

Dam Operation Management Criteria during Floods: Case Study of Dez Dam in Southwest Iran

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Abstract—This paper presents the principles for improving flood mitigation operation in multipurpose dams and maximizing reservoir performance during flood occurrence with a focus on the real-time operation of gated spillways. The criteria of operation include the safety of dams during flood management, minimizing the downstream flood risk by decreasing the flood hazard and fulfilling water supply and other purposes of the dam operation in mid and long terms horizons. The parameters deemed to be important include flood inflow, outlet capacity restrictions, downstream flood inundation damages, economic revenue of dam operation, and environmental and sedimentation restrictions. A simulation model was used to determine the real-time release of the Dez Dam located in the Dez Rivers in southwest Iran, considering the gate regulation curves for the gated spillway. The results of the simulation model show that there is a possibility to improve the current procedures used in the real-time operation of the dams, particularly using gate regulation curves and early flood forecasting system results. The Dez Dam operation data show that in one of the best flood control records, 17% of the total active volume and flood control pool of the reservoir have not been used in decreasing the downstream flood hazard despite the availability of a flood forecasting system.

Keywords—Dam operation, flood control criteria, Dez Dam, Iran.

I. INTRODUCTION

DUE to the influence of climate variations and changes, the river discharge fluctuation has dramatically increased, so that large dams and reservoirs played an important role in regulating water for increasing demands and mitigating flood peak discharge. Integrated operation of a river system is a complicated issue particularly in multi reservoirs systems with multiple purposes of operation for municipal, irrigation, flood control, and environmental demands. The order of water impoundment & drawdown, sediment discharge, and water discharge from the reservoir is in relation with downstream limitation for water demands, environmental requirements, and flood hazard and damages. The benefits of operation generally include flood mitigation, power generation, and regulating water to meet the water demand of industries and urban water supply, irrigation, environment, navigation, etc. The main role of dams is to redistribute the natural water flow by utilizing the reservoir's storage and regulating capacity, to meet the water requirements of the stakeholders. The dam operators and decision makers should be familiar with methods and limitations of operation in normal situation and real time flood control by empowering with data assimilation

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and flood forecast systems, simulation models, and stakeholder involvement. Robust real time monitoring and flood forecast systems are essential for optimum flood control of the dams and enhancing the benefit of the multipurpose dams. Ralph [1] has introduced and compared the developed models for river and reservoir systems.

Considering the climate of Iran, major portions of annual precipitation (about 70% of the rains) happen in fall and winter. So, the rivers basin runoff is quite high in the wet season compared to the dry season of summer. Due to low weather temperature in the winter, a portion of precipitation is stored in high elevated mountains as snowpack. However; the climate change has led to temperature rising during the cold season and the snowpack budget has remarkably decreased in the end of the season. On the other hand, water demand is high in the hot season when the natural flow of the rivers is low. Therefore, it is essential to develop reservoirs in upstream basins to store water and fulfill downstream demand in the dry season. Historical extreme flood records [2] show that many high floods occur in spring due to high density of precipitation and snowmelt contribution in most parts of Iran. For instance, the recent extreme flood occurred on Apr 2016 and devastated the Dezful city located downstream of the DEZ dam. Although the flood had been anticipated as per the metrological maps, the operators of the dam had not prepared to mitigate the flood and manage the downstream vulnerable areas. On this circumstance, the rule curves of dams imply that the reservoirs impounding should start in the spring and finish before the dry season. Therefore, the most serious flood problems occur when flood control pool of the reservoirs is full or nearly full in the spring. There is less capability for flood mitigation by the reservoirs in these circumstances e.g. March, 2019 flood in north east and south west of Iran. Early flood forecasting systems enhance the capability of the dams for flood mitigation by early evacuation of the reservoir, however, it is essential for using robust models for numerical weather forecast and rainfall-runoff simulation, collecting real time/ online data in the upstream and downstream basins and as well as developing high capacity of release in the dams particularly in lower elevations. The criteria of the flood control in the reservoir should include following topics:

- Safety of dam during flood situation;
- Integrated operation of multi-objective reservoirs with a focus on strategic targets of water supply such as domestic water, energy demand, and so on;
- Flood mitigation and optimal operation of reservoirs in the cascade and parallel systems for minimizing flood damages in the basin wide scale.

Integrated operation of multipurpose reservoirs is a coordinated operation of reservoirs, and related engineering facilities in a basin which have interactions with each other. Optimal operation is used to meet the multi-objective demand of stakeholders for water resources utilization. According to the operation objects, integrated operation can be divided into two aspects: disaster mitigation operation and operation for utilization benefits. The disaster mitigation in dams' operation aims to control flood by making a rational arrangement of the reservoirs' capacity on the premise of ensuring the dams' safety, as well as giving full play for flood mitigation downstream and comprehensive utilization benefits of reservoirs [2].

Ahmad and Simonovic [3] developed a system dynamics, a feedback-based object-oriented simulation approach for modeling reservoir operations in Shellmouth reservoir on the Assiniboine River in Canada. Impacts on the flood management capacity of the reservoir were investigated by simulating a gated spillway in addition to an existing unregulated spillway. Ahmad and Simonovic [4] presented an intelligent decision support system (DSS) to assist decision makers during different phases of flood management including a virtual planning tool that addresses both engineering and non-engineering issues. They developed a DSS to provide suitable flood damage reduction options, forecasting floods, modeling the operation of flood control structures; and describing the impacts for the Red River Basin in Manitoba, Canada.

World Meteorological Organization (WMO) and the Global Water Partnership (GWP) associated Programme on Flood Management [5] have developed a tool to address the needs of practitioners and allows them to easily access relevant guidance materials. The central theme of the tool is to bring the different aspects of climate variability and climate change as it effects flood risks. This shift is enshrined in the Integrated Flood Management (IFM) approach. Cheng et al. [6] developed a web-based flood control system for reservoirs to support the entire decision-making process, including preprocessing the real-data observed data, setting initial conditions, selecting reservoirs constraints, interactively generating alternatives, evaluating alternatives and querying modeling analysis results and recommending alternatives in China.

Ngo et al. [7] used Mike 11 river modelling tool to analyze the operation rules of the reservoir in the Red River basin in China. Flood control strategies were evaluated by using twenty years of flood season data with respect to flood control and hydropower generation. Hosseini et al. [8] used multi-objective particle swarm optimization (MOPSO) algorithm and VENSIM model to optimize the operation of cascaded reservoirs during flood through allocating an initial flood control storage to each reservoir. They have applied the model in Karkheh Dam in Iran and two parameters of downstream flood damage and hydropower generation losses have been considered in objective function. Karaboga et al. [9] used control method based on fuzzy logic for the real-time operation of spillway gates of a reservoir during floods. They

have claimed that the method indicates superior performance over conventional reservoir flood operation with much more reliable results.

II. CRITERIA AND PRINCIPALS OF THE RESERVOIR FLOOD CONTROL

The procedures and analytical methods that are required for real time flood management by reservoirs, should be identified and used in the reservoir simulation. Critical conditions occur when the reservoir has reached normal water level and downstream areas are inundated by flood at the same time. The tradeoff between dam safety and downstream flood risk reduction including loss-of-life and direct damages are usually complicated issues and real time effective management needs simulation models and robust monitoring and data assimilation systems.

