U.S.- Italy Research Workshop on the
Hydrometeorology, Impacts, and Management of Extreme Floods
Perugia (Italy), November 1995

MANAGING RESERVOIRS FOR FLOOD CONTROL

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Abstract. The impact of streamflow forecasting on reservoir operations is a function of several factors, including the size of the system, the time scale of operation, the relative size of regulation capacity of the system, and the use of the water stored in the system. Flow forecasting techniques have been extensively developed in literature. However, the inclusion of these forecasts in stochastic optimization models have not obtained wide acceptance among engineers responsible for systems operations, in particular, real time flood control in multiple reservoir systems. The premise of this paper is that the reluctance of practitioners to embrace these methods in flood control does not result from theoretical inadequacy of the stochastic optimization models to represent complex multi-reservoir systems. Rather, the problem may stem from the lack of completeness of the optimization models: inadequate representation of all relevant objectives and constraints in the operation of a reservoir system, and inadequate mechanisms to incorporate risk within the decision-making process. Extensive research has been carried out to determine operating policies of a multi-reservoir system, but the area remains open for further research. One reason research in this field remains active is the number of simplifications that have to be made in order to make a complex system more tractable. An issue that very few papers have dealt with is the combination of both long and short term operation, in which the long term policies are used as boundary conditions for the short term optimization algorithm.

1. INTRODUCTION

Since the Harvard Water Program in the ‘60s, there has been considerable interest in the theory and application of optimization and forecasting techniques to water resources systems, in general, and to reservoir operations, in particular. Numerous optimization techniques have been proposed to address the problem of short- and long-term operation of single and multi-reservoir systems; each involving, to various degrees, sophisticated forecasting models. Comprehensive reviews of state of the art applications of optimization techniques for operation of multi-reservoir systems, particularly Dynamic Programming (DP) techniques, may be found in Yakowitz (1982) and Yeh (1982, 1985). A review of multi-reservoir systems operation in North America was made by Loucks and Sigvaldason (1982). Wurbs et al. (1985) present a detailed state-of-the art-review and references on simulation and optimization techniques applied to reservoir operations. Most of the developed reservoir management techniques fail to address the specificities of flood control. Flood control is commonly dealt with as a constraint to a main conservation objective. In the United States, the U.S. Army Corps of Engineers (USACE) is the largest reservoir management agency charged primarily with flood control and navigation. In a USACE report cited by Wurbs (1991), 516 reservoirs are under USACE administration, with a total controlled storage capacity of 220,615,000 acre-feet. Of this storage amount, 43% is designated solely for flood control (330 reservoirs). Of the remaining reservoirs, an additional 207 have flood control as one of their purposes (Wurbs, 1991). Other agencies charged with flood control are the U.S. Bureau of Reclamation (USBR) and the Tennessee Valley Authority (TVA).

2. RESERVOIR FLOOD CONTROL

A reservoir is a depository for the storage of water, up to a maximum level. This is defined as the maximum static full pool, which coincides with the level attained when water crests and spills over without a release device. This is the gate-top level for controlled reservoirs, and the spilling crest for uncontrolled reservoirs. Since spilling water implies passage through a critical hydraulic section, a dynamic storage volume can be filled up only during spills. Defined as the discharge pool, its upper boundary is the maximum design water surface. Normally, it is taken as the level at which water spills over the dam.

The operational pool is the volume between the minimum level at which controlled releases can be made and the maximum static full pool. It is the water volume under control. For multi-purpose dams, the operational pool is conceptually divided into conservation and flood control pools. This conceptual division stems from the way a reservoir must act to fulfill its objective. The maximum possible empty space is desirable for flood control, while water storage is required for the remaining objectives of water supply, irrigation, hydropower, etc. The upper level of the conservation pool may or may not coincide with the spillway crest. The water level can only exceed this level during and shortly after a flood event. Since flood risk differs according to the season, the flood control pool typically varies according to the time of the year.

