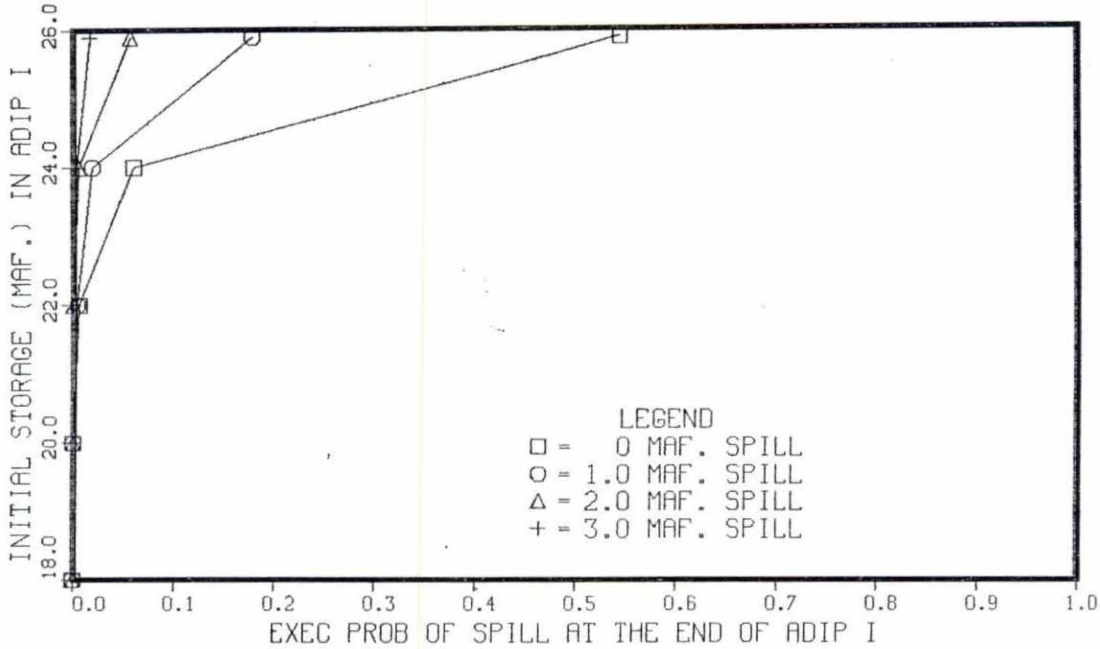

Fig. B3(a) Exec. Prob. of Powell Spill As A Function of Initial Storage in July

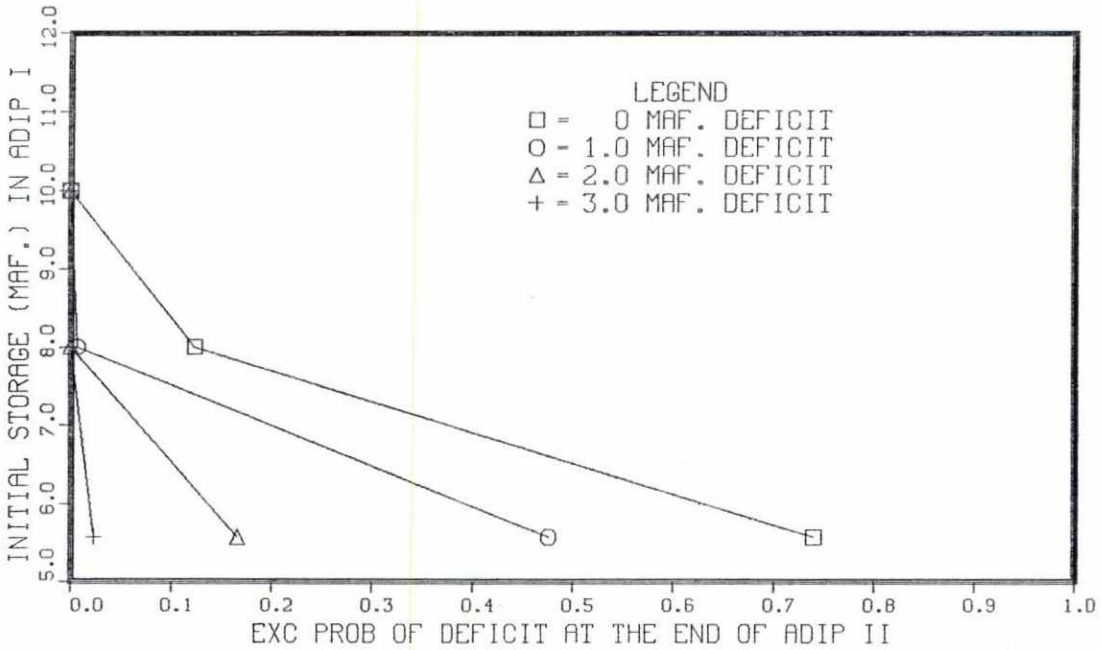

Fig. B3(b) Exec. Prob. of Powell Deficit As A Function of Initial Storage in July

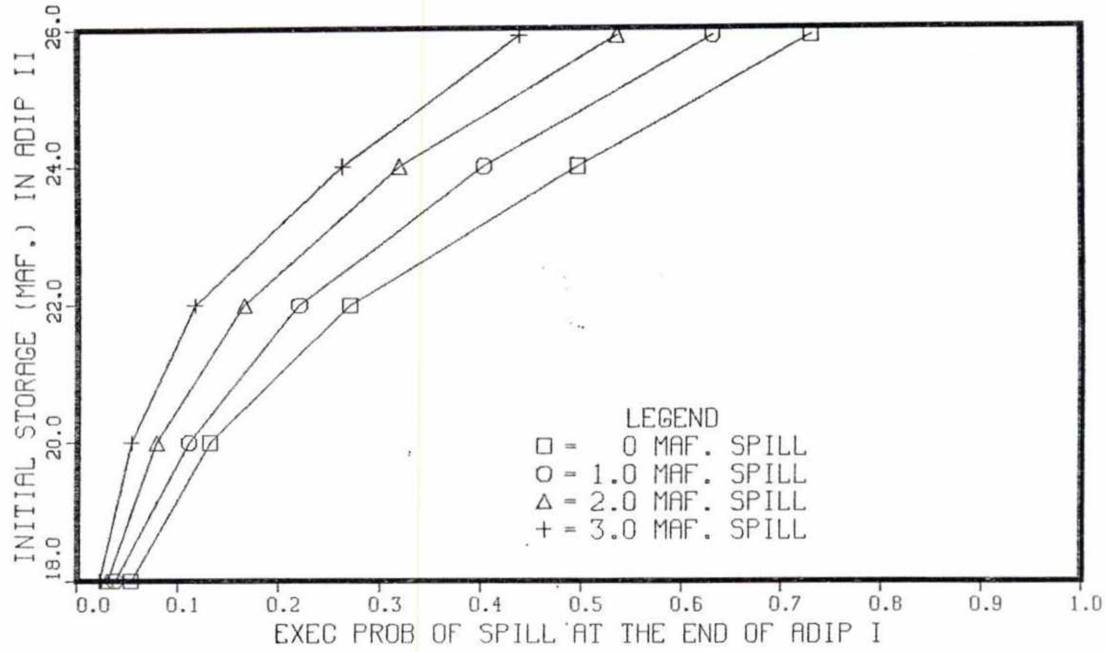

Fig. B4(a) Exec. Prob. of Powell Spill As A Function of Initial Storage in August

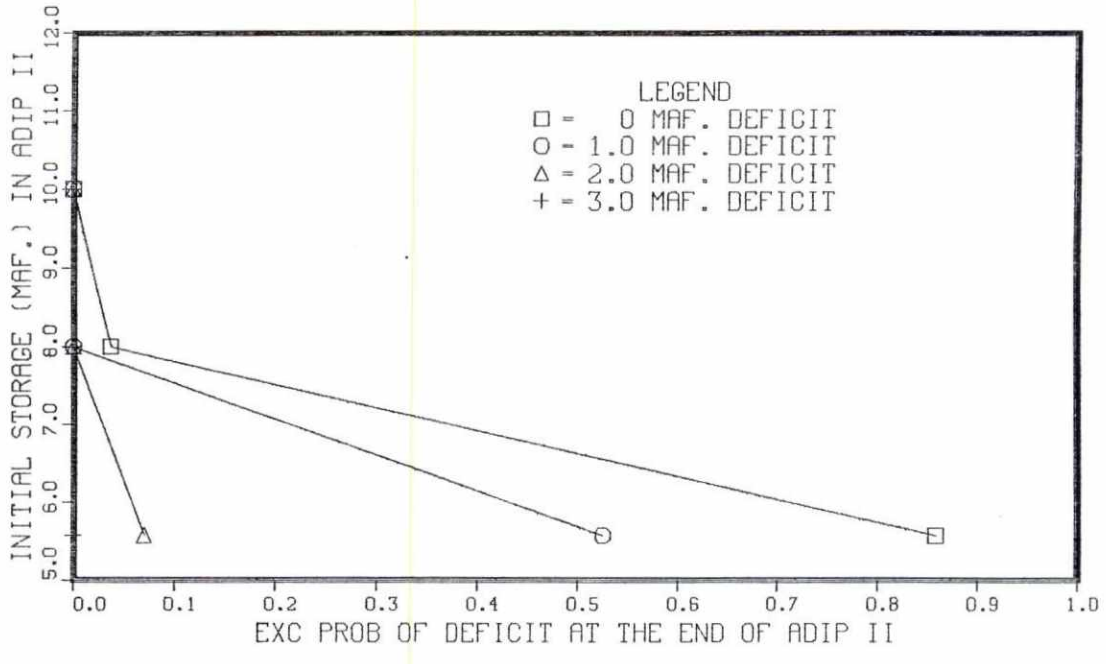

Fig. B4(b) Exec. Prob. of Powell Deficit As A Function of Initial Storage in August

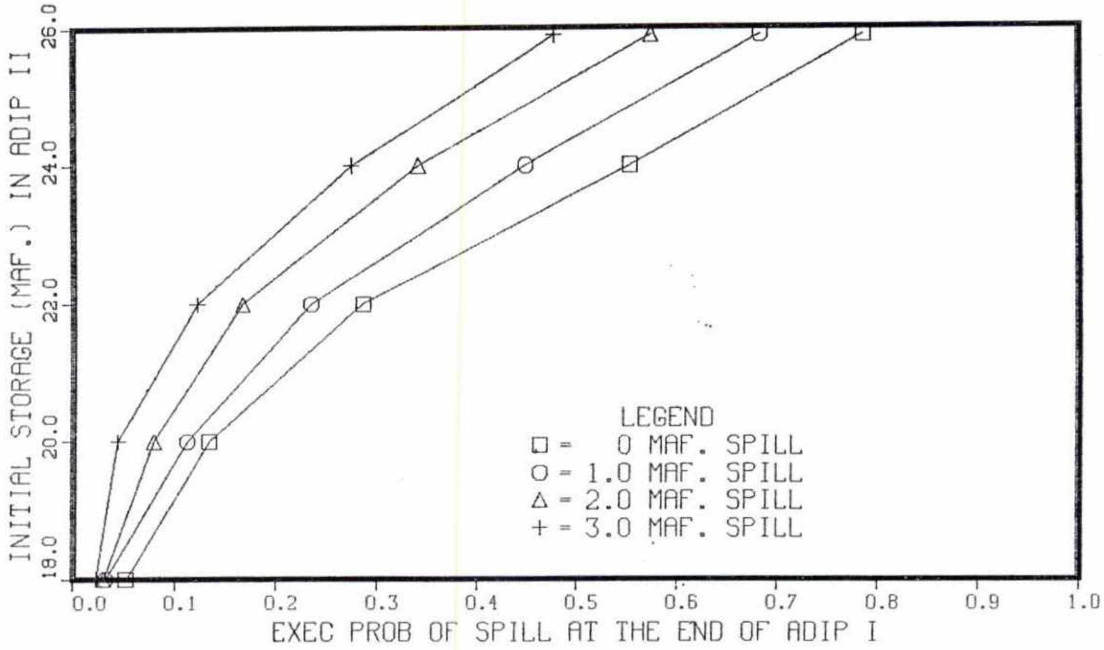

Fig. B5(a) Exec. Prob. of Powell Spill As A Function of Initial Storage in September

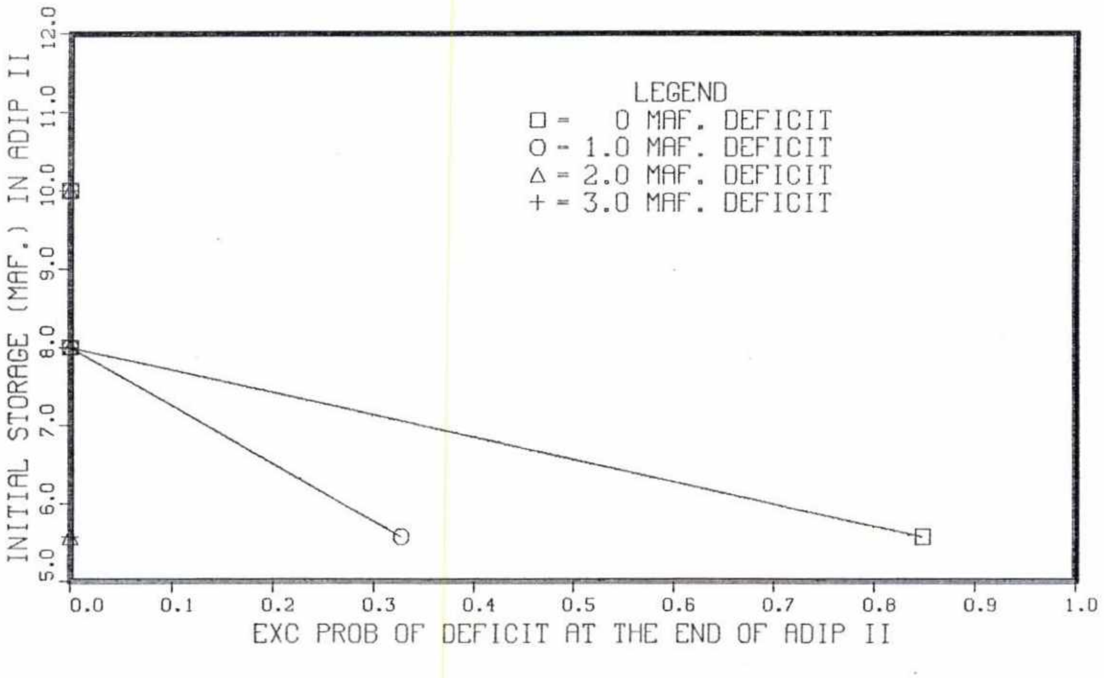

Fig. B5(b) Exec. Prob. of Powell Deficit As A Function of Initial Storage in September