The mathematical methods in dam operation should fully account for flood mitigation in vulnerable areas and other benefits/restrictions of dam operation. Multi reservoir systems should give full play to their regulating capacity and compensation ability and improve the utilization efficiency of water supply and also enhance the flood safety. The models provide a tradeoff to minimize the downstream flood threat considering flood forecast abilities by considering constraints of water supply, hydropower generation, and ecological/environmental requirements of the river basin. The advantages of reservoir regulation should be taken into account to improve the flood control capacity of the whole basin through reduction and stagger of flood peaks. A convenient flood control model should be selected for flood routing and regulation in the reservoir based on the specification of outlets and downstream rivers. It is essential to implement an online monitoring system for minimizing flood damages in basin wide scale. Flood forecasting system not only provides reliable information for flood control by reservoirs, but also helps the flood control headquarters to make rapid decisions on dispatch schemes for flood risk reduction. Flood forecasting methods depend on available technology and monitoring of the basin, accuracy of forecast, and required information for flood management. Since, flood hydrograph is an essential input of flood control management by reservoirs, flood forecasting methods should forecast flood hydrograph indicating the maximum peak discharge and flood volume. In order to make decision on the spillway release, safe capacity of the downstream rivers and incremental flood damages in the different zones of the region should be quantified based on upcoming flood. For this purpose, flood routing and inundation models should be applied to provide essential information for decision makers and dam operators to optimize the flood damages and ensure the safety of dams during flood events.

Flood release plans are developed to address the particular conditions associated with each individual reservoir in a multi-reservoir multipurpose system. Peculiarities and exceptions to standard operating procedures occur at various projects. However, operating schedules for most reservoirs follow the same general strategy. Flood release decisions depend on

exceeding the flood control storage capacity and downstream flood discharge capacity. Although reservoir storage capacities at many reservoirs are exceeded more frequently, in many countries, reservoirs are typically sized to contain at least a 50-year return period flood. However, in some projects, design floods are more significant than the 100-year flood, perhaps much more extraordinary. The Federal Emergency Management Agency (FEMA) [10] has introduced a guideline to provide thorough and consistent procedures for selecting and accommodating inflow design floods.

Normally, no flood control releases are made if the reservoir level is at or below the top of the conservation pool. However, in some cases, if flood forecasts indicate that the inflow volume will exceed the available conservation storage, the releases from the conservation storage may be made if downstream conditions permit. The idea is to release some water before the stream rises downstream, if practical, to maximize storage capacity available for regulating the forecasted flood. Pre-releases are particularly important in operating reservoirs with only limited amounts of flood control storage capacity.

For many reservoirs, the allowable flow rate associated with a given location is constant regardless of the volume of water in storage. However, the allowable flow rates at one or more control points may vary depending upon the volume of water currently stored in the flood control pool. This allows stringently low flow levels to be maintained at certain locations as long as only a relatively small portion of the flood control pool is occupied, with the flows increased to a higher level, at which minor damages could occur, as the reservoir fills.

Flood control reservoirs are typically operated based on maintaining flow rates at several gages located various distances below the dam. The most downstream control points may be several hundred kilometers below the dam. Lateral inflows from uncontrolled watershed areas below the dam increase with distance downstream. Thus, the impact of the reservoir on flood flows decreases with distance downstream. Operating to downstream sites requires streamflow forecasts. Flood attenuation and travel time from the dam to the control point and inflows from watershed areas below the dam must be estimated as an integral part of the reservoir operating procedure.

Most flood control reservoirs are components of basin wide multiple-reservoir systems. Two or more reservoirs located in the same river basin will have common control points. A reservoir may have one or more control points which are influenced only by that reservoir and several other control points which are influenced by other reservoirs as well. Multiple-reservoir release decisions may be based on maintaining some specified relative balance between the percentages of flood-control storage capacity utilized in each reservoir. For example, if unregulated flows are below the maximum allowable flow rates at all the control points, the reservoir with the greatest amount of water in storage, expressed as a percentage of flood control storage capacity, might be selected to release water. Various balancing criteria

may be adopted. Releases from all reservoirs, as well as runoff from uncontrolled watershed areas, must be considered in forecasting flows at control points.

A. Flood Inflow to Reservoir

Inflow to the reservoir is determined based on hydrological response to the rainfall and upstream reservoirs performance. Advancing the technology for numerical weather forecasting has led to known upcoming floods to the reservoirs with short-term lead times. Following items are deemed important for flood forecasting and its application in the reservoirs management:

1. Weather forecasting technology
- ✓ Short-time imminent quantitative precipitation forecasting technology
- ✓ Short and medium-term precipitation forecasting methods
2. Hydrological forecasting technology
- ✓ Statistical forecasts mainly for peak discharge or water level
- ✓ Basin response simulation by empirical or analytical methods

One of the main and key inputs of reservoir flood control is flood discharge for upcoming rainfall. The global and local numerical weather forecast models are used for flood forecasting by developing hydrological and river hydraulic models. The flood forecasting models have been developed in many main basins of Iran particularly in the south west, however, many small basins have yet to be equipped to use the advantages of flood forecasting models. Flood control by reservoirs can be divided to following categories:

- ✓ Flood control operations using known and forecasted hydrologic quantities
- ✓ Flood control operations using known hydrologic quantities

Flood forecasts and predictions give a better flexibility to the reservoir operator to manage flows that could mimic the natural flows to certain extent. In addition to reservoir situation in real time, inflow flood hydrograph characteristics are also required for reservoir flood control operations using known hydrologic quantities particularly in gated spillway dams. These characteristics that can be determined by analyzing recorded historical flood data are used for determining gate regulation curves. The main required characteristics for historical and upcoming inflow floods are as follows:

1. Flood hydrograph index extracted from maximum annual flood hydrographs
2. Recession constant determined based on inflow flood hydrograph index
3. Flood hydrographs with different return period using frequency analysis techniques
4. Inflow flood discharge and volume forecasts for upcoming flood
5. Observed real time flood discharge and water level using online monitoring system

Each of the above information has certain applications for reservoir flood operation simulation and monitoring

depending on the cases. For instance, the three first items of the above items are applied for extracting gate regulation curves in the gated spillways and are used in the real-time operation of the dam based on information in the last two items mentioned above.

B. Reservoir Characteristics and Initial Condition for Flood Attenuation

The online monitoring system should provide the initial condition of each reservoir before and during flood occurrence as per the decision makers and operators demands. The dam operation data are collected in daily bases in Iran and shared through a website. The website is not publicly available; however, the operators and decision makers can get access to read and edit the latest situation of reservoirs including water level, empty volume of the reservoir, and all other relevant information needed for the dams' operation.

In order to determine the dam release during flood, reservoir flood routing should be taken into account due to reservoir impact on flood peak discharge attenuation and time delay. Delaying the peak discharge is an important issue where downstream intermediate basin floods contribute for flooding the damage centers. Rating curves of dam outlets, reservoir area-volume-height curves, and minimum and normal water levels of the reservoir are the most important data for estimating flood attenuation by the reservoir. Methods of estimating flood routing by reservoir depend on the available data and objectives of dam operation. The downstream intermediate basin floods should be anticipated for gated spillways in order to avoid magnifying downstream floods. Regulating the radial gates of spillways is determined based on flood magnitude in downstream flood damage area considering the combined hydrograph peak discharge of dam release and intermediate basin. Therefore, an online monitoring system is required for optimum operation of gated spillways during flood occurrence.