For countries where dam property and objectives are clearly defined, the flood control pool is contractually established and the conservation managers are constrained from exceeding that level (USACE, 1991). If a single agency is responsible for flood control and all remaining objectives, the upper level of the conservation pool is more closely considered. In the latter case, added flexibility commonly results in better economic performance but with a substantial risk increase (Votruba and Breza, 1989).

2.1 IMPACT OF EMPTY STORAGE UNDER CONTROLLED FLOOD POOL

Incoming floods first fill up the empty space under the controlled flood pool. The initial level can be at the top of the conservation pool, or below. The hydrograph will be wholly absorbed by the reservoir. This volume will not be released later, at least within the same time scale, due to the usually small capacity of the ordinary exploitation intakes. For the same reason, anticipated drawdowns are very seldom feasible unless flood forecasting is reliable for a time lead over the exploitation time scale. Only very large continental basins with an extensive reservoir capacity can have this possibility. The Lake Mead and Hoover Dam system in the Colorado River (Burke and Stevens, 1984) is one of the most studied cases. When the flood occurs, the water level can be somewhere within the conservation pool. The initial storage position strongly depends on two conservation related ratios, namely, the relative size of the reservoir with respect to the mean yearly flow and the average ratio of water demand to streamflow. The larger these two parameters, the closer the initial water level is to the top of the conservation pool. It is then concluded that even if the flood control pool is strictly fixed and enforced, efficiency of the reservoir for flood control depends on its normal operation. This link has very seldom been addressed. The uncontrolled empty space within the flood control pool acts similarly, absorbing the whole hydrograph until it is full. It should be noted that the entire flood control pool is uncontrolled for ungated spillways. All three proposed possibilities are passive, since the previously uncontrolled empty space cannot be altered within the flood time scale.

2.2 IMPACT OF THE CONTROLLED FLOOD POOL

The volume affected by the gate operation usually defines the controlled flood pool. In contrast to the uncontrolled empty space, its role is dynamic in nature. The performance and effects are dependent on flood management through gate operation; that is to say the sequence of gate openings during the flood. Basically, as will be explained later, there are two groups of strategies, depending on the desired effect. As with any discharge structure, gated spillways are hydraulic controls fixing a unique relationship between the upstream level and the discharge. The reservoir and discharge levels increase as the flood enters. The storage equation basically governs the phenomena:

$$\frac{dS(t)}{dt} = I(t) - O(t)$$

The discharge $O(t)$ is nonlinearly related to the stored volume through the outlet equation $O=f_1(h)$ and the stored volume equation $S=f_2(H)$. The storage equation was solved graphically in days past; today, it is solved numerically. Dynamic methods based on the Saint-Venant equations are considered only in long, shallow reservoirs (Glen and McMahon, 1987). The net effect is to damp the peak, delay its appearance in time and extend the duration of the hydrograph. The stored volume in the reservoir will be released later, however, within the same time scale of the flood.

These three effects are interchangeable. Basically, if a “closing” strategy is adopted (Wurbs and Carriere, 1988), e.g., closing the gates as soon as a flood event is detected and until the flood generated downstream of the dam has peaked, the time delay for the peak is increased, but the stored volume increases faster and the resulting peak will be larger. This is justified if a sizable catchment exists between the dam and the potential damage site. This is a common situation in the United States. If, however, an ”opening” type of strategy is adopted, significant and potential flooding flows are released in advance. The flood peak is more effectively dampened, but the delay is reduced. These latter strategies are safer for dam overtopping, but risk producing more significant flooding than anticipated with smaller floods and the likelihood of lawsuits. Because it is safer for the dam itself, the opening strategies are adopted mostly for high dams or large floods. As will be explained later, the management strategy can be expressed as a set of rule curves; or, a real-time management model, combined with a suitable forecasting system, can be adopted.