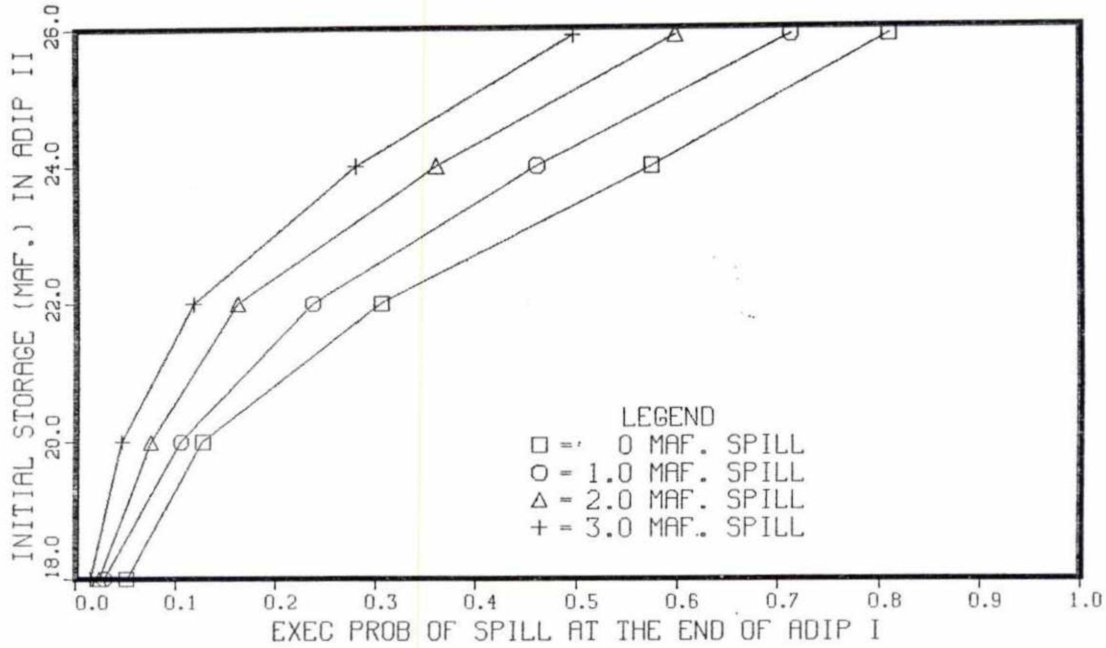

Fig. B7(a) Exec. Prob. of Powell Spill As A Function of Initial Storage in November

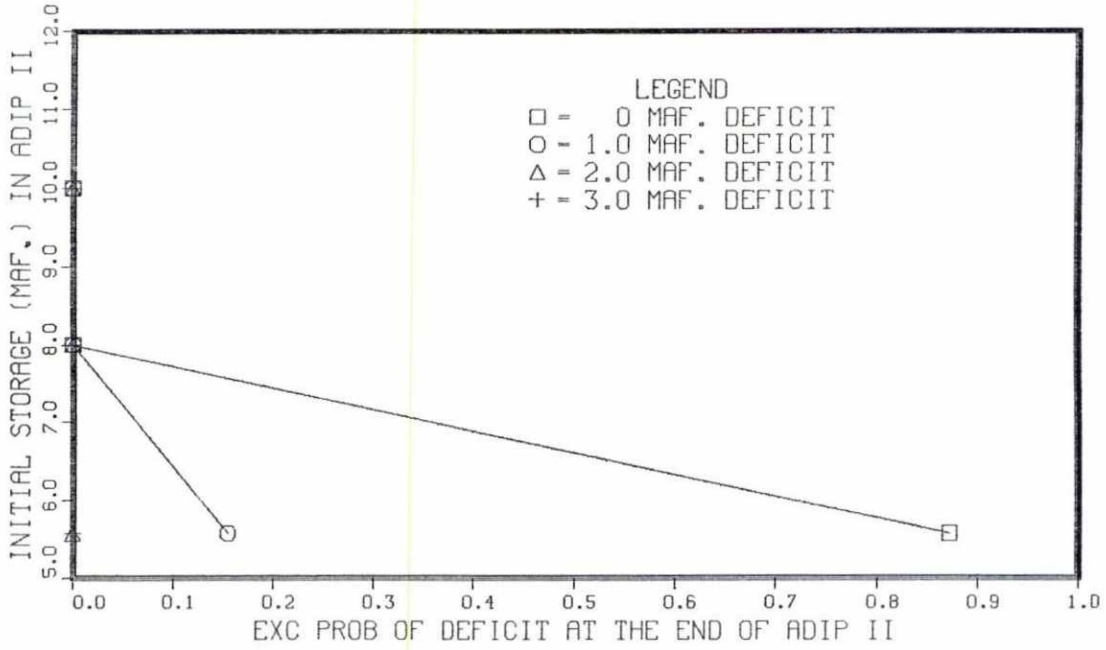

Fig. B7(b) Exec. Prob. of Powell Deficit As A Function of Initial Storage in November

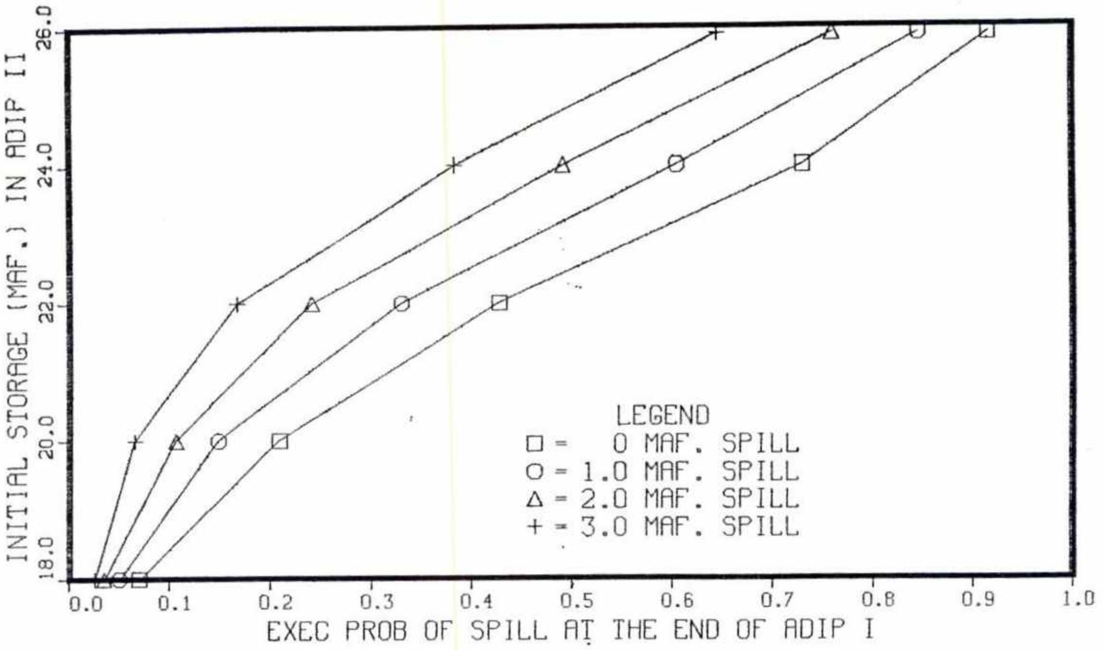

Fig. B12(a) Exec. Prob. of Powell Spill As A Function of Initial Storage in April

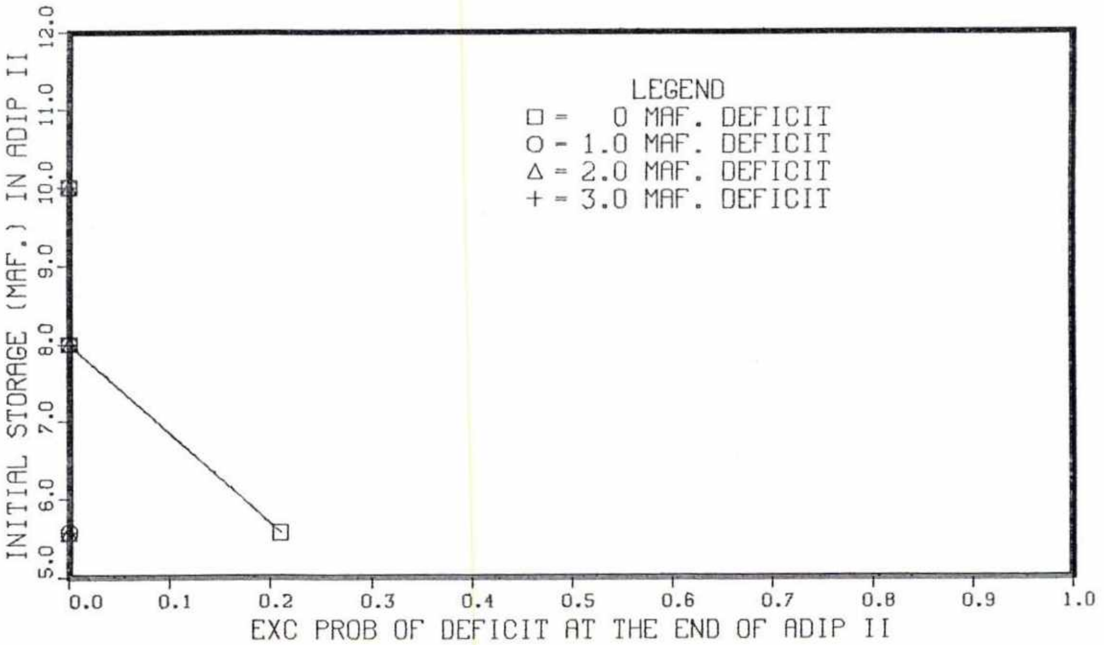

Fig. B12(b) Exec. Prob. of Powell Deficit As A Function of Initial Storage in April

Table B1(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in May

MAY	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0									
		5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.006	.012	.028	.202
		20.00	0.000	0.000	0.000	.006	.010	.043	.116	.248
		22.00	0.000	0.000	0.000	.015	.044	.123	.272	.430
		24.00	0.000	0.000	0.000	.074	.173	.325	.556	.708
		25.90	0.000	0.000	0.000	.171	.345	.586	.815	.907
	1.0									
		5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.008	.021	.029
		20.00	0.000	0.000	0.000	.006	.008	.023	.071	.118
		22.00	0.000	0.000	0.000	.012	.024	.068	.183	.276
		24.00	0.000	0.000	0.000	.045	.115	.245	.426	.562
		25.90	0.000	0.000	0.000	.115	.254	.456	.707	.819
	2.0									
		5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.006	.012	.022
		20.00	0.000	0.000	0.000	.005	.006	.010	.043	.073
		22.00	0.000	0.000	0.000	.008	.015	.044	.122	.188
		24.00	0.000	0.000	0.000	.025	.074	.172	.324	.432
		25.90	0.000	0.000	0.000	.072	.170	.343	.585	.712
	3.0									
		5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	.002	.006	.008	.012
		20.00	0.000	0.000	0.000	.002	.006	.008	.023	.044
		22.00	0.000	0.000	0.000	.007	.012	.024	.068	.124
		24.00	0.000	0.000	0.000	.014	.045	.115	.244	.328
		25.90	0.000	0.000	0.000	.043	.114	.253	.454	.591

Table B1(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in May

MAY	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0									
		5.57	.199	.041	.007	0.000	0.000	0.000	0.000	0.000
		8.00	.026	.002	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0									
		5.57	.108	.015	.003	0.000	0.000	0.000	0.000	0.000
		8.00	.008	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0									
		5.57	.039	.007	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0									
		5.57	.014	.002	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B2(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in June

JUN.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	.006	.332
		20.00	0.000	0.000	0.000	0.000	.005	.008	.013	.417
		22.00	0.000	0.000	0.000	.005	.009	.041	.137	.487
		24.00	0.000	0.000	0.000	.009	.045	.152	.394	.720
		25.90	0.000	0.000	0.000	.038	.145	.369	.706	.900
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	.002	.006
		20.00	0.000	0.000	0.000	0.000	.002	.006	.010	.013
		22.00	0.000	0.000	0.000	.002	.006	.021	.086	.137
		24.00	0.000	0.000	0.000	.006	.021	.088	.249	.401
		25.90	0.000	0.000	0.000	.020	.081	.234	.551	.712
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.003
		20.00	0.000	0.000	0.000	0.000	0.000	.005	.008	.010
		22.00	0.000	0.000	0.000	0.000	.005	.009	.041	.089
		24.00	0.000	0.000	0.000	.005	.008	.045	.151	.255
		25.90	0.000	0.000	0.000	.008	.038	.144	.368	.560
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	.002	.006	.008
		22.00	0.000	0.000	0.000	0.000	.002	.006	.021	.042
		24.00	0.000	0.000	0.000	.002	.006	.021	.087	.154
		25.90	0.000	0.000	0.000	.006	.020	.080	.233	.374

Table B2(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in June

JUN.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.246	.043	.002	0.000	0.000	0.000	0.000	0.000
		8.00	.018	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.115	.012	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.002	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	.039	.002	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B3(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in July

JUL.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
JUL.	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	.004	1.000
		24.00	0.000	0.000	0.000	0.000	0.000	.004	.025	1.000
		25.90	0.000	0.000	0.000	0.000	.004	.021	.237	1.000
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.004
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	.006	.027
		25.90	0.000	0.000	0.000	0.000	0.000	.006	.072	.252
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	.004	.006
		25.90	0.000	0.000	0.000	0.000	0.000	.004	.021	.077
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	.004
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	.006	.022

Table B3(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in July

JUL.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
JUL.	0.0	5.57	.463	.035	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.014	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.181	.002	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	.029	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B4(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in August

AUG.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.008	.012	.026	.079	.601
		20.00	0.000	0.000	0.000	.013	.025	.061	.147	.668
		22.00	0.000	0.000	0.000	.036	.067	.127	.258	.744
		24.00	0.000	0.000	0.000	.088	.171	.281	.468	.749
		25.90	0.000	0.000	0.000	.183	.294	.466	.666	.820
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.007	.008	.018	.033	.093
		20.00	0.000	0.000	0.000	.009	.019	.041	.090	.156
		22.00	0.000	0.000	0.000	.026	.048	.095	.179	.269
		24.00	0.000	0.000	0.000	.062	.122	.225	.340	.481
		25.90	0.000	0.000	0.000	.134	.239	.375	.554	.672
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.008	.011	.026	.034
		20.00	0.000	0.000	0.000	.008	.013	.024	.060	.092
		22.00	0.000	0.000	0.000	.019	.036	.066	.124	.184
		24.00	0.000	0.000	0.000	.044	.087	.168	.279	.345
		25.90	0.000	0.000	0.000	.099	.181	.290	.461	.560
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.005	.007	.008	.018	.026
		20.00	0.000	0.000	0.000	.006	.009	.019	.041	.060
		22.00	0.000	0.000	0.000	.012	.026	.047	.094	.126
		24.00	0.000	0.000	0.000	.030	.061	.120	.223	.282
		25.90	0.000	0.000	0.000	.069	.133	.237	.371	.466

Table B4(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in August

AUG.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.621	.012	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.195	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	.009	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B5(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in September

SEP.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.008	.009	.023	.041	.508
		20.00	0.000	0.000	0.000	.010	.023	.055	.126	.585
		22.00	0.000	0.000	0.000	.030	.057	.121	.240	.624
		24.00	0.000	0.000	0.000	.080	.155	.280	.444	.692
		25.90	0.000	0.000	0.000	.172	.297	.474	.682	.811
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.008	.015	.031	.041
		20.00	0.000	0.000	0.000	.008	.016	.033	.084	.131
		22.00	0.000	0.000	0.000	.023	.039	.085	.167	.247
		24.00	0.000	0.000	0.000	.056	.109	.219	.342	.450
		25.90	0.000	0.000	0.000	.124	.229	.381	.569	.685
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.005	.008	.009	.022	.031
		20.00	0.000	0.000	0.000	.008	.009	.023	.054	.085
		22.00	0.000	0.000	0.000	.014	.030	.056	.120	.171
		24.00	0.000	0.000	0.000	.037	.079	.153	.278	.346
		25.90	0.000	0.000	0.000	.090	.170	.294	.471	.572
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.008	.015	.024
		20.00	0.000	0.000	0.000	.006	.008	.016	.033	.055
		22.00	0.000	0.000	0.000	.010	.023	.038	.084	.122
		24.00	0.000	0.000	0.000	.024	.055	.107	.216	.281
		25.90	0.000	0.000	0.000	.062	.122	.226	.378	.475

Table B5(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in September

SEP.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.688	.001	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	.005	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.161	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B6(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in October