C. Dam Facilities for Flood Control

There is less flexibility for operators to attenuate floods in free spillway dams, however; flood release can successfully be managed by operators in the gated spillways. Nonetheless, human mistakes are the most common malfunctions of operation that happen in the gated spillways compared to free spillways. Depending on spillway type and specification of dam outlets, flood discharge can be determined through simulation models before flood occurrence and in real time flood situation. The important criteria for dam operation in flood situations include safety of the dam, not flooding the downstream more than the natural floods, and mitigating downstream floods as much as possible considering restrictions of the multipurpose dams. In gated spillways, using gate regulation curves ensures following outcomes in real time flood control:

- ✓ Over topping never happens unless the inflow flood magnitude is larger than safety flood of dam and full opening of the gates does not provide sufficient discharge.
- ✓ Downstream flood peak discharge never exceeds inflow

flood peak discharge

- ✓ Flood control pool of reservoir should fully be used for flood attenuation

The regulation curves of a gated spillway indicate the discharge based on two parameters of water level and rising speed of water level. Early warning systems can provide great advantages for gated spillway dams to evacuate the reservoir before flood occurrence. Therefore, operators have a main role in reservoir flood management in this type of dams. Reservoir flood control regulations are based on minimizing downstream flood risk ensuring that the maximum water surface is never exceeded from allowable water levels defined in the design stage.

Another advantage of the gated spillway dam is to use the surcharge volume of reservoirs for attenuating flood as much as possible. When the gates are opened during flood, it allows the maximum allowable level of reservoir to increase up to top of the radial gates. This surcharge volume of the reservoir can play a key role for more mitigation of downstream floods. However, flood control pools must quickly be evacuated with a safe discharge depending on downstream flooding conditions to reduce the risk of current and future possible floods. Filling of the available storage capacity may necessitate highly damaging releases. Minimizing the risks and consequences of storage backwater effects contributing to flooding upstream of the dam is also an important tradeoff consideration at some reservoirs. The spillways type category and outlets in the dams are important factors in real time flood operation summarized as follows:

- ✓ Bottom outlets operation purposes and limitation
- ✓ Hydropower release capacities and power generation constraints
- ✓ Type of spillways and their functions
- ✓ Estimation and application of regulation rules for gated spillways
- ✓ Other intakes and dams' facilities for real time flood control

D. Constraints of Dams' Operation

The constraints that should be considered in flood control of dams are as follow:

- ✓ Technical feasibility;
- ✓ Cost benefit analysis;
- ✓ Water allocations; and
- ✓ Flood risks

The capacity and function of the outlets are usually determined by the operators to which the water is put and whether the sediment laden water is acceptable for diversion or to be let into the turbines. Many times, the outlets are not located in the body of the main dam and the released water does not join the river directly downstream of the dam but rather joins after a certain distance downstream. The spillway releases surplus water resulting from flood inflows that cannot be contained within the reservoir and cannot be released through a low level outlet. A further function of the low level outlet is to enable the reservoir level to be drawn down in a controlled manner that be required for dam safety reasons.

In order to manage the release flows by non-structural measures, different scenarios should be checked based on rule curves with minimum negative impacts on different users including the following strategies:

- ✓ Adopting water saving policies and practices;
- ✓ Revised rule curves and operation practices;

The requirements of managed flows can be met if the available water could be efficiently managed through the reservoirs for various uses. Most planning and development decisions to build and operate a reservoir are based on an economic assessment of its benefits compared to its costs, although other factors such as environmental impact are increasingly deemed important. Multipurpose reservoir establishes certain rights for use of water by different sectors or sections of society. Flood control purposes of the reservoir usually oppose the water supply objective in multipurpose dams. Uncertainty of flood forecasting systems helps this conflict to be more serious. Early evacuation of the reservoirs in case of wrong flood forecasting can lead to catastrophe for other objectives of the dam, particularly domestic water supply. Therefore, decision makers should consider the consequence of water allocation failure in flood management of the reservoirs. On the other hand, risk of flooding for dam safety and downstream vulnerable areas is the other concern of dam operation during flood seasons. However, maximum and minimum allowable reservoir level in the rule curves of dam operation, can help to have more confident policies for flood management purposes of dams.

1. Powerhouse Intakes and Requirements

Reservoir operating rules for hydroelectric power generation assume many different forms depending on the characteristics of the electric utility system, reservoirs system, hydrologic characteristics of the river basin, and institutional constraints. If the reservoir contains flood control pool, water will be stored in the flood control pool above the top of the power pool during flood events. This may pose some limitations for power generation depending on electromechanical equipment of hydropower plants. On the other hand, in case of reservoir evacuating, power generation is curtailed any time the water surface elevation drops below the designated minimum power pool elevation. Moreover, sediment trapping during flood occurrence may pose limitations for power generation in case of entering sediment particles to the intake of power plants. Nonetheless, producing electricity in must run status (power plant is not subjected to merit order dispatch principles) during flood, not only increases electricity generation, but also helps to manage the reservoirs for flood mitigation purposes. Understanding all constraints and limitations of the powerhouse outlets helps the operator to be prepared for any unexpected situations during real time operation of the dam. In summary, following factors should be taken into account for powerhouse if any:

- ✓ Maximum and minimum allowable level of reservoir according to electromechanical equipment of hydropower plant
- ✓ Merit order dispatch principles for must run status of

power plant

- ✓ Intake level and updated sediment deposit level in the intake area of reservoir
- ✓ Knowledge of operators from the sediment problems of the reservoir
- ✓ Tailrace limitation for rising water level in high discharges

2. Outlet Requirements

The operation plans provide guidance for real-time release decisions, but typically leave a significant degree of flexibility. Information regarding current storage levels and stream flows is used in combination with the regulation schedule, to make release decisions. Real-time operations often involve collection of current precipitation and streamflow data and forecasting flows to be expected at pertinent locations during the next several hours or days, to enable more effective release decisions. During normal non-flooding conditions, flood control operations consist simply of passing inflows to maintain empty storage capacity and make release based on downstream required demands.

Operating rules of dams during flood should be determined based on minimum flood risk in downstream areas and maximum safety for dam and appurtenant structures. Considering these two criteria, the outlet/s of the dam in the level below the spillway level should effectively be used for early evacuation of flood control or even conservation pool based on flood forecasting system results. In the meantime, using bottom outlet/s of the dams confronts limitations in most of the cases. Full close or opening of the bottom outlet/s is allowed in many dams and partial opening causes a threat for dam safety. Sedimentation of reservoirs makes the issue to be complicated particularly in the old reservoirs systems. The risk of not being able to close the bottom outlet/s after flood recession is one of the main concerns for operation of outlets during floods. However, early action plans known as non-structural approaches provide more flood control pool before the flood occurrence and increase the efficiency of reservoirs flood control.

3. Downstream Safe Discharge Capacity

Downstream river safe capacity for flood discharge is one of the important factors in reservoir flood management. The safe capacity is mainly can be divided into two categories: 1) the design flood of river infrastructures such as weirs and bridges and 2) floodplain safe discharge without any damages to residential, industrial, and agricultural areas.

When a river and its floodplain are prone to flooding, infrastructures such as roads, railways, pipelines, are normally designed and constructed to avoid or withstand flooding. Nevertheless, floods higher than the designed floods still cause damage to infrastructure and disrupt activities particularly where protective measures have been poorly or under-designed. In the floodplain downstream of a reservoir, small and medium sized floods may be significantly reduced or virtually eliminated which often leads to new houses, schools, clinics, factories and roads being constructed on previously

flood-prone land. It will thus be important to consider the impact of managed flows on this infrastructure. In some cases, facilities within the “floodway” may be relocated before managed flows can be implemented. However, it may not always be possible to relocate the facilities, and the only alternative may be to construct protective embankments around such flood-prone infrastructure.