2.3 IMPACT OF THE SURCHARGE STORAGE

If the flood pool is full or the reservoir is ungated, the surcharge pool will produce similar results: delay of the flood peak, damping, and extension of the flood duration. However, with the possibility for control and modification in real time, these effects disappear. This strategy is preferred in many remote areas and small basins with short response times, in that no real time management is involved. Surcharge storage effect can be very notorious for large surface and low depth reservoirs, since a large amount of water can be stored with very small surcharge. If urban development and recreational use are factors at the reservoir, flood risk through backwater effects must be considered. Spillway hydraulic design, especially in ungated reservoirs, remains the critical issue for surcharge storage.

2.4 FLOOD CONTROL THROUGH SYSTEMS OF RESERVOIRS

The focus, thus far, has been on the effect of a single reservoir on flood control. A skillfully combined reservoir system, however, can be even more effective. A cascade of reservoirs is more effective in terms of peak delay than the equivalent storage capacity combined in one reservoir, because cascading tends to generate a multi-peaked hydrograph. Dam sites are always scarce, however, and choices in terms of reservoir sites and volume are very limited. The management of reservoir systems, in line or parallel, is more efficient than independent single reservoir operation. If controllable, they can combine peak delays or advances with travel times to reduce damage at the points of interest.

2.5 RISKS INDUCED BY RESERVOIRS

The key difference between reservoirs and all other flood protection measures lies in the fact that dams introduce a new risk, albeit small, to dam break by overtopping. This must always be kept in mind, since dam overtopping usually results in dam break. Dam break damage usually exceeds that caused by the break-producing flood alone. A minor risk, occurring more frequently than foreseen, is gate opening due to operational error under non-flooding conditions.

3. FLOOD POOL DESIGN

Flood pool capacity is the most important variable on which control relies. As has been noted, it is strongly user-dependent. If control is not contractually fixed, its determination is largely decided on the basis of hydrologic studies. Usually, it is fixed at the capacity to hold a design flood or involve certain probabilistic statements, a 1% to 2% exceedence design flood (USACE, 1991). However, as stated by Beard (1990), the attachment of a given probability to flood events described by many attributes-- not only a flood peak--is heuristic. This is more difficult for small basins where the correlation among flood characteristics is low. Simulation, with historical events of reservoir filling and routing, is the most commonly used procedure. The design flood is computed through simulation with a rainfall-runoff model, using a known rainfall event. Storm transposition is frequently applied. The sample of observed flood events usually is too small to assess a strongly seasonal event.

A number of simulation models are typically applied in the computation. Among them, HEC-5 is likely to receive the most widespread use due to its high versatility and the large number of flood control dams managed by USACE (Feldman, 1981). Models like SUPER (Hula, 1981) or SSARR (USACE, NPD, 1975) can be advantageous for certain purposes. BRASS (McMahon, *et al*., 1984) has a unique advantage in its fully dynamic streamflow routing capabilities through incorporation of the NWS DWOPER model (Fread, 1978).

The initial level of the reservoir is usually assumed at the top of the conservation pool, a conservative situation. Votruba and Breza (1989) recommend running simulations of the conservation pool to find the distribution of initial level and compute the required volume by convoluting numerically with the flood volume distribution. Goodrich's probability distribution is usually considered for flood volumes.

Optimization techniques have also been applied to size the flood pool since Duren and Beard (1972) used a gradient search method combined with simulation. An economic objective function is considered, usually the flood control benefits as computed by the expected annual damage curve (Arnell, 1989), with many refinements. Objective functions are usually nonlinear, implying simulation runs for evaluation. Search methods are hence particularly useful. A common flaw of optimization methods, the objective function uniqueness, is particularly notorious since the expected damage for dam break is not considered. Frequently, optimization techniques lead to solutions with undue risk (Stedinger *et al*., 1995).