OCT.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.008	.009	.020	.034	.522
		20.00	0.000	0.000	0.000	.008	.021	.050	.120	.594
		22.00	0.000	0.000	0.000	.023	.056	.118	.243	.631
		24.00	0.000	0.000	0.000	.078	.157	.284	.461	.704
		25.90	0.000	0.000	0.000	.175	.306	.494	.698	.819
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.007	.008	.014	.025	.035
		20.00	0.000	0.000	0.000	.008	.015	.028	.074	.128
		22.00	0.000	0.000	0.000	.020	.033	.083	.174	.247
		24.00	0.000	0.000	0.000	.054	.111	.215	.366	.465
		25.90	0.000	0.000	0.000	.123	.233	.396	.585	.703
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.008	.009	.020	.025
		20.00	0.000	0.000	0.000	.008	.008	.021	.049	.075
		22.00	0.000	0.000	0.000	.012	.022	.055	.117	.177
		24.00	0.000	0.000	0.000	.033	.077	.155	.281	.366
		25.90	0.000	0.000	0.000	.084	.173	.303	.491	.591
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.007	.008	.014	.020
		20.00	0.000	0.000	0.000	.007	.008	.015	.028	.050
		22.00	0.000	0.000	0.000	.009	.019	.032	.082	.119
		24.00	0.000	0.000	0.000	.020	.054	.109	.213	.281
		25.90	0.000	0.000	0.000	.056	.121	.231	.392	.496

Table B6(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in October

OCT.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.686	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.091	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B7(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in November

NOV.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.008	.008	.017	.033	.552
		20.00	0.000	0.000	0.000	.008	.019	.053	.118	.605
		22.00	0.000	0.000	0.000	.024	.059	.120	.248	.619
		24.00	0.000	0.000	0.000	.076	.160	.283	.463	.707
		25.90	0.000	0.000	0.000	.174	.310	.499	.701	.827
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.008	.013	.024	.035
		20.00	0.000	0.000	0.000	.008	.015	.028	.077	.122
		22.00	0.000	0.000	0.000	.019	.036	.082	.174	.253
		24.00	0.000	0.000	0.000	.055	.111	.222	.360	.468
		25.90	0.000	0.000	0.000	.122	.237	.398	.596	.708
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.003	.008	.008	.017	.024
		20.00	0.000	0.000	0.000	.007	.008	.019	.052	.079
		22.00	0.000	0.000	0.000	.011	.024	.059	.118	.178
		24.00	0.000	0.000	0.000	.032	.075	.159	.282	.363
		25.90	0.000	0.000	0.000	.084	.172	.308	.496	.602
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.008	.013	.017
		20.00	0.000	0.000	0.000	.006	.008	.014	.028	.054
		22.00	0.000	0.000	0.000	.009	.018	.035	.081	.120
		24.00	0.000	0.000	0.000	.021	.054	.110	.220	.285
		25.90	0.000	0.000	0.000	.057	.121	.235	.395	.502

Table B7(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in November

NOV.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.681	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	.004	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.048	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B8(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in December

DEC.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.008	.008	.018	.035	.543
		20.00	0.000	0.000	0.000	.008	.019	.050	.119	.565
		22.00	0.000	0.000	0.000	.022	.058	.120	.251	.580
		24.00	0.000	0.000	0.000	.076	.163	.285	.471	.700
		25.90	0.000	0.000	0.000	.184	.324	.516	.728	.839
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.008	.012	.024	.036
		20.00	0.000	0.000	0.000	.008	.015	.030	.079	.125
		22.00	0.000	0.000	0.000	.019	.035	.081	.179	.255
		24.00	0.000	0.000	0.000	.052	.117	.221	.370	.474
		25.90	0.000	0.000	0.000	.127	.245	.412	.624	.733
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.003	.008	.008	.018	.025
		20.00	0.000	0.000	0.000	.007	.008	.019	.050	.080
		22.00	0.000	0.000	0.000	.010	.022	.057	.119	.181
		24.00	0.000	0.000	0.000	.033	.076	.162	.284	.373
		25.90	0.000	0.000	0.000	.088	.182	.321	.513	.629
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.008	.012	.019
		20.00	0.000	0.000	0.000	.006	.008	.015	.030	.051
		22.00	0.000	0.000	0.000	.009	.019	.034	.080	.121
		24.00	0.000	0.000	0.000	.021	.052	.115	.219	.284
		25.90	0.000	0.000	0.000	.060	.126	.243	.410	.518

Table B8(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in December

DEC.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.663	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	.006	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.021	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B9(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in January

JAN.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.008	.009	.018	.038	.278
		20.00	0.000	0.000	0.000	.008	.020	.058	.123	.392
		22.00	0.000	0.000	0.000	.026	.063	.133	.264	.483
		24.00	0.000	0.000	0.000	.083	.169	.305	.489	.660
		25.90	0.000	0.000	0.000	.196	.331	.526	.735	.837
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.008	.013	.026	.039
		20.00	0.000	0.000	0.000	.008	.016	.033	.087	.125
		22.00	0.000	0.000	0.000	.019	.036	.091	.189	.265
		24.00	0.000	0.000	0.000	.059	.124	.232	.394	.490
		25.90	0.000	0.000	0.000	.132	.255	.421	.632	.739
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.005	.008	.008	.018	.026
		20.00	0.000	0.000	0.000	.007	.008	.020	.058	.089
		22.00	0.000	0.000	0.000	.014	.025	.062	.132	.191
		24.00	0.000	0.000	0.000	.036	.082	.168	.303	.394
		25.90	0.000	0.000	0.000	.091	.194	.329	.523	.636
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.008	.013	.018
		20.00	0.000	0.000	0.000	.006	.008	.016	.033	.059
		22.00	0.000	0.000	0.000	.009	.019	.036	.090	.134
		24.00	0.000	0.000	0.000	.023	.059	.123	.231	.305
		25.90	0.000	0.000	0.000	.065	.131	.253	.419	.526

Table B9(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in January

JAN.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.724	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.584	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	.584	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.012	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B10(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in February

FEB.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.008	.009	.020	.045	.097
		20.00	0.000	0.000	0.000	.008	.020	.053	.124	.199
		22.00	0.000	0.000	0.000	.026	.064	.137	.254	.390
		24.00	0.000	0.000	0.000	.082	.180	.312	.507	.638
		25.90	0.000	0.000	0.000	.200	.341	.541	.755	.837
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.008	.012	.030	.046
		20.00	0.000	0.000	0.000	.008	.016	.031	.083	.126
		22.00	0.000	0.000	0.000	.020	.039	.096	.193	.258
		24.00	0.000	0.000	0.000	.060	.121	.242	.402	.510
		25.90	0.000	0.000	0.000	.135	.267	.439	.657	.759
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.003	.008	.009	.020	.031
		20.00	0.000	0.000	0.000	.006	.008	.020	.053	.084
		22.00	0.000	0.000	0.000	.014	.026	.063	.136	.192
		24.00	0.000	0.000	0.000	.036	.082	.178	.311	.406
		25.90	0.000	0.000	0.000	.093	.199	.339	.538	.662
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.008	.012	.021
		20.00	0.000	0.000	0.000	.006	.008	.015	.030	.054
		22.00	0.000	0.000	0.000	.009	.020	.038	.096	.138
		24.00	0.000	0.000	0.000	.023	.059	.120	.241	.313
		25.90	0.000	0.000	0.000	.070	.134	.266	.437	.541

Table B10(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in February

FEB.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.990	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.987	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	.987	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.036	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B11(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in March

MAR.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.007	.009	.020	.047	.082
		20.00	0.000	0.000	0.000	.010	.020	.057	.128	.239
		22.00	0.000	0.000	0.000	.028	.071	.149	.274	.412
		24.00	0.000	0.000	0.000	.089	.187	.327	.526	.653
		25.90	0.000	0.000	0.000	.215	.362	.570	.772	.854
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.008	.013	.033	.048
		20.00	0.000	0.000	0.000	.009	.017	.033	.088	.130
		22.00	0.000	0.000	0.000	.020	.046	.096	.196	.279
		24.00	0.000	0.000	0.000	.062	.123	.253	.418	.531
		25.90	0.000	0.000	0.000	.149	.282	.463	.680	.776
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.003	.007	.009	.019	.033
		20.00	0.000	0.000	0.000	.006	.010	.020	.057	.090
		22.00	0.000	0.000	0.000	.014	.028	.071	.148	.200
		24.00	0.000	0.000	0.000	.036	.088	.185	.325	.423
		25.90	0.000	0.000	0.000	.102	.214	.360	.568	.685
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.008	.013	.020
		20.00	0.000	0.000	0.000	.006	.009	.016	.032	.058
		22.00	0.000	0.000	0.000	.011	.020	.045	.095	.149
		24.00	0.000	0.000	0.000	.025	.062	.122	.252	.329
		25.90	0.000	0.000	0.000	.072	.148	.281	.461	.573

Table B11(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in March

MAR.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.997	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.996	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	.996	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	.007	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Table B12(a) Exc. Prob. of Mead Spill As A Function of Initial Storages of Powell and Mead in April

APR.	SPILL	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.009	.016	.042	.160
		20.00	0.000	0.000	0.000	.010	.021	.055	.138	.271
		22.00	0.000	0.000	0.000	.025	.066	.142	.291	.431
		24.00	0.000	0.000	0.000	.093	.195	.355	.547	.679
		25.90	0.000	0.000	0.000	.220	.379	.595	.804	.882
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.006	.008	.013	.030	.043
		20.00	0.000	0.000	0.000	.010	.015	.032	.093	.140
		22.00	0.000	0.000	0.000	.019	.041	.091	.209	.296
		24.00	0.000	0.000	0.000	.061	.128	.267	.442	.552
		25.90	0.000	0.000	0.000	.148	.292	.487	.706	.808
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.009	.016	.031
		20.00	0.000	0.000	0.000	.006	.010	.020	.054	.095
		22.00	0.000	0.000	0.000	.013	.024	.065	.141	.213
		24.00	0.000	0.000	0.000	.038	.092	.193	.353	.446
		25.90	0.000	0.000	0.000	.097	.219	.378	.593	.711
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	.002	.006	.008	.013	.017
		20.00	0.000	0.000	0.000	.006	.010	.015	.031	.056
		22.00	0.000	0.000	0.000	.010	.019	.041	.091	.144
		24.00	0.000	0.000	0.000	.022	.061	.127	.266	.356
		25.90	0.000	0.000	0.000	.069	.147	.291	.485	.598

Table B12(b) Exec. Prob. of Mead Deficit As A Function of Initial Storages of Powell and Mead in April

APR.	DEFICIT	VP\VM	10.02	12.00	14.00	22.00	24.00	26.00	28.00	29.05
	0.0	5.57	.992	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	.990	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	.990	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	1.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	2.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	3.0	5.57	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		8.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		10.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		18.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		20.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		22.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		24.00	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
		25.90	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

APPENDIX C

MASS BALANCE ANALYSIS

Powell Mass Balance Equation is :

$$S_t^p = S_{t-1}^p + I_t^p - R_t^p - E_t^p + BS_t^p \qquad (C1)$$

If $S_t^p > S^p_{max}$,

$SP_t^p = S_t^p - S^p_{max}$ and $S_t^p = S^p_{max}$

If $S_t^p < S^p_{min}$,

$DF_t^p = S^p_{min} - S_t^p$ and $S_t^p = S^p_{min}$

Mead Mass Balance Equation is :

$$S_t^m = S_{t-1}^m + I_t^m + R_t^p + SP_t^p - DF_t^p - R_t^m$$

$$- D_t^m - E_t^m + BS_t^m \qquad (C2)$$

If $S_t^m > S^m_{max}$,

$SP_t^m = S_t^m - S^m_{max}$ and $S_t^m = S^m_{max}$

If $S_t^m < S^m_{min}$,

$$DF_t^m = S^m_{min} - S_t^m \quad \text{and} \quad S_t^m = S^m_{min}$$

where

S is the storage at the end of the month,

I is the inflow (obtained from Table C1),

R is the release,

E is the evaporation which is calculated by multiplying the monthly evaporation rate (Table A4 of Appendix A) to the average reservoir surface area (Figures C1 and C2 of Appendix C),

BS is the bank storage loss/gain which is equal to $CB(S_{t-1} - S_t)$ where CB is the bank storage loss/gain coefficient,

S_{max} is the maximum capacity,

S_{min} is the minimum capacity,

SP is the spill,

DF is the deficit,

D is the diversion (obtained from Table C1),

t subscript is the current month,

p and m superscript are Powell and Mead respectively.

Table C1 Powell Mass Balance for Illustration No.1

(Units are in maf.)

Month	S_{t-1}^{p}	I_t^{p}	R_t^{p}	E_t^{p}	BS_t^{p}	S_t^{p}	SP_t^{p}	S_t^{p*}
Apr.	22.78							
May		2.78	1.63	.07	−.08	23.79		
Jun.		5.70	1.66	.08	−.17	27.57	1.67	25.90
Jul.		3.73	2.12	.09	.0	27.42	1.52	25.90
Jul.	25.90							
Aug.		1.48	1.55	.10	.01	25.75		
Sep.		.75	1.15	.08	.04	25.31		
Oct.		.90	1.10	.07	.02	25.05		
Nov.		.78	1.10	.06	.03	24.71		
Dec.		.81	1.39	.05	.05	24.12		
Jan.		.82	1.43	.04	.05	23.53		
Feb.		.88	1.06	.04	.02	23.32		
Mar.		1.05	1.05	.04	.0	23.28		
Apr.		1.50	1.05	.05	−.03	23.65		

* Truncated storage at the end of the month when the calculated end of month storage is greater than the maximum capacity

Table C2 Mead Mass Balance for Illustration No. 1

(Units are in Maf.)

Month	S_{t-1}^m	I_t^m	X_t^m	SP_t^m	X_t^m	D_t^m	E_t^m	BS_t^m	S_t^m	SP_t^m
Apr.	24.59									
May		.24	1.63	-	1.85	.01	.08	.01	24.51	
Jun.		.08	1.66	1.67	1.78	.02	.10	-.09	25.93	
Jul.		.23	2.12	1.52	1.75	.02	.13	-.12	27.79	
Jul.	26.80									
Aug.		.15	1.55		1.16	.01	.14	-.02	27.16	
Sep.		.04	1.15		1.09	.01	.11	.0	27.13	
Oct.		.16	1.10		1.07	.01	.08	-.01	27.23	
Nov.		.13	1.10		1.05	.01	.08	-.01	27.31	
Dec.		.06	1.39		1.08	.01	.07	-.02	27.58	
Jan.		-.01	1.43		.93	.01	.06	-.03	27.98	
Feb.		-.01	1.06		1.14	.01	.05	.01	27.84	
Mar.		.09	1.05		1.33	.01	.06	.02	27.58	
Apr.		.10	1.05		1.35	.01	.08	.02	27.33	

Table C3 Powell Mass Balance for Illustration No.2

(Units are in maf.)

Month	S_{t-1}^{p}	I_t^{p}	R_t^{p}	E_t^{p}	BS_t^{p}	S_t^{p}	SP_t^{p}	S_t^{p*}
Apr.	22.78							
May		2.78	1.65	.07	−.08	23.77		
Jun.		5.70	1.72	.08	−.17	27.50	1.60	25.90
Jul.		3.73	2.65	.09	.0	26.89	.99	25.90
Aug.		1.48	1.50	.10	.01	25.79		
Sep.		.75	1.14	.08	.04	25.36		
Oct.		.90	1.10	.07	.02	25.10		
Nov.		.78	1.13	.06	.03	24.73		
Dec.		.81	1.45	.05	.05	24.09		
Jan.		.82	1.55	.04	.06	23.39		
Feb.		.88	1.26	.04	.03	23.00		
Mar.		1.05	1.37	.04	.03	22.66		
Apr.		1.50	1.43	.05	.0	22.68		

* Truncated storage at the end of the month when the calculated end of month storage is greater than the maximum capacity

Table C4 Mead Mass Balance for Illustration No. 2

(Units are in maf.)