Usually, flood risk of downstream which is a combination of flood magnitude and vulnerabilities, is unknown due the land use changes and variable hydrological and hydraulic condition of the rivers in many basins of the country. In Iran, crisis management authority has recently started to complete and update the flood risk maps in the vulnerable areas in the main rivers [12]. According to historical data recoded in the dams operation [18], unknown flood risk reduction in real time operation of dams has led to conservative plans for flooding downstream in earlier stages of flood with the aim of providing more flood control pool. Notwithstanding flood warning systems for recent extreme floods, the early evacuation of the reservoirs was not sufficient to optimize flood control operation.

In summary, following data should be determined for downstream discharge capacity:

- ✓ Downstream infrastructures feature and functions along the river
- ✓ Vulnerability of flood plain to flooding for different sectors corresponding to different discharges
- ✓ Emergency action plans for evacuating the damages centers
- ✓ Crisis management rules and regulations

The managed flood peak discharge will have to be smaller than those that would have occurred without the reservoir. Moreover, one of the objectives of flood management is to reduce the disruptions that are caused by flooding to the economic activities and consequently the wellbeing of flood plain dwellers. It is thus important to use floodplain inundation models in the most effective way. Embankments constructed to protect one area will mean that water is diverted to another part of the floodplain. Additional embankments may be constructed with sluice gates to enable particular areas of the floodplain to be inundated to specified depths at particular times, thus fine-tuning the effectiveness of the managed flow. These issues may have an impact on flood control rules of the reservoir to provide sufficient time for the organizations and people in flood management activities. Some of the issues that need to be considered while looking at the effectiveness of the reservoir managed flows are as follows:

- ✓ Different floodplain stakeholders (including farmers, fishermen and herders) should be included in managing at different times
- ✓ Where the target floodplain is a significant distance downstream of the reservoir, flow from the intermediate catchment and tributaries need to be taken into account in achieving target levels of inundation
- ✓ Indirect impacts of managed flows, such as health issues, may be significant

Flood routing and inundation models need to be available in the flood management systems based on online monitoring data. Decision maker and dam operators will be able to simulate flood inundation and damages in each scenario of reservoir flood control plan and will choose the best scenario based on minimum damages.

E. Environmental Issues

Environmental resources management opportunities and problems associated with reservoir operations vary widely between regions and between reservoirs. Reservoir operations influence fish, wildlife, and ecological systems both in the reservoir pool and in the river downstream. Reservoir releases contribute to maintenance of instream flows necessary for the support of aquatic habitat and species, protection or enhancement of water quality, preservation of wetlands, and provision of freshwater inflows to bays and estuaries. Reservoir operating plans may include maintenance of specified minimum flow rates at downstream locations and periodic flooding. Low flow augmentation may be important for certain ecosystems. The required flow rates may be specified as a function of season, reservoir storage, reservoir inflows, and other factors.

Reservoir releases for downstream fishery management depends upon water quality characteristics and water control capabilities. Achieving optimal temperatures for either cold water or warm water fisheries through selective multilevel releases may be an operating objective. Maintenance of dissolved oxygen levels may be an operating objective. Releases can be beneficial for maintaining gravel beds for certain fish species. Dramatic changes in release rates, typically associated with hydropower and flood control operations can be detrimental to downstream fisheries.

Flooding of the floodplains attenuates flood peaks downstream. So most important damage areas should be considered in high priority of protection in case of major flood happening. The inundated floodplains can retain the moisture for long duration and thereby provide agricultural opportunity in rain-fed agriculture. At the same time, it replenishes groundwater, which forms an essential source of water for drinking and irrigation. The wetlands on the floodplains also get replenished and provide different ecosystem services. In some cases, building upstream reservoirs and flood control projects has led to the floodplain to be dried and become out of vegetation. This is one of the main reasons for dust storms in the south west of Iran and Arab countries in recent decades. Therefore, the demand of flooding the floodplain that is known as green demand, should be considered as one of the objectives of dams' operation along with other targets. In summary, following environmental factors should be taken into account for reservoir operation in flood situation:

- ✓ Allowable downstream discharge variation for satisfying environmental requirements
- ✓ Allowable level of reservoir to release water according to required water temperature
- ✓ Maximum allowable sediment discharge
- ✓ Requirements of floodplain green demand

F. Sedimentation and Erosion

The potential of erosion and sediment deposition processes are significantly altered by construction of reservoirs. The impacts of individual dams depend on the streamflow and sediment load of the river, and the operating rules of the dam. Large reservoir projects frequently trap and retain essentially all of the suspended sediment and bed material load within the upstream delta, thus releasing sediment free water. Deposition of sediment in the upstream reservoirs generally results in erosion and degradation of the streambed and banks downstream of the dams. The amount and gradation of the sediments depend on the size of the reservoir and the pool level at the time of significant inflow.

The extent of downstream erosion is a function of the composition of the bed and bank material, the annual volume of released water, flow velocities, and so on. Fluctuating releases often result in an initial loss of the banks that closely related to the magnitude of the stage fluctuation. Periodic wetting and drying of the river banks by fluctuating releases accelerates recession process. The recession of banks usually stabilizes in the first few years of operation, as the underwater river slope reaches a quasi-state of equilibrium. Once the equilibrium slope of river achieved, the bank erosion process behaves like in the natural channel. Reservoir releases also result in lowering the river bed and the maximum amount of lowering occurs immediately downstream of the dam outlets. This degradation process continues until the river slope reaches to its equilibrium value and/or the bed becomes naturally armored by exposing the coarse and non-erodible bed materials.

Channels downstream from small and medium size reservoir projects often exhibit entirely different characteristics than described above for large reservoirs. Channel capacity below the smaller reservoirs tends to be lost over time. Reservoir projects that make only limited releases may result in extensive deposition and subsequent vegetative encroachment in the downstream channel. With construction of a reservoir, the pre-construction periodic flushing flows, that are capable of removing deposits near the mouth of tributaries, are often replaced by low non-erosive reservoir releases. This contributes to the loss of channel capacity and reservoir operating flexibility.

Sediment deposits in the reservoir pool are another important consideration, since storage capacity and many reservoir management activities are adversely impacted. Sediment deposits occur throughout a reservoir but particularly in the upper reaches where inflow velocities are reduced by the impoundment. The impacts of sediment accumulations, over the life of the reservoir, should be recognized in project planning and operation. Although much of the erosion and deposition process is beyond the control of reservoir managers, precautions can significantly minimize problems. In summary, the dam operator and decision maker should take into account these precautions as follow:

- ✓ Taking any sediment flashing rule into account based on design criteria of dam
- ✓ Considering latest hydrography and sediment profile of

- the reservoir in flood control rules
- ✓ Maximum allowable eroding discharge if any
- ✓ Maximum density flows if any

III. CASE STUDY FOR FLOOD DISCHARGE PLANNING

Karun River basin located in south west of Iran, consists of upper Karun and Dez Rivers that flow together before metropolitan city of Ahwaz. Dez double arch concrete dam with height of 230 m has been under operation since 1960 [18]. As shown in Fig. 1, Dez dam located in upstream of Dezful city in Dez river has a major role in flood damage mitigation of the downstream floodplain in the extreme floods, supplying water demands of the vast Khuzestan irrigation networks and municipals, and last but not least frequency control of national power network. Sedimentation in the reservoir is one of the major problems of the dam and high density flow inters to power intake in some circumstances in addition to reduction of effective volume of the reservoir. The spillway of dam has 2 gated tunnels with discharge capacity of 6000 m³/s. The regulation curves of the Dez dam are shown in Fig. 2.