Explicit risk computation has received very little attention. At most, dam overtopping risk is assumed to be heuristically included within a risk-tree evaluation along with other dam associated risks such as earthquakes, embankment failure, etc. (Moser and Stakhiu, 1987). The above-mentioned overtopping risk, however, depends strongly on the flood pool volume and the initial water level within the conservation pool. Similarly, the flood risk downstream is modified by the same variables. No method is available to explicitly and rigorously compute risk modification from its upstream characteristics. Dufilho (1994) has attempted to compute it through derived distribution techniques; however, the differential nature of the storage equation greatly limits its applicability. To solve this problem, the multivariate analysis of flood characteristics, at least flood peak-flood volume, must be previously addressed.

Lately, the USACE has adopted new risk and uncertainty analysis procedures for the evaluation of water resources projects that explicitly include uncertainties in hydrology, hydraulics and economics (USACE, 1994). That report concedes the new methodology is similar to the current practice, but differs in that uncertainty is explicitly quantified and integrated in the project analysis (USACE, 1994). An evaluation of this new approach as applied to the American River Basin is presented in a draft of a National Research Council report (NRC, 1995).

For reservoir systems, much less specific techniques are available. Trial-and-error, coupled with extensive simulation, seems to be the rule. There is ample room, however, for optimization techniques to distribute the global flood control pool among the various reservoirs. Lin and Tedrow (1973) used dynamic programming coupled with multivariable pattern search techniques to reduce dimensionality of the problem.

In general, flood pool design has received very little attention compared with its real time management. It appears that legal, socio-economic, and construction funding problems place so many constraints on reservoir capacity decision that, in practice, hydrologic and purely technological issues remain secondary. Increasing public opposition to large dams, however, is forcing reconsideration of pools as a method for increasing water availability without new facilities. The storage reallocation problem is becoming increasingly important (Wurbs and Cabezas, 1987). Surprisingly, this problem has been extensively dealt with for detention reservoirs within the urban hydrology framework. Detention storage is a crucial problem in urban hydrology because land development increases the natural flood peak and storage is needed to allow for pollution removal through settlement or subsequent treatment. A considerable body of literature exists for detention storage design, summed up in the excellent work by Urbonas and Stahre (1993) and Hall, *et al*. (1993).

Detention storage reservoirs have only a flood control pool, usually uncontrolled. In other situations, they are fed laterally by a canal with limited capacity. For their analysis, besides the customary simulation models reviewed by Nix (1994) and optimization techniques, a generation of risk-based methods has been developed. Di Toro (1979) introduced a probabilistic approach to capacity design that has been extended to all general curve parameters (Loganathan, *et* al., 1985) and, more importantly, to water quality characteristics such as uncontrolled spills, pollutant removal efficiency, etc. (Ormsbee, *et al*., 1987) through the use of derived distribution techniques, even considering random pollution loads (Segarra-García and Loganathan, 1992) or environmental problems (Akan and Antoun, 1994). The degree of sophistication attained in detention reservoir design is in striking contrast to the trial-and-error simulation procedures common for larger reservoirs.

Many of these techniques could be adopted and would be very beneficial for flood control reservoirs in small basins that are usually ungated and where forecasting is of little help, given its short lead time. Parameterization of the damping efficiency, to overcome difficulties posed by the storage differential equation, must be tackled.