Month	S_{t-1}^m	I_t^m	X_t^m	SP_t^m	X_t^m	D_t^m	E_t^m	BS_t^m	S_t^m	SP_t^m
Apr.	24.59									
May		.24	1.65	-	2.05	.01	.08	.02	24.34	
Jun.		.08	1.72	1.60	1.95	.02	.09	-.08	25.59	
Jul.		.23	2.64	.99	1.75	.02	.13	-.12	27.44	
Aug.		.15	1.50		1.58	.01	.14	.01	27.36	
Sep.		.04	1.14		1.58	.01	.11	.03	26.87	
Oct.		.16	1.10		1.53	.01	.08	.02	26.53	
Nov.		.13	1.13		1.55	.01	.08	.02	26.17	
Dec.		.06	1.45		1.62	.01	.07	.01	25.99	
Jan.		-.01	1.55		1.57	.01	.06	.01	25.90	
Feb.		-.01	1.26		1.89	.01	.05	.04	25.25	
Mar.		.09	1.37		2.15	.01	.06	.05	24.53	
Apr.		.10	1.43		2.22	.01	.07	.05	23.81	

Table C5 Powell Mass Balance for Illustration No.3
(Units are in maf.)

Month	S_{t-1}^p	I_t^p	R_t^p	E_t^p	BS_t^p	S_t^p	SP_t^p	S_t^{p*}
Apr.	22.78							
May		2.78	.55	.07	-.16	24.79	-	
Jun.		5.70	.78	.08	-.09	29.53	3.63	25.90
Jul.		3.73	2.65	.09	.0	26.89	.99	25.90

* Truncated storage at the end of the month when the calculated end of month storage is greater than the maximum capacity

Table C6 Mead Mass Balance for Illustration No. 3
(Units are in maf.)

Month	S_{t-1}^m	I_t^m	X_t^m	SP_t^m	X_t^m	D_t^m	E_t^m	BS_t^m	S_t^m	SP_t^m
Apr.	24.59									
May		.24	.55	-	.79	.01	.08	.01	24.50	
Jun.		.08	.78	3.63	.72	.02	.10	-.22	27.92	
Jul.		.23	2.65	.99	4.08	.02	.13	.02	27.58	

Table C7 Regulated Inflows to Lakes Powell and Mead and Diversion from Lake Mead during May 1983 to April

Year	Month	Inflow to Powell (maf)	Side Flow to Mead (maf)	Diversion (maf)
1983	May	2.78	.24	.01
	Jun.	5.70	.08	.02
	Jul.	3.73	.23	.02
	Aug.	1.48	.15	.01
	Sep.	.75	.04	.01
	Oct.	.90	.16	.01
	Nov.	.78	.13	.01
	Dec.	.81	.06	.01
1984	Jan.	.82	-.01	.01
	Feb.	.88	-.01	.01
	Mar.	1.05	.09	.01
	Apr.	1.50	.10	.01

Source : The Operation Plan for the Colorado River Storage Project of 1983 - 1984, USBR, Denver, Colorado

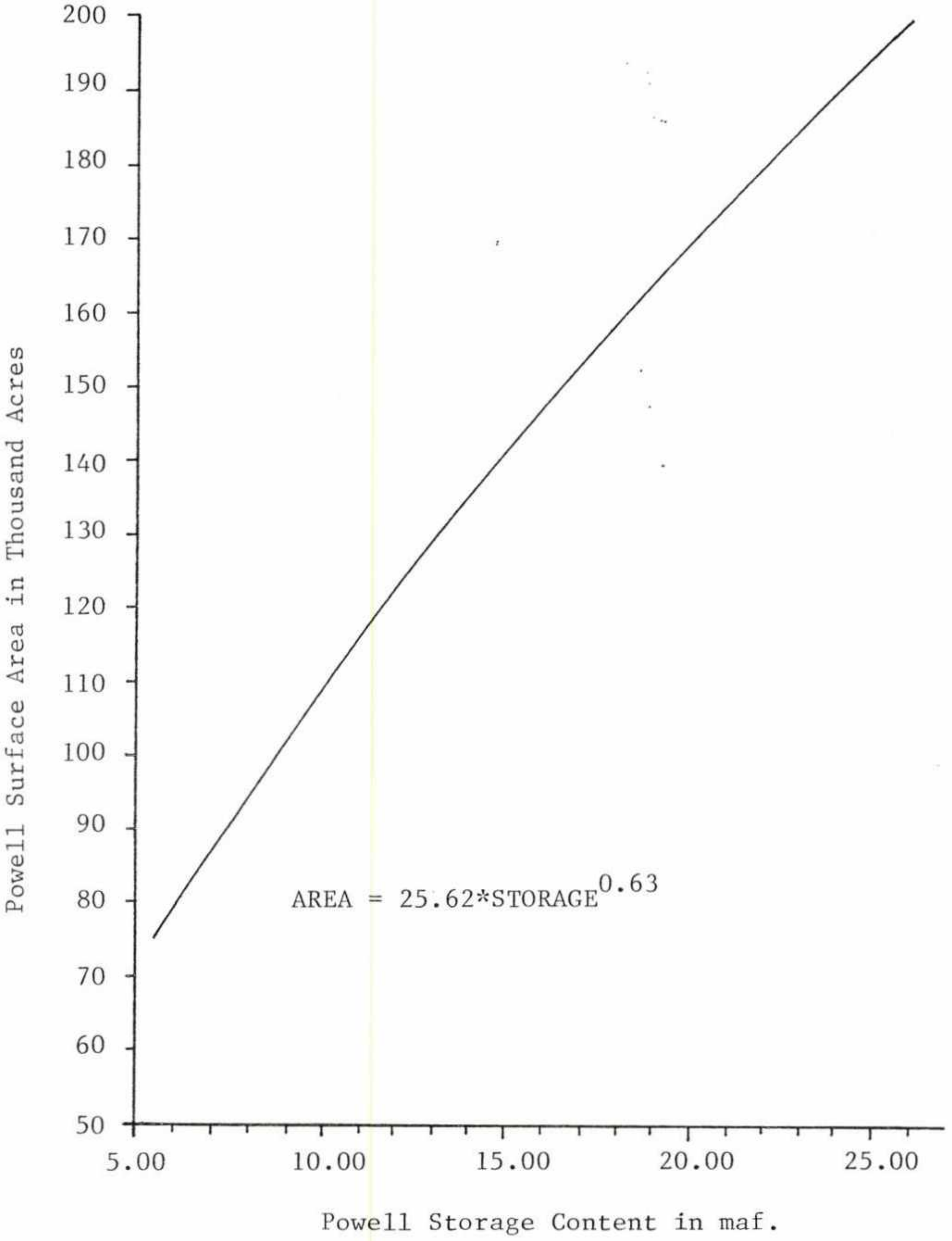

Figure C1 Area-Storage Relationship for Lake Powell

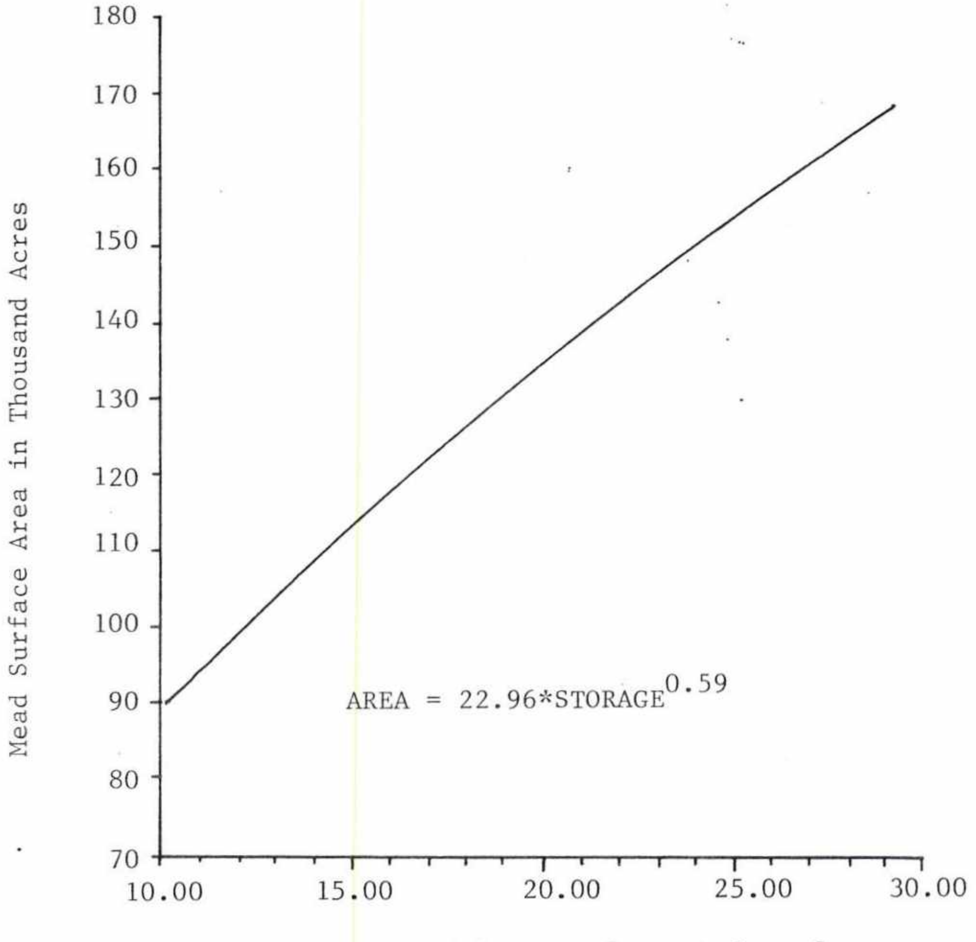

Figure C2 Area-Storage Relationship for Lake Mead

APPENDIX D

THE FAILURE PROBABILITY CRITERIA DERIVED FROM THE ACTUAL OPERATION OF 1981 TO 1985

The probability of Powell spill is determined from Figures B1(a,b) to B12(a,b) based on the recalculated initial storage. From the current initial storage, the known actual release during the current ADIP and the target release of the current ADIP (the 1985 USBR estimate depletion schedule is assumed to be the target release), the new initial storage for Lake Powell is calculated from the following equation:

$$S_t^{P'} = S_t^{P} - \sum_{t}^{\text{ADIP End}} X_t^{P} + \sum_{t}^{\text{ADIP End}} Y_t^{P} \qquad \text{(D1)}$$

where

$S_t^{P'}$ is the Powell recalculated initial storage,

S_t^{P} is the Powell current initial storage,

X_t^{P} is the Powell additional release when the actual release is greater than the target release,

Y_t^{P} is the Powell cutback release when the actual release is less than the target release.

Table D1 shows how to determine the probability of spill from Lake Powell during 1981 to 1985.

Similarly the probability of Mead spill is determined from Tables B1(a,b) to B12(a,b). The new initial storage for Lake Mead is calculated from the following equation :

$$S_t^{m'} = S_t^m + \sum_t^{\text{ADIP End}} X_t^p - \sum_t^{\text{ADIP End}} X_t^m - \sum_t^{\text{ADIP End}} Y_t^p - \sum_t^{\text{ADIP End}} Y_t^m \qquad \text{(D2)}$$

where

$S_t^{m'}$ is the Mead recalculated initial storage,

S_t^m is the Mead current initial storage,

X_t^m is the Mead additional release when the actual release is greater than the target release,

Y_t^m is the Mead cutback release when the actual release is less than the target release,

X_t^p and Y_t^p are previously defined.

Table D2 shows how to determined the probability of spill from Lake Mead during 1981 to 1985.

<u>For Lake Powell</u>

The average spill probability = 0.13

The maximum spill probability = 0.44

The minimum spill probability = 0.

<u>For Lake Mead</u>

The average spill probability = 0.01

The maximum spill probability = 0.04

The minimum spill probability = 0.

Table D1 The Probability of Spill from Lake Powell during 1981 to 1985

Year	Month	S_t^p	Actual Release	Target Release	X_t^p	Y_t^p	$S_t^{p'}$	$P[S_t^{p'} \geq 0]$
1981	Apr.	21.59	.47	.52		-.05	21.63	0.39
	May	21.51	.55	.55	.0		21.77	0.36
	Jun.	21.59	.53	.59		-.06	21.84	0.16
	Jul.	22.01	.85	1.05		-.20	22.20	0.01
	Aug.	21.59	.90	1.01		-.11	21.49	0.23
	Sep.	20.96	.67	.61	.06		20.75	0.19
	Oct.	20.75	.61	.57	.04		20.60	0.18
	Nov.	20.75	.59	.56	.03		20.63	0.18
	Dec.	20.57	.84	.86		-.02	20.48	0.18
1982	Jan.	20.12	.90	.89	.01		20.01	0.17
	Feb.	19.61	.68	.53	.16		19.51	0.18
	Mar.	19.47	.51	.51		.0	19.53	0.19
	Apr.	19.64	.61	.52	.10		19.69	0.19
	May	19.86	.62	.56	.07		20.01	0.16
	Jun.	21.13	.63	.59	.05		21.34	0.12
	Jul.	22.65	.78	1.05		-.27	22.91	0.03
	Aug.	23.02	.92	1.01		-.09	18.99	0.09
	Sep.	22.90	.62	.61	.01		18.78	0.09
	Oct.	23.01	.79	.57	.22		18.90	0.09
	Nov.	23.06	.98	.56	.42		19.18	0.09
	Dec.	22.85	.98	.86	.12		19.38	0.11
1983	Jan.	22.62	.91	.89	.03		19.27	0.12
	Feb.	22.41	.85	.53	.33		19.09	0.14
	Mar.	22.23	.64	.51	.13		19.23	0.17
	Apr.	22.60	.93	.52	.41		19.74	0.19

(Units are in maf.)

Table D1(cont.) The Probability of Spill from Lake Powell during 1981 to 1985

Year	Month	S_t^p	Actual Release	Target Release	X_t^p	Y_t^p	$S_t^{p'}$	$P[S_t^{p'} \geq 0]$
	May	22.78	1.24	.55	.69		20.33	0.20
	Jun.	24.21	1.64	.59	1.06		22.45	0.25
	Jul.	26.17	1.76	1.05	.71		25.46	0.44
1984	Aug.	26.22	1.75	1.01	.74		15.55	0.
	Sep.	25.72	1.66	.61	1.05		15.79	0.
	Oct.	24.81	1.65	.57	1.09		15.93	0.
	Nov.	24.08	1.52	.56	.96		16.28	0.
	Dec.	23.40	1.54	.86	.68		16.56	0.
	Jan.	22.70	1.55	.89	.66		16.54	0.
	Feb.	21.99	1.48	.53	.95		16.50	0.
	Mar.	21.48	1.49	.51	.98		16.93	0.
	Apr.	21.06	1.51	.52	.99		17.49	0.
	May	21.07	1.63	.55	1.08		18.49	0.07
	Jun.	23.09	1.50	.59	.92		21.60	0.14
	Jul.	25.21	1.62	1.05	.58		24.63	0.23
1985	Aug.	25.35	1.58	1.01	.57		18.27	0.06
	Sep.	25.06	1.42	.61	.81		18.55	0.08
	Oct.	24.35	1.42	.57	.85		18.64	0.08
	Nov.	23.93	1.54	.56	.98		19.08	0.09
	Dec.	23.30	1.55	.86	.69		19.42	0.11
	Jan.	22.63	1.61	.89	.72		19.44	0.13
	Feb.	21.99	1.51	.53	.98		19.52	0.18
	Mar.	21.35	1.28	.51	.77		19.86	0.21
	Apr.	21.40	1.23	.52	.72		20.68	0.28

(Units are in maf.)