As shown in Fig. 2, in higher speeds of water level rising, the release is closer to the open gate situation in the same water level. The full open gate rating curve should be considered in the dam regulation when water level approaches to maximum flood level. The regulation curves are extracted based on specification of inflow flood hydrographs such as recession constant and physical/hydraulic characteristic of the reservoir and spillway [11]-[14].

The tradeoff between different purposes of operation of the dam should be considered in flood control planning and sometimes the conflict of targets has led to huge flood damages in Dezful City e.g., 2014 Oct flood. Reservoir Simulation models help the decision makers to evaluate different scenarios of dam operation in terms of powerhouse performance, opening rate of spillway gates, maximum peak discharge, maximum allowable level of reservoir before, during, and after flood recession, and so on. Operating rules are not necessarily similar in different flood events. The downstream intermediate flood effluence on the reservoirs' flood management depends on the status of the flood and operators should select the best scenario among the possible scenarios. Gate regulation curves can also help operators for gated spillway dams to prevent any major mistakes in real time flood management.

A set of operating rules based on downstream flow rates is followed as long as water level of the reservoir is lower than the top of the flood control pool. Operation is switched over to an alternative approach, based on reservoir inflows and storage levels, during extreme flood conditions when the anticipated inflows are expected to deplete the controlled storage capacity remaining in the reservoir. The reservoir release rates necessitated by the flood control storage capacity being exceeded will contribute for flooding downstream. The objective is to assure that reservoir releases do not contribute to downstream damages as long as the storage capacity is not exceeded. However, for extreme flood events which would

exceed the reservoir storage capacity, moderately high damaging discharge rates should be released before the flood control pool is full otherwise a full reservoir would necessitate to have much higher release rates.

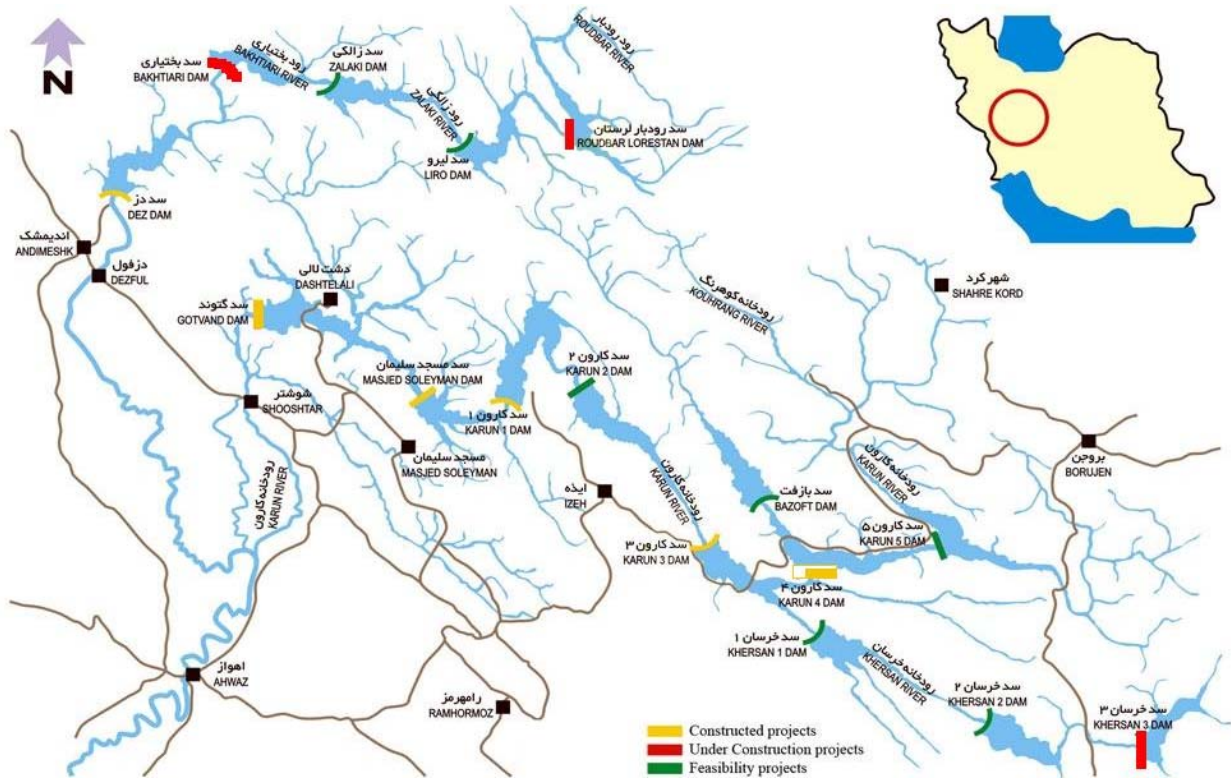


Fig. 1 Location of Dez dam in Karun River system in south west of Iran

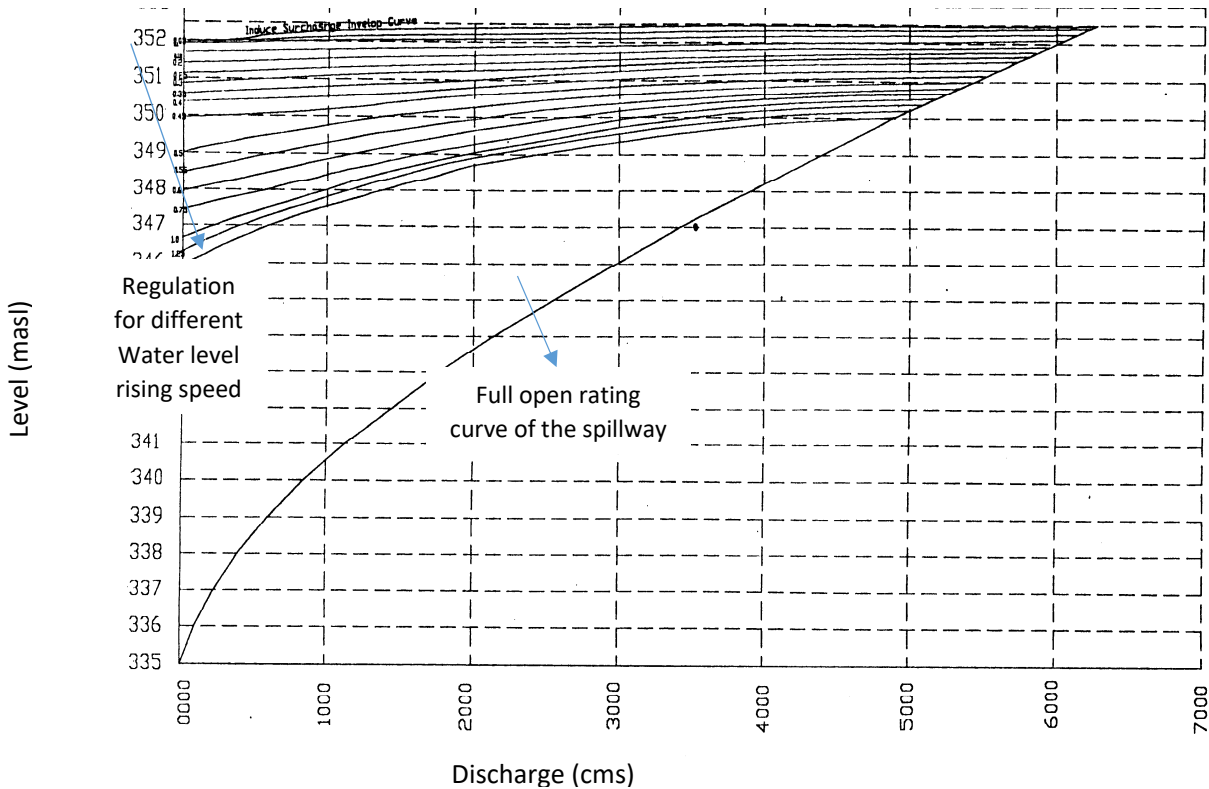


Fig. 2 Dez spillway (Radial) Gates regulation curves

Flood control operations are based on minimizing the risk and consequences of making releases that contribute to downstream flooding. Maximum allowable flow rates and stages at downstream control points are set based on bank-full stream capacities, stages at which significant damages occur, environmental considerations, and/or constraints such as

inundation of road crossings or other facilities. The data of stream gaging stations located at the control points should be available for real time management of flood. Releases are made to empty the flood control pool as quickly as possible without contributing to stream flows exceeding specified maximum allowable flow levels at downstream gages.