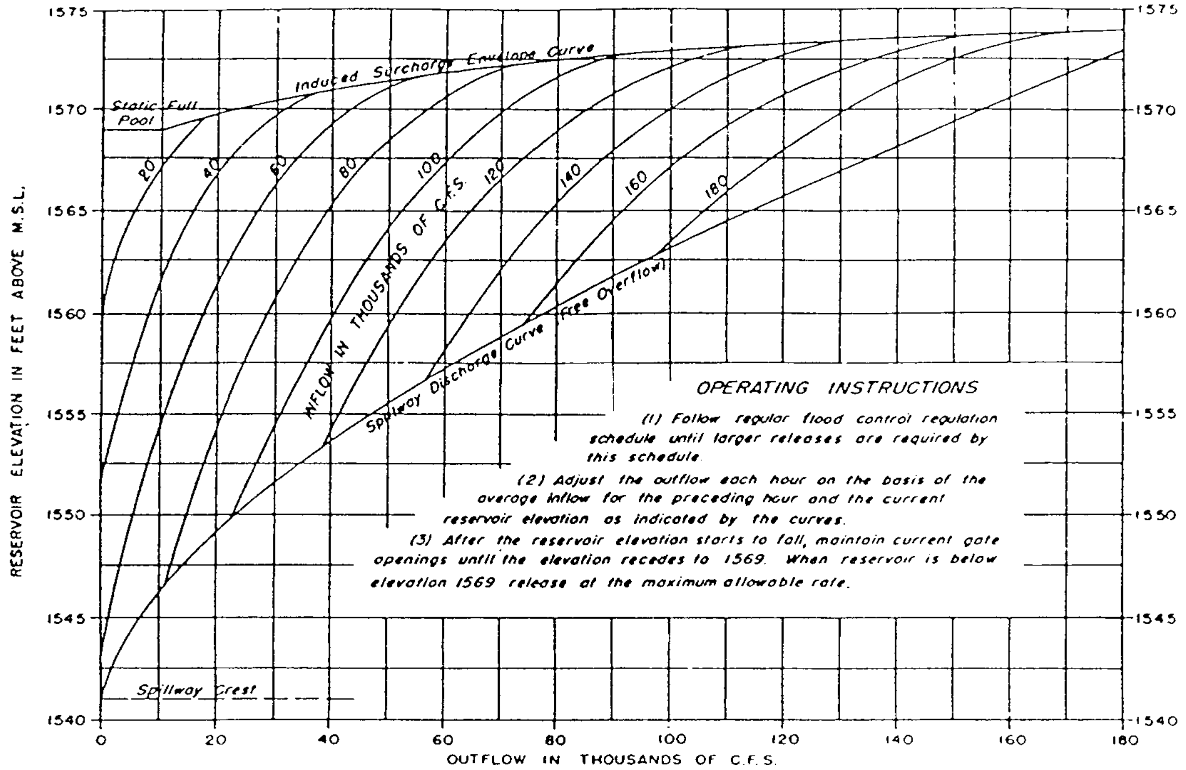
4. FLOOD RESERVOIR MANAGEMENT

Only a small fraction of the extensive literature on reservoir management (Wurbs, 1988) deals with flood control management. A reason for that is the intrinsic difference in time scale (monthly, weekly, or even daily) of the conservation management and the very short time scale required for flood control. The usual approach is to consider the flood pool as a restriction for the optimization or simulation of the conservation pool. Operation under flood conditions can be performed through a previously set rule curve or within a real time framework. The second approach uses as much real time information as possible from the whole system, as well as its near future. Hence, the decision system is closely related to the real time operational forecasting and warning availability. This topic deserves a separate chapter for discussion and is presented in Section 5 of this paper.

4.1 RULE CURVE FLOOD MANAGEMENT

Rule curves are decision tools in the form of equations or, more frequently, graphs relating the outlet and spillway gate openings to reservoir state parameters. The main difference with real time management is that rule curves do not depend on data external to the reservoir itself. The downstream situation or upstream river forecasting requires, at minimum, a real time information system. The availability of this information dramatically improves the management possibility; but, since this system can fail or have important forecasting errors, engineers tend to use rule curves as a back up even where real time management systems are operational. These types of "blind" decision curves can be used by reservoir managers in complete isolation at the dam, a common situation under emergency conditions. In small basins, when response and forecasting lead times are very short, information collected at dam site is the most important and reliable. Hence, rule curves are crucial for flash flood control through dams.