Table D2 The Probability of Spill from Lake Mead during 1981 to 1985

Year	Month	S_t^m	Actual Release	Target Release	X_t^m	Y_t^m	$S_t^{m'}$	$P[S_t^{m'} \geq 0]$
1981	Apr.	23.23	1016	878	138		23046	0.04
	May	22.69	857	743	.11		21.96	0.01
	Jun.	22.37	835	678	.16		21.75	0.
	Jul.	22.02	864	655	.21		21.61	0.
	Aug.	21.90	.91	.64	.28		21.74	0.03
	Sep.	21.89	.66	.55	.12		22.01	0.02
	Oct.	21.87	.38	.50		-.12	22.10	0.01
	Nov.	22.07	.39	.49		-.10	22.19	0.01
	Dec.	22.26	.40	.58		-.19	22.28	0.01
1982	Jan.	22.67	.46	.43	.03		22.60	0.01
	Feb.	23.08	.55	.60		-.05	22.94	0.01
	Mar.	23.26	.79	.91		-.12	23.08	0.01
	Apr.	23.06	1.04	.88	.16		22.76	0.01
	May	22.67	.84	.74	.10		22.38	0.01
	Jun.	22.47	.64	.68		-.04	22.22	0.
	Jul.	22.40	.74	.66	.08		22.06	0.
	Aug.	22.41	.76	.64	.13		19.67	0.
	Sep.	22.54	.39	.55		-.16	19.93	0.
	Oct.	22.77	.39	.50		-.10	20.00	0.
	Nov.	23.07	.38	.49		-.11	20.20	0.
	Dec.	23.61	.46	.58		-.12	20.63	0.
1983	Jan.	24.15	1.16	.43	.73		21.05	0.
	Feb.	23.92	.37	.60		-.23	21.55	0.01
	Mar.	24.44	.63	.91		-.28	21.83	0.01
	Apr.	24.64	1.06	.88	.18		21.76	0.

(Units are in maf.)

Table D2(cont.) The Probability of Spill from Lake Mead during 1981 to 1985

Year	Month	S_t^m	Actual Release	Target Release	X_t^m	Y_t^m	$S_t^{m'}$	$P[S_t^{m'} \geq 0]$
	May	24.59	1.22	.74	.47		24.35	0.02
	Jun.	24.75	2.08	.68	1.41		24.30	0.02
	Jul.	25.98	1.48	.66	.82		25.87	0.02
	Aug.	26.80	1.55	.64	.91		11.86	0.
	Sep.	26.28	2.21	.55	1.66		12.25	0.
	Oct.	25.66	2.18	.50	1.68		13.29	0.
	Nov.	25.21	1.82	.49	1.33		14.53	0.
	Dec.	24.91	1.69	.58	1.11		15.56	0.
1984	Jan.	24.75	1.89	.43	1.45		16.51	0.
	Feb.	24.37	1.77	.60	1.17		17.58	0.
	Mar.	24.05	1.77	.91	.86		18.43	0.
	Apr.	23.80	1.56	.88	.69		19.05	0.
	May	23.78	1.89	.74	1.14		22.29	0.01
	Jun.	24.36	2.08	.68	1.40		22.93	0.01
	Jul.	24.73	2.19	.66	1.53		23.77	0.
	Aug.	24.84	1.91	.64	1.27		23.13	0.01
	Sep.	24.61	1.62	.55	1.07		25.63	0.03
	Oct.	24.41	1.59	.50	1.09		23.66	0.01
	Nov.	24.19	1.54	.49	1.06		23.68	0.01
	Dec.	24.14	1.62	.58	1.04		23.71	0.01
1985	Jan.	24.08	1.77	.43	1.34		23.99	0.02
	Feb.	23.94	1.58	.60	.99		24.47	0.02
	Mar.	23.90	1.40	.91	.49		24.44	0.03
	Apr.	23.86	1.33	.88	.45		24.12	0.04

(Units are in maf.)

APPENDIX E

LISTING OF THE COMPUTER PROGRAM

X |

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      PROGRAM MONCAR
     *        (INPUT,OUTPUT,PWLOS,PWDEF,MDLOS,MDDEF,
     *        TAPE5=INPUT,TAPE6=OUTPUT,
     *        TAPE7=PWLOS,TAPE8=PWDEF,TAPE9=MDLOS,TAPE10=MDDEF)
C***********************************************************************
C
C     WRITTEN BY VARAWOOT VUDHIVANICH        COLORADO STATE UNIVERSITY
C
C     DATE FALL 1985
C
C***********************************************************************
C
C     THE PROGRAM MONCAR IS WRITTEN TO IDENTIFY ADIP , TO GENERATE A
C     CONDITIONAL PROBABILITY OF STORAGES AT THE END OF ADIP TYPE I
C     AND ADIP TYPE II AND THE EXCEEDANCE PROBABILITIES OF SPILL AND
C     DEFICIT AS A FUNCTION OF INITIAL STORAGES AND INITIAL MONTH OF
C     A SERIES OF TWO RESERVOIRS.
C
C     THE PROGRAM CONSISTS OF A MAIN PROGRAM AND 9 SUBROUTINES AND
C     HAS THE FOLLOWING STRUCTURE:
C
C         MONCAR CALL READDAT (TO READ IN THE DATA)
C                CALL FIADIP  (TO IDENTIFY ADIP)
C                CALL SIMULAT (TO PERFORM MONTE CARLO SIMULATION)
C         SIMULAT CALL POWST  (TO PERFORM POWELL MASS BALANCE)
C                 CALL MEADST (TO PERFORM MEAD MASS BALANCE)
C                 CALL CPROBP (TO DETERMINE A CONDITIONAL PROBABILITY
C                              OF POWELL STORAGE AT THE END OF ADIP)
C                 CALL CPROBM (TO DETERMINE A CONDITIONAL PROBABILITY
C                              OF MEAD STORAGE AT THE END OF ADIP)
C                 CALL XPROBP (TO DETERMINE THE EXCEEDANCE
C                              PROBABILITY OF POWELL SPILL AND
C                              DEFICIT AT THE END OF ADIP)
C                 CALL XPROBM (TO DETERMINE THE EXCEEDANCE
C                              PROBABILITIES OF MEAD SPILL AND
C                              DEFICIT AT THE END OF ADIP)
C
C     LIMITATIONS OF THE PROGRAM
C     (1) THE MAXIMUM OF 2 RESERVOIRS,
C     (2) THE MAXIMUM OF 500 YEARS OF MONTHLY SIMULATION,
C     (3) THE MAXIMUM OF 10 INCREMENTS OF INITIAL STORAGES FOR
C         EACH RESERVOIRS,
C     (4) THE MAXIMUM OF 20 CLASS INTERVALS OF STORAGES AT THE
C         END OF ADIP TYPE I AND II,
C     (5) THE MAIXMUM OF 5 DISCRETE LEVELS OF SPILL AND DEFICIT,
C
C     INPUT DATA REQUIRED
C     (1) THE DESCRIPTION OF THE RUN,
C     (2) NUMBER OF YEARS AND NUMBER OF PERIODS IN A YEAR,
C     (3) INFLOW DATA,
C     (4) TARGET DEMAND DATA,
C     (5) THE MAXIMUM AND MINIMUM STORAGES,
C     (6) SPECIFY ADIP TYPE I OR II OR BOTH TO BE RUN,
C     (7) NUMBER OF CLASS INTERVALS OF STORAGES AT THE END OF ADIP,
C         NUMBER OF INITIAL STORAGE INCREMENTS, AND NUMBER OF
C         DISCRETE LEVELS OF SPILL AND DEFICIT.
C     (SEE FORMAT IN SUBROUTINE READDAT)
C     NOTE: ALL DATA ARE IN THE UNIT OF THOUSAND ACRE-FEET.
C
C***********************************************************************
      COMMON /DEFLOW/ QIM(500,12) , QIP(500,12) ,
     *        CDEPU(12) , CDEPL(12) , CSNDEP(12) , CMEXCO(12) ,
     *        CRP(12) , DEPU , DEPL , SNDEP , DMEXCO , RPMIN ,
     *        DEPUM(12) , DEPLM(12) , SNDEPM(12) , DMEXCM(12)
      COMMON /CONTR1/ VMMAX1(12) , VMMIN1(12) , VPMAX1(12) , VPMIN1(12)
      COMMON /CONTR2/ NYR , NP , TMONTH(12)      .
      COMMON /CADIP/ MA1B , MA1E , MA2B , MA2E , MADIP1 , MADIP2
      COMMON /SIMIND/ M , JSP , JSM , JP , STORAGP(10) , STORAGM(10)
      COMMON /MASSB/ RM(12) , RP(12) , VMM , VMM1 , VPM , VPM1 ,IN , MP1
      COMMON /CONST1/ NINC , NINCS , NINCP
      COMMON /CONST2/ VMMAX , VMMIN , VPMAX , VPMIN
      COMMON /PROB/ STOR1(500) , STOR2(500) ,
     *              STRMX1 , STRMX2 , STRMN1 , STRMN2
      COMMON /PROBM/ CCONDM1(10,10,20) , CCONDM2(10,10,20) ,
     *               LOSSM(10,10,20) , DEFM(10,10,20)
      COMMON /PROBP/ CCONDP1(10,20) , CCONDP2(10,20) ,
     *               LOSSP(10,20) , DEFP(10,20)
      COMMON /XPROB/ PERLOS(5) , PERDEF(5)
      COMMON /OUT/ IOUT7 , IOUT8 , IOUT9 , IOUT10
      COMMON /WRIT/ IWRT1
      COMMON /LOGVAR/ CYCI , CYCII
      DATA IOUT7/7/ , IOUT8/8/ , IOUT9/9/ , IOUT10/10/
C***********************************************************************
C
C     CYCI  = ADIP TYPE I
C     CYCII = ADIP TYPE II
C     IWRT1 = 0 (NO PRINT OUT THE INPUT DATA)
C     IWRT1 = 1 (PRINT OUT THE INPUT DATA)
C
C***********************************************************************
      DATA IWRT1 /0/
      CALL READDAT
      CALL FIADIP
      CALL SIMULAT
      STOP
      END
C***********************************************************************
      SUBROUTINE READDAT
C***********************************************************************
      DIMENSION DESCPT(20)
C***********************************************************************
      COMMON /DEFLOW/ QIM(500,12) , QIP(500,12) ,
     *        CDEPU(12) , CDEPL(12) , CSNDEP(12) , CMEXCO(12) , CRP(12) ,
     *        DEPU , DEPL , SNDEP , DMEXCO , RPMIN
      COMMON /CONTR1/ VMMAX1(12) , VMMIN1(12) , VPMAX1(12) , VPMIN1(12)
      COMMON /CONTR2/ NYR , NP , TMONTH(12)
      COMMON /CONST1/ NINC , NINCS , NINCP
      COMMON /CONST2/ VMMAX , VMMIN , VPMAX , VPMIN
      COMMON /WRIT/ IWRT1
      COMMON /LOGVAR/ CYCI , CYCII
      LOGICAL CYCI , CYCII
C***********************************************************************
      DATA TMONTH/4HOCT. , 4HNOV. , 4HDEC. , 4HJAN. , 4HFEB. , 4HMAR. ,
     *            4HAPR. , 4HMAY  , 4HJUN. , 4HJUL. , 4HAUG. , 4HSEP. /
      DATA TQIP/3HQIP/ , TQIM/3HQIM/
      DATA VMMAX/29054./ , VMMIN/10024./ , VPMAX/25902./ , VPMIN/5574./
C**********************************************************************
C     READ IN DATA
C     FIRST: THE DESCRIPTION OF RUN
      READ(5,105) (DESCPT(I),I=1,20)
  105 FORMAT(20A4)
```

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C     SECOND: NO. OF YEARS(NYR) AND THE NO. OF PERIODS WITHIN A YEAR(NP)
C              TO BE RUN
      READ(5,115) NYR , NP
 115  FORMAT(2I5)
C     THIRD: THE INFLOW TO POWELL (QIP)
C             THE INFLOW TO MEAD (QIM)
      READ(5,125) ((QIP(I,J),J=1,NP),I=1,NYR)
      READ(5,125) ((QIM(I,J),J=1,NP),I=1,NYR)
 125  FORMAT(12F6.0)
C     FOURTH: THE ANNUAL DEMANDS WHICH ARE ASSUMED CONSTANT FOR A PERIOD
C              OF TIME.
C              DEPU = ANNUAL UPPER BASIN DEPLETION SCHEDULE
C              DEPL = ANNUAL LOWER BASIN DEPLETION SCHEDULE
C              SNDEP = ANNUAL SOUTHERN NEVADA DEPLETION SCHEDULE
C              DMEXCO = ANNUAL MEXICAN DELIVERY SCHEDULE
C              RPMIN = POWELL MINIMUM OBJECTIVE RELEASE
      READ(5,135) DEPU , DEPL , SNDEP , DMEXCO , RPMIN
 135  FORMAT(5F6.0)
C     FIFTH: THE MONTHLY DISTRIBUTION COEFFICIENTS OF THE DEMANDS
      READ(5,145) (CDEPU(J),J=1,NP)
      READ(5,145) (CDEPL(J),J=1,NP)
      READ(5,145) (CSNDEP(J),J=1,NP)
      READ(5,145) (CMEXCO(J),J=1,NP)
      READ(5,145) (CRP(J),J=1,NP)
 145  FORMAT(12F6.4)
C     SIXTH: THE MAXIMUM AND MINIMUM ALLOWABLE STORAGES OF MEAD AND
C             POWELL
      READ(5,125) (VMMAX1(J),J=1,NP)
      READ(5,125) (VMMIN1(J),J=1,NP)
      READ(5,125) (VPMAX1(J),J=1,NP)
      READ(5,125) (VPMIN1(J),J=1,NP)
C     IF ICYCLE IS 1 , ONLY ADIP I IS ANALYZED.
C     IF ICYCLE IS 2 , ONLY ADIP II IS ANALYZED.
C     IF ICYCLE IS 12 , BOTH ADIPS ARE ANALYZED.
      READ(5,155) ICYCLE
 155  FORMAT(I2)
C*****************************************************************
C
C     NINC  = NUMBER OF CLASS INTERVALS OF STORAGES
C     NINCS = NUMBER OF DISCRETE LEVELS OF INITIAL STORAGE
C     NINCP = NUMBER OF DISCRETE LEVELS OF SPILL AND DEFICIT
C
C*****************************************************************
      READ(5,165) NINC , NINCS , NINCP
 165  FORMAT(4I2)
      IF (ICYCLE-2) 1 , 2 , 3
 1    CYCI = .TRUE.
      CYCII = .FALSE.
      GO TO 4
 2    CYCI = .FALSE.
      CYCII = .TRUE.
      GO TO 4
 3    CYCI = .TRUE.
      CYCII = .TRUE.
C     OPTION: IF IWRT1 = 0 NO PRINT OUT IS REQUIRED
C                IWRT1 = 1 PRINT OUT THE INPUT DATA
 4    IF ( IWRT1 .EQ. 0 ) RETURN
      WRITE(6,106)
 106  FORMAT(1H1///5X,49(1H*)/5X,1H*,47X,1H*/5X,1H*,10H  MONTHLY ,
     *       38HSIMULATION OF LAKES MEAD AND POWELL  */5X,1H*,47X,1H*/
     *       ,5X,49(1H*)//5X,10HINPUT DATA/5X,10(1H-)/5X,
     *       47H(ALL UNITS ARE IN TAF. UNLESS STATED OTHERWISE))
      WRITE(6,116) (DESCPT(I),I=1,20)
 116  FORMAT(5X,20A4)
      WRITE(6,126) NYR , NP , VMMAX , VPMAX , VMMIN , VPMIN
 126  FORMAT(5X,15HNUMBER OF YEARS,17X,1H=,I10/5X,18HNUMBER OF PERIODS ,
     *       9HIN A YEAR,5X,1H=,I10/5X,24HMAXIMUM CAPACITY OF MEAD,8X,
     *       1H=,F10.1/5X,26HMAXIMUM CAPACITY OF POWELL,6X,1H=,F10.1/5X,
     *       25HMEAD MINIMUM STORAGE REQ.,7X,1H=,F10.1/5X,
     *       27HPOWELL MINIMUM STORAGE REQ.,5X,1H=,F10.1)
      WRITE(6,136)
 136  FORMAT(/10X,31HMAX. AND MIN. ALLOWABLE STORAGE/10X,31(1H-)/
     *       5X,5HMONTH,8X,4HMEAD,15X,6HPOWELL/16X,4HMAX.,6X,
     *       4HMIN.,6X,4HMAX.,6X,4HMIN./)
      DO 10 J=1,NP
        WRITE(6,146) TMONTH(J),VMMAX1(J),VMMIN1(J),VPMAX1(J),VPMIN1(J)
 146    FORMAT(5X,A4,1X,4F10.1)
 10   CONTINUE
      WRITE(6,156) TQIP,(TMONTH(J),J=1,NP)
 156  FORMAT(1H1//55X,10HTABLE OF  ,A3//5X,4HYEAR,12(5X,A4),3X,6HANNUAL)
      DO 20 I=1,NYR
        SUM = 0.0
        DO 30 J=1,NP
          SUM = SUM + QIP(I,J)
 30     CONTINUE
        WRITE(6,166) I,(QIP(I,J),J=1,NP) , SUM
 166    FORMAT(I9,13F9.1)
 20   CONTINUE
      WRITE(6,156) TQIM,(TMONTH(J),J=1,NP)
      DO 40 I=1,NYR
        SUM = 0.0
        DO 50 J=1,NP
          SUM = SUM + QIM(I,J)
 50     CONTINUE
        WRITE(6,166) I,(QIM(I,J),J=1,NP),SUM
 40   CONTINUE
      WRITE(6,176) DEPU , DEPL , SNDEP , DMEXCO , RPMIN
 176  FORMAT(1H1///28X,18HTHE ANNUAL DEMANDS/28X,18(1H-)//20X,
     *       11HUPPER BASIN,6X,1H=,F10.1/20X,11HLOWER BASIN,6X,1H=,F10.1/
     *       20X,15HSOUTHERN NEVADA,2X,1H=,F10.1/20X,14HMEXICAN TREATY,
     *       3X,1H=,F10.1/20X,16HOBJ. POWELL REL.,1X,1H=,F10.1)
      WRITE(6,186)
 186  FORMAT(//23X,26HMONTHLY DISTRIBUTION COEF./23X,26(1H-)/5X,5HMONTH,
     *       5X,11HUPPER BASIN,5X,11HLOWER BASIN,11X,5HSNDEP,9X,
     *       7HMEXICAN,11X,5HRPMIN//)
      DO 60 J=1,NP
        WRITE(6,196) TMONTH(J),CDEPU(J),CDEPL(J),CSNDEP(J),CMEXCO(J)
     *                , CRP(J)
 196    FORMAT(5X,A4,1X,5(5X,F11.4))
 60   CONTINUE
      RETURN
      END
C*****************************************************************
      SUBROUTINE FIADIP
C*****************************************************************
      DIMENSION DEMAND(12) , NADIP1(12) , NADIP2(12) , PADIP1(12) ,
     *          PADIP2(12) , FLOW(500,12)
C*****************************************************************
      COMMON /DEFLOW/ QIM(500,12) , QIP(500,12) ,
     *        CDEPU(12) , CDEPL(12) , CSNDEP(12) , CMEXCO(12) , CRP(12),
```