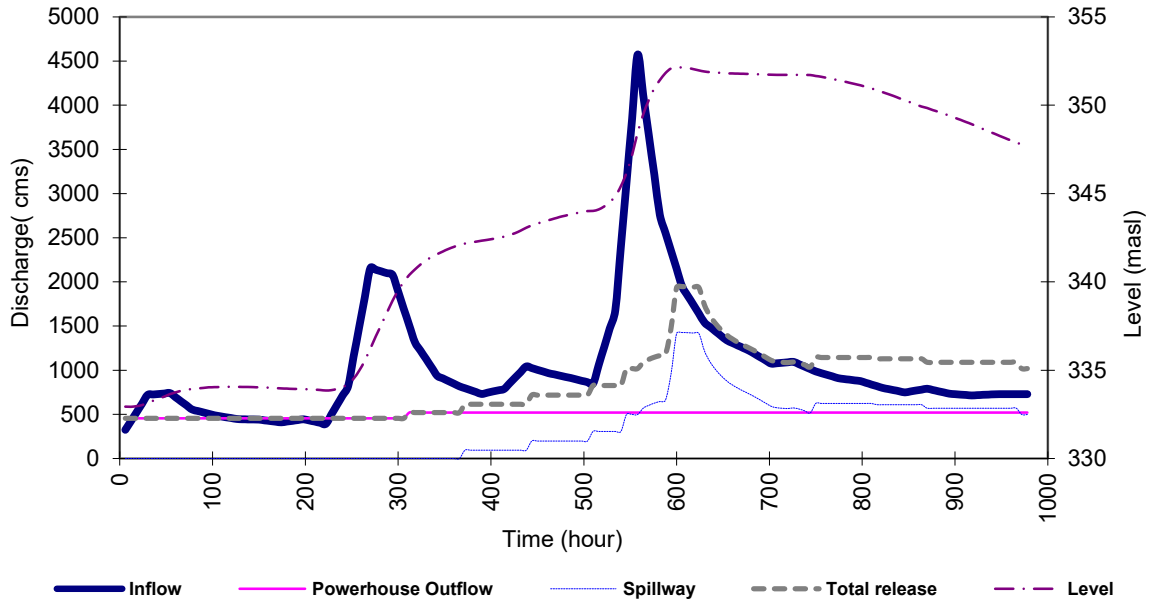


Fig. 3 Flood control simulation results of Dez dam in 6 Hour time step

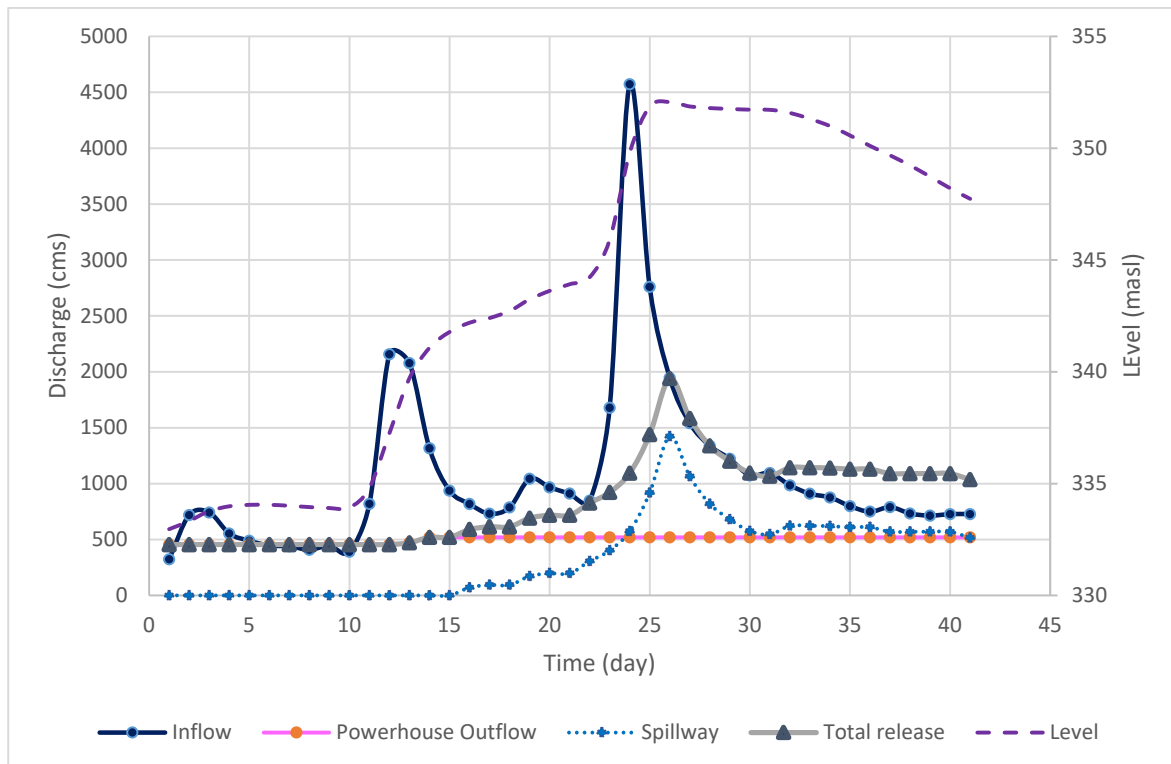


Fig. 4 Flood control simulation results of Dez dam in daily time step

When a flood occurs, the spillway and outlet work gates are closed. The gates are operated based on reservoir level

observation or hydrological forecasting depending on the facilities of the basin for flood forecasting systems. The gates are then operated to empty the flood control pool as quickly as possible without exceeding the allowable flows at the downstream locations.

Dez dam flood control has been simulated using HEC-Resim [14], [15] and the results are shown in Figs. 3 and 4 for 6 hour and daily time steps, respectively. The gated spillway release rate has been set on the water level and gate regulation curve (Fig. 2) has been used in upper levels of the reservoir in the simulation model. As shown in Fig. 3, the peak discharge of flood has decreased from 4500 m³/s to less than 2000 m³/s and the reservoir level has risen from 333 to maximum 352.14 masl (meters above sea level) at the peak discharge release. Normal and minimum operation level of the dam are 310 and 352 masl, respectively and the surcharge flood pool has efficiently been used by opening 3 radial gates during flood to increase the water level up to 352.14 masl. Moreover, 60% of flood pool has been considered for emergency evacuation of the reservoir and water level has decreased to 347.8 masl in 15 days.