Rule curves are usually of two types (USACE, 1991). For ordinary flood situations, releases are decided only as a function of current water surface elevation and inflow rate. Alternatively, inflows can be expressed as a rate of rise of the water surface that can be measured at the dam itself. It is operationally safer, but both systems are equivalent. Rule curves are developed by simulation. The sample of observed floods, however, is usually so small that design hydrographs must be synthesized from hydrometeorological information tending to reflect most extreme flood situations. As a consequence, the performance of rule curve under moderate floods tends to be weak and frequently results in a more serious flood. An example of a rule curve is shown in Figure 1.



OPERATING INSTRUCTIONS

(1) Follow regular flood control regulation schedule until larger releases are required by this schedule.

(2) Adjust the outflow each hour on the basis of the average inflow for the preceding hour and the current reservoir elevation as indicated by the curves.

(3) After the reservoir elevation starts to fall, maintain current gate openings until the elevation recedes to 1569. When reservoir is below elevation 1569 release at the maximum allowable rate.

Figure 1. Example of a Rule Curve (source USACE EM 1110-2-3600)

Rule curve methods, based on risk estimation, can be developed for small basins following an urban hydrology line. Relationships between hydrometeorological models and runoff hydrographs must be researched to ascertain hydrograph shape variability and a search of complementary local severity indexes must be performed to improve these types of methods. Optimization procedures to develop rule curves are also lacking. Threshold-type decision methods could also be developed to handle the problem pointed out by Beard (1963), namely, under the performance of rule curves developed with a catastrophic flood in mind under moderate flood conditions. As pointed out by Windsor (1973), “a fixed release rule” developed under a range of hydrologic conditions is unable to make the best use of the available storage for the entire range of possible flood conditions.

For reservoir system operation, individual rule curves must be balanced to avoid excessive local risk. The common approach is to allocate individual releases according to the relative filling of the flood pool (USACE, 1991). Windsor (1973) used linear programming to allocate releases from a system of reservoirs within a single operational period. The global release was the variable included within the real time management policy. Developing and balancing rule curves for a system of flood control reservoirs out of a real time framework, however, remains unexplored. Again, technology developed for similar urban hydrology problems can set research directions.

4.2 SEDIMENT RELATED PROBLEMS

As is well known, most sediment erosion and transport occurs during floods. The management policy and characteristics of deep outlets greatly influence the rate and localization of sediment deposition within the reservoir and its overall sediment retention efficiency. Although important research is occurring in China (Cao and Fang, 1991; Wan and Wang, 1994), it must be integrated with the general management problem. Reservoir management during floods often implies fast ascent and drawdown of the water level. These sudden changes can result in landslides within the reservoir itself. Proper consideration of these safety limitations has not been systematized for rule curve or real time management development. It seems that systems analysis can provide the framework for a comprehensive approach.

5. REAL TIME STREAMFLOW FORECASTING AND RESERVOIR MANAGEMENT

5.1 FLOOD FORECASTING AND WARNING

Significant advances have been made in flood forecasting in the last few decades. Ground-based Doppler radars are becoming more common in developed countries. Passive--and in the near future, active--space-borne sensors monitor areas in developed and developing countries and transmit the information in real time to weather and river forecast centers. These satellites are also used as antennas to receive and retransmit information from telemetric stations on the ground. High-speed computers process this massive information and combined in databases that have Geographic Information Systems (GIS) and other Decision Support Systems to provide and update flood forecastings and warnings. Seasonal to interannual climate predictions, in particular those related to El Niño-Southern Oscillation (ENSO) are becoming increasingly reliable. These are currently producing forecasts up to 24 months in advance and have successfully detected the 1991 ENSO event almost a year in advance (Kerr, 1992). Several attempts to use these climatic forecasts in the production of operational hydrologic forecasts have been proposed in the literature and offer promising research opportunities. However, in most cases of real time reservoir management using forecasts, the time steps and the horizon are measured in hours or days, not months or seasons.