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     *        DEPU , DEPL , SNDEP , DMEXCO , RPMIN ,
     *        DEPUM(12) , DEPLM(12) , SNDEPM(12) , DMEXCM(12)
      COMMON /CONTR2/ NYR ,NP , TMONTH(12)
      COMMON /CADIP/ MA1B , MA1E , MA2B , MA2E , MADIP1 , MADIP2
C*******************************************************************
      LOGICAL ADIP1 , ADIP2
      DATA ADIP1/.FALSE./ , ADIP2/.TRUE./
C*******************************************************************
C     ASSUMING THAT THE FIRST MONTH OF RUN IS IN ADIP2.
      DO 10 J=1,NP
        DEPUM(J) = CDEPU(J)*DEPU
        DEPLM(J) = CDEPL(J)*DEPL
        SNDEPM(J) = CSNDEP(J)*SNDEP
        DMEXCM(J) = CMEXCO(J)*DMEXCO
        DEMAND(J) = DEPUM(J) + DEPLM(J) + SNDEPM(J) + DMEXCM(J)
 10   CONTINUE
      DO 20 J=1,NP
        NADIP1(J) = 0
        NADIP2(J) = 0
        PADIP1(J) = 0.0
        PADIP2(J) = 0.0
 20   CONTINUE
      KADIP1 = 0
      KADIP2 = 0
C     IDENTIFICATION OF ADIP END
      DO 30 I=1,NYR
        DO 40 J=1,NP
C     TO AVOID THE PROBLEM OF INFLOW EXCEEDS THE DEMAND FOR
C     ONLY SHORT TIME (FOR EXAMPLE ONE MONTH), THE PROGRAM
C     IS CONSTRAINED NOT TO CHOOSE THE MONTH WHICH THE INFLOW
C     FIRST EXCEEDS THE DEMAND AND THEN DROPS BELOW THE DEMAND
C     ON THE FOLLOWING MONTH AS THE BEGINNING MONTH OF ADIP
          FLOW(I,J) = QIM(I,J) + QIP(I,J)
          IF ( ADIP2 ) GO TO 1
C         IDENTIFY THE END OF ADIP I
          IF ( FLOW(I,J) .GE. DEMAND(J) ) GO  TO 40
          NADIP1(J) = NADIP1(J) + 1
          ADIP1 = .FALSE.
          ADIP2 = .TRUE.
 1        IF ( ADIP1 ) GO TO 40
C         IDENTIFY THE END OF ADIP II END
          IF ( FLOW(I,J) .LT. DEMAND(J) ) GO TO 40
          NADIP2(J) = NADIP2(J) + 1
          ADIP1 = .TRUE.
          ADIP2 = .FALSE.
 40     CONTINUE
 30   CONTINUE
      YRS = FLOAT(NYR)
      DO 50 J=1,NP
        PADIP1(J) = FLOAT(NADIP1(J))*100.0/YRS
        PADIP2(J) = FLOAT(NADIP2(J))*100.0/YRS
 50   CONTINUE
      FADIP1 = PADIP1(1)
      FADIP2 = PADIP2(1)
      MADIP1 = 1
      MADIP2 = 1
      DO 60 J=2,NP
        FADIP1 = AMAX1(PADIP1(J),FADIP1)
        IF ( FADIP1 .EQ. PADIP1(J) ) MADIP1 = J
        FADIP2 = AMAX1(PADIP2(J),FADIP2)
        IF ( FADIP2 .EQ. PADIP2(J) ) MADIP2 = J
 60   CONTINUE
C*******************************************************************
C
C     MA1B = THE BEIGNNING MONTH OF ADIP TYPE I
C     MA1E = THE LAST MONTH OF ADIP TYPE I
C     MA2B = THE BEGINNING MONTH OF ADIP TYPE II
C     MA2E = THE LAST MONTH OF ADIP TYPE II
C
C*******************************************************************
      MA1B = MADIP2
      MA1E = MADIP1-1
      MA2B = MADIP1
      MA2E = MADIP2-1
      IF (MA1E .EQ. 0) MA1E = 12
      IF (MA2E .EQ. 0) MA2E = 12
      WRITE(6,106) TMONTH(MA1B),TMONTH(MA1E),TMONTH(MA2B),TMONTH(MA2E)
 106  FORMAT(1H1//,5X,27HTHE BEGINNING OF ADIP 1 IS ,A4/
     *             5X,27HTHE END OF ADIP 1       IS ,A4/
     *             5X,27HTHE BEGINNING OF ADIP 2 IS ,A4/
     *             5X,27HTHE END OF ADIP 2       IS ,A4//
     *             5X,41HTHE DISTRIBUTION OF ADIP-START IN PERCENT/
     *             5X,5HMONTH,5X,5HADIP1,10X,5HADIP2)
      DO 70 J=1,NP
        WRITE(6,116) TMONTH(J),PADIP2(J),NADIP2(J),PADIP1(J),NADIP1(J)
 116    FORMAT(5X,A4,2(2X,F7.3,1H(,I4,1H)))
 70   CONTINUE
      RETURN
      END
C*******************************************************************
      SUBROUTINE SIMULAT
C*******************************************************************
      DIMENSION  VPSPLL(500) , VPDEF(500)
      REAL LOSSM , LOSSP
      COMMON /DEFLOW/ QIM(500,12) , QIP(500,12) , CDEPU(12) ,CDEPL(12),
     *        CSNDEP(12) , CMEXCO(12) , CRP(12) , DEPU , DEPL , SNDEP ,
     *        DMEXCO , RPMIN , DEPUM(12) , DEPLM(12) , SNDEPM(12) ,
     *        DMEXCM(12)
      COMMON /CONTR1/ VMMAX1(12) , VMMIN1(12) , VPMAX1(12) , VPMIN1(12)
      COMMON /CONTR2/ NYR , NP , TMONTH(12)
      COMMON /CADIP/ MA1B , MA1E , MA2B , MA2E , MADIP1 , MADIP2
      COMMON /SIMIND/ M , JSP , JSM , JP , STORAGP(10) , STORAGM(10)
      COMMON /MASSB/ RM(12) , RP(12) , VMM , VMM1 , VPM , VPM1 ,IN , MP1
      COMMON /CONST1/ NINC , NINCS , NINCP
      COMMON /PROB/ STOR1(500) , STOR2(500)
     *             , STRMX1 , STRMX2 , STRMN1 , STRMN2
      COMMON /PROBM/ CCONDM1(10,10,20) , CCONDM2(10,10,20) ,
     *               LOSSM(10,10,20) , DEFM(10,10,20)
      COMMON /PROBP/ CCONDP1(10,20) , CCONDP2(10,20) ,
     *               LOSSP(10,20) , DEFP(10,20)
      COMMON /XPROB/ PERLOS(5) , PERDEF(5)
      COMMON /OUT/ IOUT7 , IOUT8 , IOUT9 , IOUT10
      COMMON /LOGVAR/ CYCI , CYCII
      LOGICAL CYCI , CYCII
      DATA PLOSS/0.05/ , PDEF/0.05/
      DATA RMEAD/6HMEAD  / , RPOW/6HPOWELL/
      DATA STORAGP/ 5574. ,  8000. , 10000. , 18000. , 20000. ,
     *              22000. , 24000. , 25902. , 2*0. /
      DATA STORAGM/10024. , 12000. , 14000. , 22000. , 24000. ,
     *              26000. , 28000. , 29054. , 2*0. /
```

```
      DO 10 J=1,NP
        RM(J)=DEPLM(J)+DMEXCM(J)
        RP(J)=CRP(J)*RPMIN
 10   CONTINUE
      NINCS1=NINCS-1
      FNINCS1= FLOAT(NINCS1)
C     IF YOU WANT ANALYSIS FOR CYCLE II ONLY THEN GO TO 500
      IF (.NOT.CYCI) GO TO 500
C     START ADIP 1 ANALYSIS-FILLING CYCLE-START ANALYSIS WITH
C     PROBABILITY VECTOR OF STORAGE FROM MONTH IN WHICH FILLING
C     CYCLE STARTED (MA1B)
      WRITE(IOUT7,106) RPOW
      WRITE(IOUT8,116) RPOW
      WRITE(IOUT9,106) RMEAD
      WRITE(IOUT10,116) RMEAD
 106  FORMAT(1H1//10X,21HBEGIN ADIP I ANALYSIS//
     *       5X,34HTHE SPILL CHARACTERISTICS OF LAKE ,A6//)
 116  FORMAT(1H1//10X,21HBEGIN ADIP I ANALYSIS//
     *       5X,36HTHE DEFICIT CHARACTERISTICS OF LAKE ,A6//)
      M=MA1B-1
 510  M=M+1
      IF(M.GT.12) M=M-12
C     BEGIN THE ANALYSIS FOR SPECIFIED INITIAL STORAGES FROM
C     MINIMUM TO MAXIMUM AND FOR ALL MONTHS STARTING FROM WHICH THE
C     FIRST MONTH OF ADIP I CYCLE (MA1B) THROUGH THE ENDING MONTH
C     OF ADIP I CYCLE(MA1E) AND ALL ENDING WITH THE LAST MONTH OF
C     ADIP II CYCLE (MA2E)
      MN1=M-1
      IF(MN1.EQ.0) MN1=12
      DO 520 ISP=1,NINCS
        JSP=ISP
        STRMX1=0.0
        STRMX2=0.0
        STRMN1=1.0E+15
        STRMN2=1.0E+15
        DO 530 N=1,NYR
         IN=N
          VPM=STORAGP(ISP)
          MP1=M
 540      CALL POWST
          VPM=VPM1
          IF(MP1.EQ.MA1E) GO TO 11
          IF(MP1.EQ.MA2E) GO TO 21
          GO TO 31
 11       STOR1(N)=VPM
          STRMX1=AMAX1(STOR1(N),STRMX1)
          STRMN1=AMIN1(STOR1(N),STRMN1)
          IF(VPM.LE.VPMAX1(MA1E)) GO TO 41
          VPSPLL(N)=VPM-VPMAX1(MA1E)
          VPM=VPMAX1(MA1E)
          GO TO 31
 41       VPSPLL(N)=0.0
          GO TO 31
 21       STOR2(N)=VPM
          STRMX2=AMAX1(STOR2(N),STRMX2)
          STRMN2=AMIN1(STOR2(N),STRMN2)
          IF(VPM.GE.VPMIN1(MA2E)) GO TO 51
          VPDEF(N)=VPMIN1(MA2E)-VPM
          GO TO 31
 51       VPDEF(N)=0.0
```

```
 31         MP1=MP1+1
            IF(MP1.GT.12) MP1=MP1-12
            IF(MP1.NE.MADIP2) GO TO 540
 530      CONTINUE
          CALL CPROBP
          DO 550 ISM=1,NINCS
            IF(ISP.LE.3.AND.ISM.GT.3) GO TO 550
            IF(ISP.GT.3.AND.ISM.LT.4) GO TO 550
            JSM=ISM
            STRMX1=0.0
            STRMX2=0.0
            STRMN1=1.0E+15
            STRMN2=1.0E+15
      IF(.NOT.CYCII) RETURN
      WRITE(IOUT7,126) RPOW
      WRITE(IOUT8,136) RPOW
      WRITE(IOUT9,126) RMEAD
      WRITE(IOUT10,136) RMEAD
 126  FORMAT(1H1//10X,22HBEGIN ADIP II ANALYSIS//
     *       5X,34HTHE SPILL CHARACTERISTICS OF LAKE ,A6//)
 136  FORMAT(1H1//10X,22HBEGIN ADIP II ANALYSIS//
     *       5X,36HTHE DEFICIT CHARACTERISTICS OF LAKE ,A6//)
C     START ADIP II ANALYSIS-DRAWDOWN CYCLE-START ANALYSIS WITH
C     PROBABAILITY VECTOR OF STORAGE FROM MONTH IN WHICH THE DRAWDOWN
C     CYCLE STARTED
      M=MA2B-1
 610  M=M+1
      IF(M.GT.12) M=M-12
C     BEGIN THE ANALYSIS FOR INITIAL SOTRAGES FROM
C     MINIMUM TO MAXIMUM AND FOR ALL MONTHS STARTING WITH THE FIRST
C     MONTH OF ADIP II CYCLE TO THE ENDING MONTH OF ADIP II CYCLE AND
C     ALL ENDING WITH THE LAST MONTH OF THE ADIP II CYCLE
      MN1=M-1
      IF(MN1.EQ.0) MN1=12
      DO 620 ISP=1,NINCS
        JSP=ISP
        STRMX1=0.0
        STRMX2=0.0
        STRMN1=1.0E+15
        STRMN2=1.0E+15
        DO 630 N=1,NYR
          IN=N
          VPM=STORAGP(ISP)
          MP1=M
 640      CALL POWST
          VPM=VPM1
          IF(MP1.EQ.MA1E) GO TO 111
          IF(MP1.EQ.MA2E) GO TO 121
          GO TO 131
 111      STOR1(N)=VPM
          STRMX1=AMAX1(STOR1(N),STRMX1)
          STRMN1=AMIN1(STOR1(N),STRMN1)
          IF(VPM.LE.VPMAX1(MA1E)) GO TO 141
          VPSPLL(N)=VPM-VPMAX1(MA1E)
          GO TO 131
 141      VPSPLL(N)=0.0
          GO TO 131
 121      STOR2(N)=VPM
          STRMX2=AMAX1(STOR2(N),STRMX2)
          STRMN2=AMIN1(STOR2(N),STRMN2)
```