Fig. 5 shows the recorded data of Dez dam operation during the same flood. The peak discharge of the flood by real operation of dams has decreased the same as simulation one, however, the observed maximum level of reservoir (346.9 masl) is much less than simulation result i.e. 352.14 masl. In other words, in real operation of the dam, the spillway gates have been opened earlier and the rate of opening was higher than the simulation scenario in the lower levels of reservoir. This issue was due to the operators' awareness for occurring flood based on flood forecasting systems results, whereas in the simulation scenario, the opening of gates was only based on the water level. Nonetheless, the flood control pool has not efficiently been used in the real operation and by increasing the water level up to 352.14 masl. The empty volume of the reservoir in the peak discharge of the flood is 326 MCM (Million Cubic Meter) according to maximum flood control level of 352.14, i.e. 17% of total active volume and flood control pool. Therefore, it was possible to decrease the peak discharge of flood more than the recorded discharge by using 100% of active volume and flood control pool.

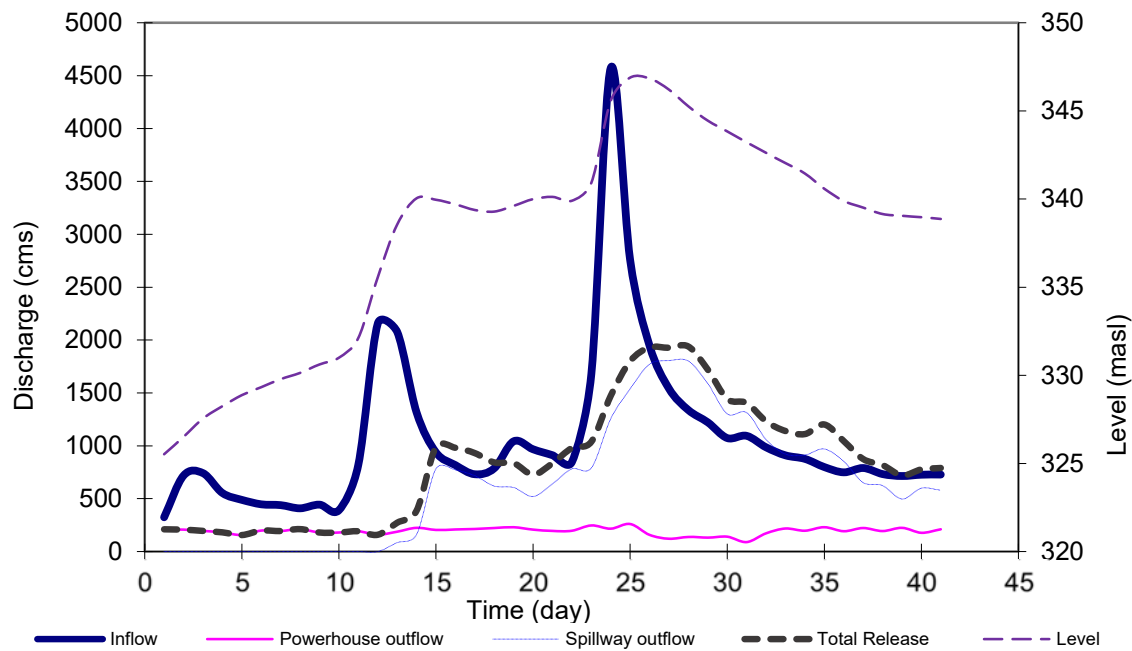


Fig. 5 Daily recorded flood control of Dez dam during flood

Karun flood forecasting system [16] consists of four components including local numerical weather forecast model, rainfall – runoff model, a short – term reservoir operation model and hydrodynamic river routing model. These four components are interconnected by a GIS platform as shown in Fig. 6. The local weather forecast models of MM5 and WRF have been developed by national meteorological research institute based on initial and boundary condition obtained from the global models results and observed stations data.

Rainfall-runoff (RR) simulation was carried out by HEC-HMS [17] by dividing the basin into 26 sub-catchments as shown in Fig. 7. RR simulation was based on unit hydrograph for direct runoff routing, exponential infiltration for loss rate estimation and degree-day method for snow melt snow fall simulation after calibrating the model.

The result of flood forecast model is shown with lead time of 4 days rainfall forecast in Fig. 8 and compared with recorded flood hydrograph.

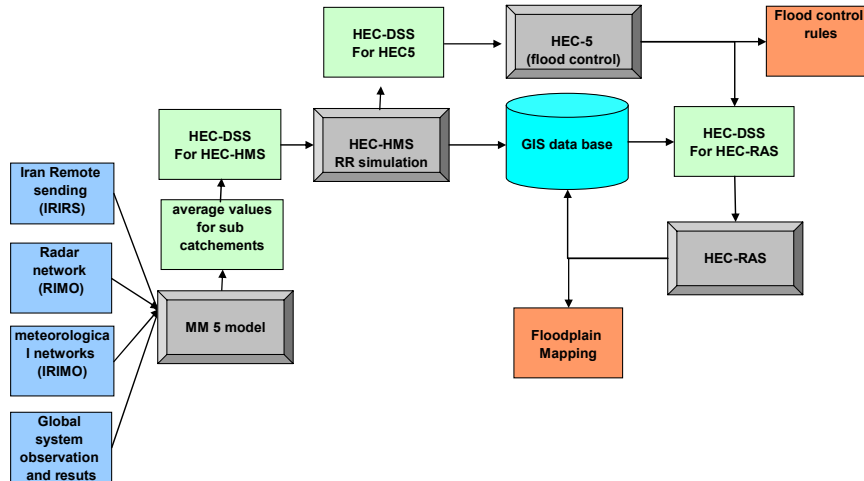


Fig. 6 Configuration of Dez and Karun rivers flood forecast system

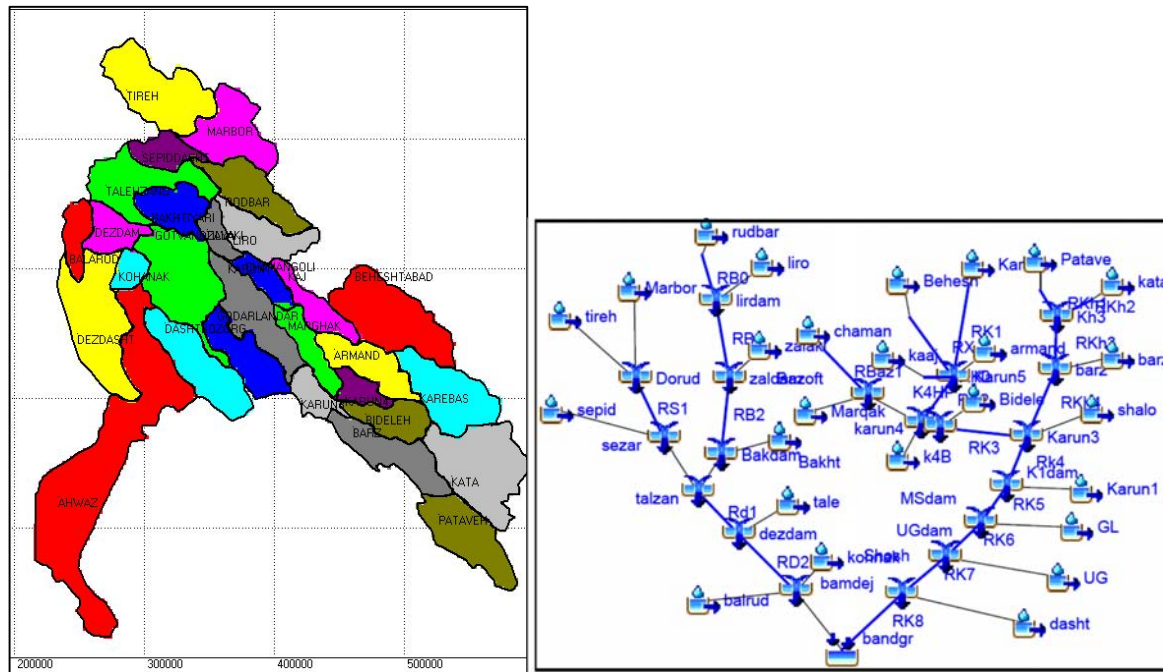


Fig. 7 Sub-catchments and schematic of Dez and Karun rivers in hydrological model