5.2 REAL TIME FLOOD MANAGEMENT

Several algorithms have been proposed in the literature to handle the uncertainty of forecasts on reservoir operations. A good summary is given in Stedinger *et al*., (1995). For example, Grygier and Stedinger (1985) compare several algorithms: successive Linear Programming (LP), an optimal control method, and a combined LP-DP method for the operation of multi-reservoir systems with deterministic inputs. In their work, maximization of economic benefits was also used. Stedinger, et al. (1984), compared the impact of alternative forecasting methods for inflows and stochastic DP techniques for the operation of a single reservoir. Mariño and Loaiciga (1985) and Soliman and Christensen (1986) suggest other approaches. Likewise, McLoughin and Velasco (1990) and Díaz and Fontane (1989) have dealt with large hydropower systems in Latin America where the objective was not the minimization of a penalty function, but rather the maximization of economic benefits. Trezos (1991) uses an integer programming approach to the planning of the operation of a hydroelectric system in southern California. Monthly operational policies were obtained in all of these cases.

Real time flood management differs from other reservoir management problems in a number of important ways. First, the considerably shorter time scale precludes the use of many time-consuming techniques. Second, the objectives of flood control management cannot be easily reduced to economic, or comparable, terms. Reservoir management during floods mostly involves a sizable risk of dam overtopping, an ever present stress factor for the manager. Flood control through reservoirs can worsen the situation to the point of catastrophic dam break, very likely involving the loss of human life. It is for this reason that, although algorithms for real time systems analysis incorporating forecasts to the decision-making process are available in the reservoir management literature (Stedinger *et al*., 1995), only a small fraction are flood control oriented and are very seldom used in practice. An example of application of real time forecasting algorithms in the operation of reservoirs is the Han River Basin system where Kalman-based derived forecasts were used in the operation of reservoirs for flood control (Valdés *et al*., 1994).

Engineers prefer to rely on simple, well-written and documented action lines instead of computer algorithms. Regardless of how good they might be, it is doubtful that they could be used in court to back up the manager's decision. Real time dam management during floods must rely on an operational, hydrological forecasting system. Today's computers are fast enough so that operational forecasting tends to become a decision support system (Brazil and Ludlow, 1992), offering the decision-maker a wide range of forecasts and leading to many scenarios. Artificial intelligence methods (Abbott *et al*., 1989; Cuena, 1994) can help provide a wider decision framework to the manager. For many years into the future, however, personal expertise and leadership will be the key factors, much more so than during normal reservoir operation.

In this situation, research on incorporating forecasts into real time flood management is scarce and ill oriented. It is beyond the scope of this paper to discuss ongoing research on river flow real time forecasting (refer to Georgakakos, this Workshop). Improved management will be a direct result of more and better reliable forecasts becoming available to the manager. Research on systems analysis for real time flood management of reservoirs, however, has concentrated on algorithms without proper regard to flood specificities in terms of objectives and the time scale and span of the problem.

Even the most basic philosophy of real time flood reservoir management is lacking. For instance, recent flood risk management documents (NRC, 1995) state "planners and engineers...be able to reduce such delays (in releases)." Delays can be beneficial or dangerous, if the system is complex. The basic strategic decisions, especially for groups of reservoirs, are not defined or systematized according to the hydrologic and hydraulic characteristics of the reservoirs, such as basin equilibrium time, expected time to overtopping, or travel time of the flood wave to the downstream protection objective.

Objectives for reservoir management are generally of two types. Most frequently, the system is managed to minimize the flood peak at the protection site and to avoid exceeding the channel capacity. Sometimes, an economic damage function is specified instead. The objective definition is complex if more than one site has to be protected.

To make things more complex, flood protection can entail an ecological risk by completely suppressing small floods that are essential for ecosystem renewal and equilibrium. Methods to integrate the ecological objective with the flood protection framework or how to develop triggering algorithms or mechanisms to switch policies in case of a real time change of hydrologic characteristics (EPA, 1992; Suter, 1993) are unclear.