```
          IF(VPM.GE.VPMIN1(MA2E)) GO TO 151
          VPDEF(N)=VPMIN1(MA2E)-VPM
          VPM=VPMIN1(MA2E)
          GO TO 131
  151     VPDEF(N)=0.0
  131     MP1=MP1+1
          IF(MP1.GT.12) MP1=MP1-12
          IF(MP1.NE.MADIP1) GO TO 640
  630   CONTINUE
        CALL CPROBP
        DO 650 ISM=1,NINCS
          IF(ISP.LE.3.AND.ISM.GT.3) GO TO 650
          IF(ISP.GT.3.AND.ISM.LT.4) GO TO 650
          JSM=ISM
          STRMX1=0.0
          STRMX2=0.0
          STRMN1=1.0E+15
          STRMN2=1.0E+15
          DO 660 N=1,NYR
            IN=N
            VMM=STORAGM(ISM)
            MP1=M
  670       CALL MEADST
            VMM=VMM1
            IF(MP1.EQ.MA1E) GO TO 161
            IF(MP1.EQ.MA2E) GO TO 171
            GO TO 181
  161       VMM=VMM+VPSPLL(N)
            STOR1(N)=VMM
            STRMX1=AMAX1(STOR1(N),STRMX1)
            STRMN1=AMIN1(STOR1(N),STRMN1)
            GO TO 181
  171       VMM=VMM-VPDEF(N)
            STOR2(N)=VMM
            STRMX2=AMAX1(STOR2(N),STRMX2)
            STRMN2=AMIN1(STOR2(N),STRMN2)
            IF(VMM.LT.VMMIN1(MA2E)) VMM=VMMIN1(MA2E)
  181       MP1=MP1+1
            IF(MP1.GT.12) MP1=MP1-12
            IF(MP1.NE.MADIP1) GO TO 670
  660     CONTINUE
          CALL CPROBM
  650   CONTINUE
  620 CONTINUE
C     DETERMINE THE POWELL EXCEEDANCE PROBABILITIES OF SPILL
C     AND DEFICIT AS A FUNCTION OF POWELL INITIAL STORAGE
C     AND INITIAL MONTH, AND THE MEAD EXCEEDANCE PROBABILITIES
C     OF SPILL AND DEFICIT AS A FUNCTION OF POWELL-MEAD
C     INITIAL STORAGE AND INITIAL MONTH WHEN THE INITIAL MONTH
C     IS IN ADIP II
      STINC1=20000.0
      WRITE(IOUT7,156) TMONTH(M),(STORAGP(IS),IS=1,NINCS)
      WRITE(IOUT8,166) TMONTH(M),(STORAGP(IS),IS=1,NINCS)
      WRITE(IOUT9,176) TMONTH(M),(STORAGM(IS),IS=1,NINCS)
      WRITE(IOUT10,186) TMONTH(M),(STORAGM(IS),IS=1,NINCS)
      DO 50 IP=1,NINCP
        JP=IP
        PI=FLOAT(IP-1)
        PERLOS(IP)=PLOSS*PI*STINC1
        PERDEF(IP)=PDEF*PI*STINC1
C     DETERMINE POWELL EXCEEDANCE PROBABILITY
        CALL XPROBP
C     DETERMINE MEAD EXCEEDANCE PROBABILITY
        CALL XPROBM
   50 CONTINUE
      IF(M.NE.MA2E) GO TO 610
      RETURN
      END
C*****************************************************************
      SUBROUTINE POWST
C*****************************************************************
C     THIS SUBROUTINE IS TO DETERMINE THE END OF MONTH TARGET STORAGE
C     FOR LAKE POWELL BY ITERATIVE PROCEDURE SINCE THE EVAPORATION
C     IS ASSUMED TO BE A FUNCTION OF THE AVERAGE STORAGE VOLUME WHICH
C     IS KNOWN. IT IS PROGRAMMED TO END THE ITERATION IF THE
C     DIFFERENCE BETWEEN TWO SUCCESSIVE STORAGE VALUES IS LESS THAN
C     THE PRESPECIFIED LEVEL, TOL1.
C     VPM/VPM1= THE END OF MONTH (J-1)/J POWELL STORAGE VOLUME
C     VUBM/VUBM1= THE END OF MONTH (J-1)/J UPPER BASIN STORAGE VOLUME
C                 WHICH IS A FUNCTION OF VPM/VPM1
C     AREAP= THE AVERAGE WATER SURFACE AREA OF POWELL DURING MONTH J
C            AS A FUNCTION OF THE AVERAGE POWELL STORAGE VOLUME
C     EPM= THE EVAPORATION FROM POWELL DURING MONTH J
C*******************************************************************
      DIMENSION CAP(2) , ERATEP(12) , COEF(4)
      COMMON /DEFLOW/ QIM(500,12) , QIP(500,12) ,
     *       CDEPU(12) , CDEPL(12) , CSNDEP(12) , CMEXCO(12) , CRP(12) ,
     *       DEPU , DEPL , SNDEP , DMEXCO , RPMIN , DEPUM(12) ,
     *       DEPLM(12) , SNDEPM(12) , DMEXCM(12)
      COMMON /MASSB/ RM(12) , RP(12) , VMM , VMM1 , VPM , VPM1 ,IN ,
     *       MP1
      COMMON /CONST2/ VMMAX , VMMIN , VPMAX , VPMIN
      DATA COEF/-3358.1 , 2.1822 , -0.74251E-04 , 0.17009E-08/
      DATA BNKSTP/0.08/
      DATA TOL1/100.0/ , CAP/0.33 , 0.63/
      DATA ERATEP/ 0.375 , 0.312 , 0.261 , 0.198 , 0.186 ,
     *             0.233 , 0.265 , 0.359 , 0.411 , 0.466 ,
     *             0.478 , 0.415 /
      VPM1=VPM
      VUBM=COEF(1)+COEF(2)*VPM+COEF(3)*(VPM**2.0)+COEF(4)*(VPM**3.0)
      IF(VUBM.LT.VPM) VUBM=VPM
      IF(VUBM.GT.32228.0) VUBM=32228.0
    1 VUBM1=COEF(1)+COEF(2)*VPM1+COEF(3)*(VPM1**2.0)+COEF(4)*(VPM1**3.0)
      IF(VUBM1.LT.VPM1) VUBM1=VPM1
      IF(VUBM1.GT.32228.0) VUBM1=32228.0
      AVGVP=(VPM+VPM1)*0.5
      IF (AVGVP.GT.VPMAX) AVGVP=VPMAX
      IF (AVGVP.LT.VPMIN) AVGVP=VPMIN
      AREAP=CAP(1)*(AVGVP**CAP(2))
      EPM=AREAP*ERATEP(MP1)
      ADJUST=((VUBM-VPM)-(VUBM1-VPM1))
      BNK=BNKSTP*(VPM-VPM1)
      IF(VPM.GT.VPMAX.AND.VPM1.GT.VPMAX) BNK=0.0
      IF (VUBM1.GE.32228.0 .OR. VUBM.GE.32228.0) ADJUST=0.0
      VPML=VPM1
      VPM1=VPM+QIP(IN,MP1)+ADJUST+BNK
     *     -RP(MP1)-EPM-DEPUM(MP1)
      DELTA=ABS(VPML-VPM1)
      IF (DELTA.GT.TOL1) GO TO 1
      RETURN
```

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      END
C*******************************************************************
      SUBROUTINE MEADST
C*******************************************************************
C     THIS SUBROUTINE IS TO DETERMINE THE END OF MONTH TARGET STORAGE FOR
C     LAKE MEAD BY ITERATION PROCEDURE SINCE THE EVAPORATION IS ASSUMED
C     TO BE A FUNCTION OF AVERAGE STORAGE VOLUME WHICH IS UNKNOWN. IT IS
C     PROGRAMMED TO END THE ITERATION IF THE DIFFERENCE BETWEEN TWO
C     SUCCCESSIVE STORAGE VALUES IS LESS THA THE PRESPECIFIED TOLERANCE
C     LEVEL, TOL2.
C*******************************************************************
      DIMENSION CAM(2),ERATEM(12)
      COMMON /DEFLOW/ QIM(500,12) , QIP(500,12) ,
     *        CDEPU(12) , CDEPL(12) , CSNDEP(12) , CMEXCO(12) , CRP(12) ,
     *        DEPU , DEPL , SNDEP , DMEXCO , RPMIN , DEPUM(12) ,
     *        DEPLM(12) , SNDEPM(12) , DMEXCM(12)
      COMMON /MASSB/ RM(12) , RP(12) , VMM , VMM1 , VPM , VPM1 ,IN ,
     *               MP1
      COMMON /CONST2/ VMMAX , VMMIN , VPMAX , VPMIN
      DATA TOL2/100.0/ , CAM/0.39 , 0.59/
      DATA BNKSTM/0.065/
      DATA ERATEM/0.51 , 0.51 , 0.44 , 0.36 , 0.33 , 0.37 ,
     *             0.46 , 0.53 , 0.64 , 0.80 , 0.85 , 0.70 /
      VMM1=VMM
 1    AVGVM=(VMM+VMM1)*0.5
      IF (AVGVM.GT.VMMAX) AVGVM=VMMAX
      IF (AVGVM.LT.VMMIN) AVGVM=VMMIN
      AREAM=CAM(1)*(AVGVM**CAM(2))
      EMM=AREAM*ERATEM(MP1)
      VMML=VMM1
      BNK=BNKSTM*(VMM-VMM1)
      IF(VMM.GT.VMMAX.AND.VMM1.GT.VMMAX) BNK=0.0
      VMM1=VMM+RP(MP1)+BNK+QIM(IN,MP1)
     *     -RM(MP1)-SNDEPM(MP1)-EMM
      DELTA=ABS(VMM1-VMML)
      IF(DELTA.GT.TOL2) GO TO 1
      RETURN
      END
C*****************************************************************
      SUBROUTINE CPROBP
C*****************************************************************
      DIMENSION STRM1(21), STRM2(21), STM1(20), STM2(20), NST1(20),
     *          NST2(20) , CONDV1(20) , CONDV2(20)
      REAL LOSSP
      COMMON /CONTR1/ VMMAX1(12),VMMIN1(12),VPMAX1(12),VPMIN1(12)
      COMMON /CONTR2/ NYR , NP , TMONTH(12)
      COMMON /CADIP/ MA1B , MA1E , MA2B , MA2E , MADIP1 , MADIP2
      COMMON /SIMIND/ M , JSP , JSM , JP , STORAGP(10) , STORAGM(10)
      COMMON /CONST1/ NINC , NINCS , NINCP
      COMMON /PROB/ STOR1(500) , STOR2(500)
     *             , STRMX1 , STRMX2 , STRMN1 , STRMN2
      COMMON /PROBP/ CCONDP1(10,20) , CCONDP2(10,20) ,
     *               LOSSP(10,20) , DEFP(10,20)
      COMMON /OUT/ IOUT7 , IOUT8 , IOUT9 , IOUT10
      LOGICAL FIRSTL , FIRSTD
      NINCM1=NINC-1
      NINCP1=NINC+1
      FNINCM1=FLOAT(NINCM1)
      FNYR=FLOAT(NYR)
C     DETERMINE THEE PROBABILITY OF BEING IN DISCRETE STORAGE LEEVELS AT
C     THE END OF EACH ADIP CYCLE
      DSTR1=(STRMX1-STRMN1)/FNINCM1
      DSTR2=(STRMX2-STRMN2)/FNINCM1
      DS1=0.5*DSTR1
      DS2=0.5*DSTR2
      STRM1(1)=STRMN1-DS1
      STRM2(1)=STRMN2-DS2
      DO 10 L=2,NINCP1
        LM1=L-1
        STRM1(L)=STRM1(LM1)+DSTR1
        STRM2(L)=STRM2(LM1)+DSTR2
 10   CONTINUE
      DO 20 L=1,NINC
        LP1=L+1
        STM1(L)=STRM1(LP1)-DS1
        STM2(L)=STRM2(LP1)-DS2
        NST1(L)=0
        NST2(L)=0
 20   CONTINUE
      DO 30 N=1,NYR
        L1=0
 1      L1=L1+1
        IF(STOR1(N).GT.STRM1(L1)) GO TO 1
        NST1(L1-1)=NST1(L1-1)+1
        L2=0
 2      L2=L2+1
        IF(STOR2(N).GT.STRM2(L2)) GO TO 2
        NST2(L2-1)=NST2(L2-1)+1
 30   CONTINUE
      DO 40 L=1,NINC
        CONDV1(L)=FLOAT(NST1(L))/FNYR
        CONDV2(L)=FLOAT(NST2(L))/FNYR
        CCONDP1(JSP,L)=1.0
        LOSSP(JSP,L)= 0.0
        CCONDP2(JSP,L)=1.0
        DEFP(JSP,L)=0.0
 40   CONTINUE
C     DETERMINE THE EXCEEDANCE PROBABILITY OF SPILL (CCONDP1) AND THE
C     CORRESPONDING SPILL VOLUMES (LOSSP) AT THE END OF ADIP I
      LF=0
      CUML=0.0
      FIRSTL=.TRUE.
      DO 50 L=1,NINC
        IF(STRM1(L+1).LT.VPMAX1(MA1E)) GO TO 3
        IF(FIRSTL) GO TO 4
        LF=LF+1
        IF(LF.GT.NINC) GO TO 50
        CCONDP1(JSP,LF)=CONDV1(L)+CCONDP1(JSP,LF-1)
        GO TO 50
 4      LF=1
        VALINT=CONDV1(L)-CONDV1(L)*((VPMAX1(MA1E)-STRM1(L))/
     *           (STRM1(L+1)-STRM1(L)))
        IF (STRM1(1).GT.VPMAX1(MA1E)) VALINT=CONDV1(1)
        CCONDP1(JSP,LF)=CUML+(CONDV1(L)-VALINT)
        LOSSP(JSP,LF+1)=STRM1(L+1)-VPMAX1(MA1E)
        LF=LF+1
        CCONDP1(JSP,LF)=CCONDP1(JSP,LF-1) + VALINT
        FIRSTL=.FALSE.
        GO TO 50
 3      IF(L.EQ.1) GO TO 5
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         CUML=CUML+CONDV1(L)
         IF(L.EQ.NINC) LOSSP(JSP,2)=VPMAX1(MA1E)-STRM1(NINCP1)
         GO TO 50
 5       CUML=CONDV1(L)
 50    CONTINUE
       LOSSP(JSP,1)=0.0
       DO 60 L=1,NINC
         CCONDP1(JSP,L)=1.0-CCONDP1(JSP,L)
         IF(L.GE.NINCM1) GO TO 60
         LOSSP(JSP,L+2) = DSTR1+LOSSP(JSP,L+1)
 60    CONTINUE
C      DETERMINE THE EXCEEDANCE PROBABILITY OF DEFICIT (CCONDP2) AND THE
C      CORRESPONDING DEFICIT VOLUMES (DEFP) AT THE END OF ADIP II
       LF=0
       CUMD=0.0
       FIRSTD=.TRUE.
       DO 70 L=1,NINC
         LB=NINC-L+1
         IF(STRM2(LB).GT.VPMIN1(MA2E)) GO TO 7
         IF(FIRSTD) GO TO 8
         LF=LF+1
         IF(LF.GT.NINC) GO TO 70
         CCONDP2(JSP,LF)=CONDV2(LB)+CCONDP2(JSP,LF-1)
         GO TO 70
 8       LF=1
         VALINT=CONDV2(LB)-CONDV2(LB)*((STRM2(LB+1)-VPMIN1(MA2E))/
      *        (STRM2(LB+1)-STRM2(LB)))
         IF (STRM2(NINCP1).LT.VPMIN1(MA2E)) VALINT=CONDV2(NINC)
         CCONDP2(JSP,LF)=CUMD+(CONDV2(LB)-VALINT)