The forecasted flood hydrographs have been used in the reservoir simulation model to estimate the peak discharge release, maximum water level, energy generation, and conservation pool for water supply purposes. The best scenario of the flood control operation should be determined by defining and comparing different scenarios for flood release during flood. Monitoring downstream flood discharges and inundation areas is an important element for selecting the convenient scenario among the defined scenarios. Fig. 9 shows the results of a scenario analysis for flood control and other purposes of dam operation including water supply, power generation.

IV.CONCLUSION

This paper presents the main criteria for flood control in

multipurpose reservoirs. The criteria include safety of dams during flood, minimizing the downstream flood hazard, and fulfilling the water supply and other purposes of the dam operation in mid and long terms. The physical and technical restrictions of the dam operation should be determined along with environmental and sedimentation requirements in addition to flood mitigation criteria in the dam operation. In this paper, flood control by the reservoir was simulated for Dez Dam in south west of Iran. The spillway of the dam has been equipped with 2 radial gates and the main objectives of operation are water supply, power generation and network frequency control, and flood control. The results showed that in case of operating of the spillway gates based on reservoir water level using the gate regulation curves and full flood control pool, the release peak discharge determined by

simulation model is the same as the observed release discharges of the dam despite the operators' awareness of the flood occurrence in advance. The early flood forecast system helps to release flood before the flood occurrence and there would be more flood control pool to mitigate the peak discharge, however; in the real operation, the operators avoid

using full flood control pool because of precaution for safety of the dam. The gate regulation curves are the most effective tools to help the operators for using full flood control pool and at the same ensuring the safety of dam by avoiding any overtopping.

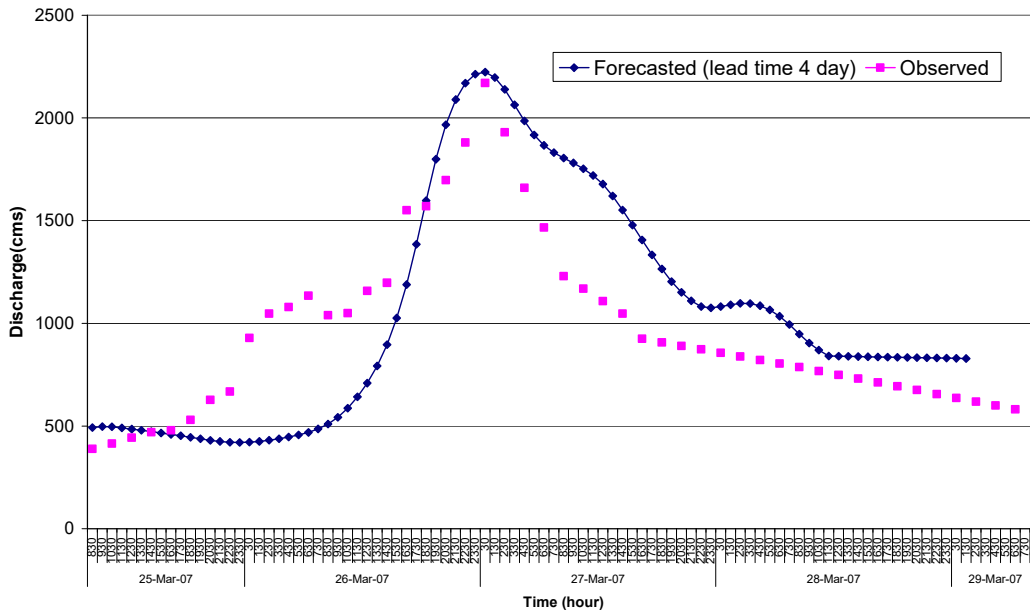


Fig. 8 Comparing observed and forecasted hydrographs with 4-day lead time in rainfall forecast

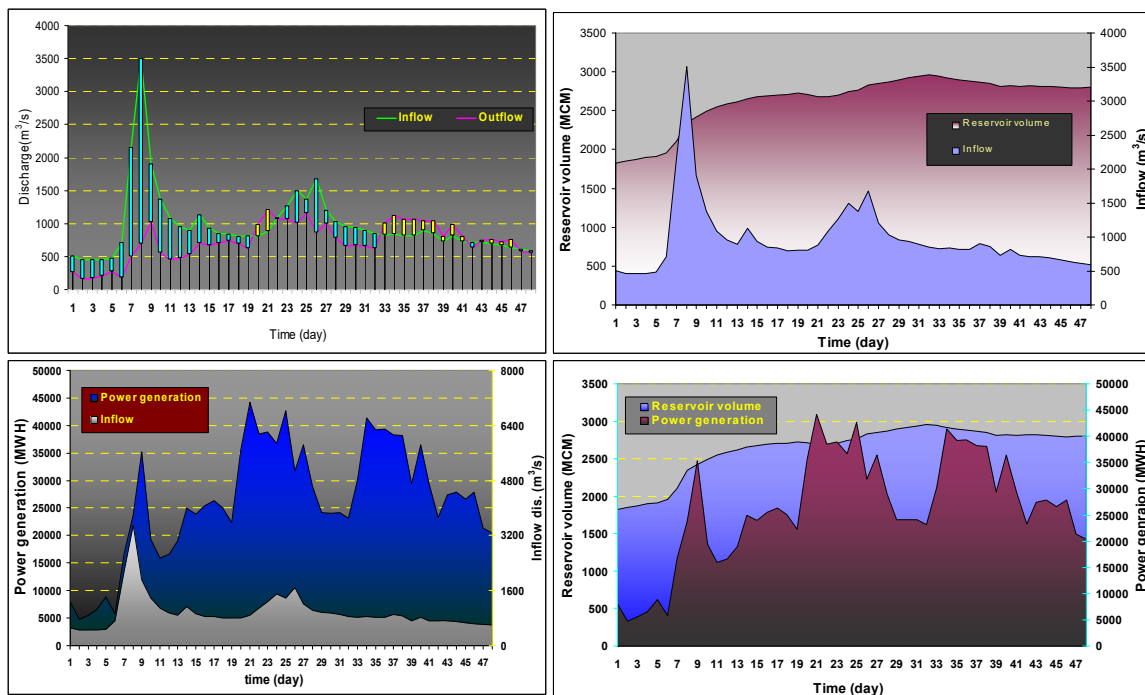


Fig. 9 Flood control scenario results considering flood forecast system results

A reliable flood forecast and robust online monitoring systems can improve the dams' operation for flood mitigation management in downstream and the safety of dam can be enhanced by using the gate regulation curves of the gated

spillways when the reservoir water level is in the flood control pool. Developing an analytical model and simulating different scenarios of the reservoir flood control provides a helpful information for the dam operators to be ready for decision

making by updating flood forecast based on the numerical weather models and online observations as well as the physical and technical criteria in the dams' operation.

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