For real time flood management, a model or, ideally, a set of forecasting models has to be available. Forecasting models can be deterministic, conceptual or distributed, if they are based on physical laws and no probabilistic statement is attached to the forecasts. Stochastic models use statistical techniques, but more than that, are able to set the contrived probability distribution of the forecasted values or, at least, their second order moments. Stochastic models are more precise for short forecast lead times smaller than the equilibrium time of the basin (Lettenmaier and Wood, 1993; Brazil, 1995). Performance of deterministic models is better if longer lead times are needed. The proper integration of both types of methods within the real time management has not been tackled.

Concerning the optimization algorithm used for real time management, the sequential nature of the reservoir problem has made dynamic programming, whether deterministic or stochastic, the basic tool (Stedinger *et al*., 1995). This leading technique has suffered from computational problems when the number of involved reservoirs is large. Some research is addressing this problem (Read, 1989; Foufoula-Georgiou and Kitanidis, 1988; Piccardi and Soncini-Sessa, 1991), but, specific algorithms for real time flood control through systems of reservoirs are lacking. Since stochastic models can explicitly compute forecasting variances if Kalman filters are used, application of the optimal control theory would be a natural step forward (Seliman and Christensen, 1986; Trezos and Yeh, 1987; Georgakakos, 1989). Bounds to space-state variables, as well as the absence of a feasible defined objective trajectory, are the major obstacles to its development.

A basic problem to be solved is the integration of the forecasting, hydrologic, and optimization time scales. Many characteristic times are involved and the proper method of selecting them remains unexplored. Instead of focusing on optimization algorithms, it seems that basic strategy and objective systematization issues need to be thoroughly explored. This will help fill the large gap between researchers and reservoir managers.

6. NEEDED RESEARCH

- RESERVOIR DESIGN. Given the risk involved in dam design, an ever-active topic is design floods and standards. Whether stochastic, risk-based design, deterministic PMF or PMP, or any other method, spillway design in hydrologic or hydraulic sense is always an issue among professional engineers. Among the hydrologic topics, multivariate analysis of flood characteristics is a perceived need. Research analysis in stochastic terms needs to go beyond flood peak frequency analysis. Risk-based methods of spillway design, embodied with an overall risk approach to dam safety, need to be developed to obtain homogeneous exposure. For reservoirs purposely designed for flood control, the analysis is poorly defined. A detention storage design and outlet characteristic for small flood control reservoirs is a research topic that can be linked to urban hydrology, although it must exceed the typical size range encountered there.

- LONG-TERM MANAGEMENT. The key problem for long-term management of reservoirs is balancing conservation and flood control objectives. The basic research line is to determine the effects of conservation characteristics and the operation of multipurpose reservoirs on flood control performance. Then, research is needed on storage reallocation of existing reservoirs. Mostly unexplored, yet deeply needed topic is that of long-term storage management of reservoir systems for flood control. Issues dealing with flood pool allocation among reservoirs, in series or parallel, have not even been scratched, not to mention its obvious coupling with real time system management. In general, management strategies for systems of reservoirs are nonexistent and must be developed. To attain this research goal, a certain number of instrumental tools must be developed, e.g., explicit flood risk analysis downstream of a reservoir, as modified by pool capacities and spillway characteristics for pre-existing conditions. Also, the inclusion of dam overtopping and inefficient gate maneuvering with the overall flood risk is an instrumental research need for downstream analysis.

- REAL TIME FLOOD MANAGEMENT. The incorporation of flood forecast uncertainty is still an open area of research. Most of the real time operation is based on simulations. The only forecasted components in real time operation are usually the rainfall-runoff transformations or routed hydrographs. There is reluctance on reservoir managers to use precipitation forecasts for liability issues. The quantification of the risk in making decisions based on precipitation forecasts and the incorporation of that uncertainty in optimization models searching for optimal policies is an important area of research. Once again the incorporation of dam overtopping risk in the objective function is an important addition in objective functions.

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