         DEFP(JSP,LF+1)=VPMIN1(MA2E)-STRM2(LB)
         LF=LF+1
         CCONDP2(JSP,LF)=CCONDP2(JSP,LF-1) + VALINT
         FIRSTD=.FALSE.
         GO TO 70
 7       IF(LB.EQ.NINC) GO TO 9
         CUMD=CUMD+CONDV2(LB)
         IF(LB.EQ.1) DEFP(JSP,2)=STRM2(1)-VPMIN1(MA2E)
         GO TO 70
 9       CUMD=CONDV2(LB)
 70    CONTINUE
       DEFP(JSP,1)=0.0
       DO 80 L=1,NINC
         CCONDP2(JSP,L)=1.0-CCONDP2(JSP,L)
         IF(L.GE.NINCM1) GO TO 80
         DEFP(JSP,L+2) = DSTR2+DEFP(JSP,L+1)
 80    CONTINUE
       WRITE(IOUT7,106) TMONTH(M),STORAGP(JSP)
       WRITE(IOUT8,106) TMONTH(M),STORAGP(JSP)
 106   FORMAT(/5X,17HINITIAL MONTH IS ,A4,3X,9HP.STORAGE,F7.0/)
       WRITE(IOUT7,116) (CONDV1(L),L=1,NINC)
       WRITE(IOUT7,126) (STM1(L),L=1,NINC)
       WRITE(IOUT7,116) (CCONDP1(JSP,L),L=1,NINC)
       WRITE(IOUT7,126) (LOSSP(JSP,L),L=1,NINC)
 116   FORMAT(5X,12F7.3)
 126   FORMAT(5X,12F7.0)
       WRITE(IOUT8,116) (CONDV2(L),L=1,NINC)
       WRITE(IOUT8,126) (STM2(L),L=1,NINC)
       WRITE(IOUT8,116) (CCONDP2(JSP,L),L=1,NINC)
       WRITE(IOUT8,126) (DEFP(JSP,L),L=1,NINC)
       RETURN
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       END
       SUBROUTINE CPROBM
C*****************************************************************
       DIMENSION STRM1(21) , STRM2(21) , STM1(20) , STM2(20) , NST1(20) ,
      *          NST2(20) , CONDV1(20) , CONDV2(20)
       REAL LOSSM
       COMMON /CONTR1/ VMMAX1(12),VMMIN1(12),VPMAX1(12),VPMIN1(12)
       COMMON /CONTR2/ NYR , NP , TMONTH(12)
       COMMON /CADIP/ MA1B , MA1E , MA2B , MA2E , MADIP1 , MADIP2
       COMMON /SIMIND/ M , JSP , JSM , JP , STORAGP(10) , STORAGM(10)
       COMMON /CONST1/ NINC , NINCS , NINCP
       COMMON /PROB/ STOR1(500) , STOR2(500)
      *             , STRMX1 , STRMX2 , STRMN1 , STRMN2
       COMMON /PROBM/ CCONDM1(10,10,20) , CCONDM2(10,10,20) ,
      *               LOSSM(10,10,20) , DEFM(10,10,20)
       COMMON /OUT/ IOUT7 , IOUT8 , IOUT9 , IOUT10
       LOGICAL FIRSTL , FIRSTD
       NINCM1=NINC-1
       NINCP1=NINC+1
       FNINCM1=FLOAT(NINCM1)
       FNYR=FLOAT(NYR)
C      DETERMINE THEE PROBABILITY OF BEING IN DISCRETE STORAGE LEVELS AT
C      THE END OF EACH ADIP CYCLE
       DSTR1=(STRMX1-STRMN1)/FNINCM1
       DSTR2=(STRMX2-STRMN2)/FNINCM1
       DS1=0.5*DSTR1
       DS2=0.5*DSTR2
       STRM1(1)=STRMN1-DS1
       STRM2(1)=STRMN2-DS2
       DO 10 L=2,NINCP1
         LM1=L-1
         STRM1(L)=STRM1(LM1)+DSTR1
         STRM2(L)=STRM2(LM1)+DSTR2
 10    CONTINUE
       DO 20 L=1,NINC
         LP1=L+1
         STM1(L)=STRM1(LP1)-DS1
         STM2(L)=STRM2(LP1)-DS2
         NST1(L)=0
         NST2(L)=0
 20    CONTINUE
       DO 30 N=1,NYR
         L1=0
 1       L1=L1+1
         IF(STOR1(N).GT.STRM1(L1)) GO TO 1
         NST1(L1-1)=NST1(L1-1)+1
         L2=0
 2       L2=L2+1
         IF(STOR2(N).GT.STRM2(L2)) GO TO 2
         NST2(L2-1)=NST2(L2-1)+1
 30    CONTINUE
       DO 40 L=1,NINC
         CONDV1(L)=FLOAT(NST1(L))/FNYR
         CONDV2(L)=FLOAT(NST2(L))/FNYR
         CCONDM1(JSP,JSM,L)=1.0
         LOSSM(JSP,JSM,L)= 0.0
         CCONDM2(JSP,JSM,L)=1.0
         DEFM(JSP,JSM,L)=0.0
 40    CONTINUE
C      DETERMINE THE EXCEEDANCE PROBABILITY OF SPILL (CCONDM1) AND THE
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C       CORRESPONDING SPILL VOLUMES (LOSSM) AT THE END OF ADIP I
        LF=0
        CUML=0.0
        FIRSTL=.TRUE.
        DO 50 L=1,NINC
          IF(STRM1(L+1).LT.VMMAX1(MA1E)) GO TO 3
          IF(FIRSTL) GO TO 4
          LF=LF+1
          IF(LF.GT.NINC) GO TO 50
          CCONDM1(JSP,JSM,LF)=CONDV1(L)+CCONDM1(JSP,JSM,LF-1)
          GO TO 50
 4        LF=1
          VALINT=CONDV1(L)-CONDV1(L)*((VMMAX1(MA1E)-STRM1(L))/
     *           (STRM1(L+1)-STRM1(L)))
          IF (STRM1(1).GT.VMMAX1(MA1E)) VALINT=CONDV1(1)
          CCONDM1(JSP,JSM,LF)=CUML+(CONDV1(L)-VALINT)
          LOSSM(JSP,JSM,LF+1)=STRM1(L+1)-VMMAX1(MA1E)
          LF=LF+1
          CCONDM1(JSP,JSM,LF)=CCONDM1(JSP,JSM,LF-1) + VALINT
          FIRSTL=.FALSE.
          GO TO 50
 3        IF(L.EQ.1) GO TO 5
          CUML=CUML+CONDV1(L)
          IF(L.EQ.NINC) LOSSM(JSP,JSM,2)=VMMAX1(MA1E)-STRM1(NINCP1)
          GO TO 50
 5        CUML=CONDV1(L)
 50     CONTINUE
        LOSSM(JSP,JSM,1)=0.0
        DO 60 L=1,NINC
          CCONDM1(JSP,JSM,L)=1.0-CCONDM1(JSP,JSM,L)
          IF(L.GE.NINCM1) GO TO 60
          LOSSM(JSP,JSM,L+2) = DSTR1+LOSSM(JSP,JSM,L+1)
 60     CONTINUE
C       DETERMINE THE EXCEEDANCE PROBABILITY OF DEFICIT (CCONDM2) AND THE
C       CORRESPONDING DEFICIT VOLUMES (DEFM) AT THE END OF ADIP II
        LF=0
        CUMD=0.0
        FIRSTD=.TRUE.
        DO 70 L=1,NINC
          LB=NINC-L+1
          IF(STRM2(LB).GT.VMMIN1(MA2E)) GO TO 7
          IF(FIRSTD) GO TO 8
          LF=LF+1
          IF(LF.GT.NINC) GO TO 70
          CCONDM2(JSP,JSM,LF)=CONDV2(LB)+CCONDM2(JSP,JSM,LF-1)
          GO TO 70
 8        LF=1
          VALINT=CONDV2(LB)-CONDV2(LB)*((STRM2(LB+1)-VMMIN1(MA2E))/
     *           (STRM2(LB+1)-STRM2(LB)))
          IF (STRM2(NINCP1).LT.VMMIN1(MA2E)) VALINT=CONDV2(NINC)
          CCONDM2(JSP,JSM,LF)=CUMD+(CONDV2(LB)-VALINT)
          DEFM(JSP,JSM,LF+1)=VMMIN1(MA2E)-STRM2(LB)
          LF=LF+1
          CCONDM2(JSP,JSM,LF)=CCONDM2(JSP,JSM,LF-1) + VALINT
          FIRSTD=.FALSE.
          GO TO 70
 7        IF(LB.EQ.NINC) GO TO 9
          CUMD=CUMD+CONDV2(LB)
          IF(LB.EQ.1) DEFM(JSP,JSM,2)=STRM2(1)-VMMIN1(MA2E)
          GO TO 70
 9        CUMD=CONDV2(LB)
 70     CONTINUE
        DEFM(JSP,JSM,1)=0.0
        DO 80 L=1,NINC
          CCONDM2(JSP,JSM,L)=1.0-CCONDM2(JSP,JSM,L)
          IF(L.GE.NINCM1) GO TO 80
          DEFM(JSP,JSM,L+2) = DSTR2+DEFM(JSP,JSM,L+1)
 80     CONTINUE
        WRITE(IOUT9,106) TMONTH(M),STORAGP(JSP),STORAGM(JSM)
        WRITE(IOUT10,106) TMONTH(M),STORAGP(JSP),STORAGM(JSM)
 106    FORMAT(/5X,17HINITIAL MONTH IS ,A4,3X,9HP.STORAGE,F7.0,
     *         3X,9HM.STORAGE,F7.0/)
        WRITE(IOUT9,116) (CONDV1(L),L=1,NINC)
        WRITE(IOUT9,126) (STM1(L),L=1,NINC)
        WRITE(IOUT9,116) (CCONDM1(JSP,JSM,L),L=1,NINC)
        WRITE(IOUT9,126) (LOSSM(JSP,JSM,L),L=1,NINC)
 116    FORMAT(5X,12F7.3)
 126    FORMAT(5X,12F7.0)
        WRITE(IOUT10,116) (CONDV2(L),L=1,NINC)
        WRITE(IOUT10,126) (STM2(L),L=1,NINC)
        WRITE(IOUT10,116) (CCONDM2(JSP,JSM,L),L=1,NINC)
        WRITE(IOUT10,126) (DEFM(JSP,JSM,L),L=1,NINC)
        RETURN
        END
C*************************************************************
        SUBROUTINE XPROBP
C*************************************************************
        DIMENSION PROBL(10) , PROBD(10)
        REAL LOSSP
        COMMON /CONST1/ NINC , NINCS , NINCP
        COMMON /SIMIND/ M , JSP , JSM , JP , STORAGP(10) , STORAGM(10)
        COMMON /PROBP/ CCONDP1(10,20) , CCONDP2(10,20) ,
     *                 LOSSP(10,20) , DEFP(10,20)
        COMMON /XPROB/ PERLOS(5) , PERDEF(5)
        COMMON /OUT/ IOUT7 , IOUT8 , IOUT9 , IOUT10
        IF(PERLOS(JP).NE.0.0.AND.PERDEF(JP).NE.0.0) GO TO 1
        DO 10 IP1=1,NINCS
          PROBL(IP1)=CCONDP1(IP1,1)
          PROBD(IP1)=CCONDP2(IP1,1)
 10     CONTINUE
        GO TO 21
 1      CONTINUE
        DO 20 IP1=1,NINCS
          PROBL(IP1)=0.0
          PROBD(IP1)=0.0
 20     CONTINUE
        DO 30 IP1=1,NINCS
          DO 40 L=1,NINC
            IF(LOSSP(IP1,L).LT.PERLOS(JP)) GO TO 40
            PROBL(IP1)=CCONDP1(IP1,L)-(LOSSP(IP1,L)-
     *        PERLOS(JP))*((CCONDP1(IP1,L)-CCONDP1(IP1,L-1))/
     *                    (LOSSP(IP1,L)-LOSSP(IP1,L-1)))
            GO TO 11
 40       CONTINUE
 11       CONTINUE
          DO 50 L=1,NINC
            IF(DEFP(IP1,L).LT.PERDEF(JP)) GO TO 50
            PROBD(IP1)=CCONDP2(IP1,L)-(DEFP(IP1,L)-
     *        PERDEF(JP))*((CCONDP2(IP1,L)-CCONDP2(IP1,L-1))/
     *                    (DEFP(IP1,L)-DEFP(IP1,L-1)))
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        GO TO 30
 50   CONTINUE
 30   CONTINUE
 21   CONTINUE
      WRITE(IOUT7,126) PERLOS(JP),(PROBL(IP1),IP1=1,NINCS)
      WRITE(IOUT8,126) PERDEF(JP),(PROBD(IP1),IP1=1,NINCS)
 126  FORMAT(9X,F6.0,11F8.3)
      RETURN
      END
C*****************************************************************
      SUBROUTINE XPROBM
C********************************************************************
      DIMENSION PROBL(10,10) , PROBD(10,10)
      REAL LOSSM
      COMMON /CONST1/ NINC , NINCS , NINCP
      COMMON /SIMIND/ M , JSP , JSM , JP , STORAGP(10) , STORAGM(10)
      COMMON /PROBM/ CCONDM1(10,10,20) , CCONDM2(10,10,20) ,
     *               LOSSM(10,10,20) , DEFM(10,10,20)
      COMMON /XPROB/ PERLOS(5) , PERDEF(5)
      COMMON /OUT/ IOUT7 , IOUT8 , IOUT9 , IOUT10
      WRITE(IOUT9,106) PERLOS(JP)
      WRITE(IOUT10,106) PERDEF(JP)
 106  FORMAT(9X,F6.0)
      IF(PERLOS(JP).NE.0.0.AND.PERDEF(JP).NE.0.0) GO TO 1
      DO 10 IP1=1,NINCS
        DO 20 IM1=1,NINCS
          PROBL(IP1,IM1)=CCONDM1(IP1,IM1,1)
          PROBD(IP1,IM1)=CCONDM2(IP1,IM1,1)
 20     CONTINUE
 10   CONTINUE
      GO TO 21
 1    CONTINUE
      DO 30 IP1=1,NINCS
        DO 40 IM1=1,NINCS
          PROBL(IP1,IM1)=0.0
          PROBD(IP1,IM1)=0.0
 40     CONTINUE
 30   CONTINUE
      DO 50 IP1=1,NINCS
        DO 60 IM1=1,NINCS
          DO 70 L=1,NINC
            IF(LOSSM(IP1,IM1,L).LT.PERLOS(JP)) GO TO 70
            PROBL(IP1,IM1)=CCONDM1(IP1,IM1,L)-(LOSSM(IP1,IM1,L)-
     *        PERLOS(JP))*((CCONDM1(IP1,IM1,L)-CCONDM1(IP1,IM1,L-1))/
     *                 (LOSSM(IP1,IM1,L)-LOSSM(IP1,IM1,L-1)))
            GO TO 11
 70       CONTINUE
 11       CONTINUE
          DO 80 L=1,NINC
            IF(DEFM(IP1,IM1,L).LT.PERDEF(JP)) GO TO 80
            PROBD(IP1,IM1)=CCONDM2(IP1,IM1,L)-(DEFM(IP1,IM1,L)-
     *        PERDEF(JP))*((CCONDM2(IP1,IM1,L)-CCONDM2(IP1,IM1,L-1))/
     *                 (DEFM(IP1,IM1,L)-DEFM(IP1,IM1,L-1)))
            GO TO 60
 80       CONTINUE
 60     CONTINUE
 50   CONTINUE
 21   CONTINUE
      DO 90 IP1=1,NINCS
          WRITE(IOUT9,126) STORAGP(IP1),(PROBL(IP1,IM1),IM1=1,NINCS)
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          WRITE(IOUT10,126) STORAGP(IP1),(PROBD(IP1,IM1),IM1=1,NINCS)
 90   CONTINUE
 126  FORMAT(15X,F8.0,11F8.3)
      RETURN
      END
```