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भारतीय मानक मसौदा

जलाशयों का प्रचालन — दिशानिर्देश

(IS 7323 का दुसरा पुनरीक्षण)

Draft Indian Standard

OPERATION OF RESERVOIRS — GUIDELINES

(*Second Revision of* IS 7323)

Reservoirs and Lakes Sectional Committee, WRD 10

Last Date for comments: 08/04/2025

FOREWORD

(*Formal clauses of the foreword will be added later*)

Water, a major natural resource, is used for multiple uses as irrigation, power generation, navigation, etc, besides industrial and domestic needs. The main source of availability of water is the surface run-off in the form of rivers. The flow in the river changes seasonally and from year to year, due to temporal and spatial variation in precipitation. Thus, the water available abundantly during monsoon season, and becomes scarce during the non-monsoon season, when it is most needed. The traditional method followed commonly for meeting the needs of water during the scarce period is construction of storage reservoir on river course. The excess water during the monsoon season is stored in such reservoirs for eventual use in lean period. Construction of storages will also help in control of flood, as well as generation of electric power. To meet the objective set forth in planning a reservoir or a group of reservoirs and to achieve maximum benefits out of the storage created, it is imperative to evolve guidelines for operation of reservoirs. Without proper regulation schedules, the reservoir may not meet the full objective for which it was planned and may also pose danger to the structure itself.

Control of flood is better achieved if the reservoir level is kept low in the early stages of the monsoon season. However, at a later stage, if the anticipated inflows do not result, the reservoir may not get filled up adequately for meeting the various water demands. On the other hand, if the reservoir is filled up to FRL in the early stages of monsoon, to avoid the risk of reservoir remaining unfilled at later stage, there may be problem of accommodating high floods occurring at later stage. In some cases, while planning reservoirs, social and other considerations occasionally result in adoption of a plan that may not be economically the best. Considering all these issues, it is proposed to lay down general guidelines for regulation of reservoirs, though it may not be possible to cover all types of cases.

This Indian Standard was first published in 1974. Since then considerable developments in the techniques of reservoir operations had taken place. The concept of operation of reservoir considering it as a single entity had given way to the concept of integrated operation of reservoirs. First revision of this standard was taken up in 1994 to include application of system engineering methods, such as mathematical optimization and simulation which were increasingly used for defining, evaluation and selection of reservoir operation policies. This revision (second revision) has been brought out to bring the standard in the latest style and format of the Indian Standards. In addition, the following major changes have been incorporated:

a) A new clause on hydropower has been incorporated to outline the operation methods of reservoirs designed for power generation, emphasizing water level management for flood and sediment control, particularly in high-flow and low-flow periods.
b) Clause on flood control zone has been modified to clarify its typical range, specifying that it lies between the Full Reservoir Level (FRL) and a predefined level between the FRL and the Minimum Drawdown Level (MDDL) or Dead Storage Level (DSL).
c) New clauses have been incorporated to enhance real-time reservoir operation by including downstream warning system, flood simulation studies, inundation mapping, and a comprehensive Early Warning System (EWS) for disaster risk reduction, particularly in the Himalayan region.
d) Clause on data collection and analysis has been modified to include various data transmission media, including GSM/GPRS communication, Radio Wave communication, and VSAT communication systems, to emphasize the diverse options available for efficient data communication.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the results of a test or analysis, should be rounded off in accordance with IS 2 : 2022 “Rules for rounding off numerical values (*second revision*)”. The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

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(*Second Revision of* IS 7323)

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1 SCOPE

1.1 This standard provides some important basic guidelines for the operation of reservoirs in order to achieve maximum benefits consistent with their physical characteristics and functions for which they are planned and constructed.

NOTE — These guidelines are broad generalization only and are indicative in nature. For actual operation of reservoir or a system of reservoirs, individual regulation schedules are required to be formulated, after considering all critical factors involved.

2 TERMINOLOGY

For the purpose of this standard, the following definitions shall apply.

2.1 Carry Over Storage — Storage left over in a reservoir at the end of the depletion period of a year, which is available for use in later years. This storage is also called 'Over Year Storage'.

2.2 Conservation Storage — Water impounded in a reservoir for conservational uses such as irrigation, power generation, industrial use, municipal supply, etc.

2.3 Dead Storage — Storage below the lowest outlet level of a reservoir, which is not susceptible to release by usual outlet means.

2.4 Depletion Period — The period during which available storage in the reservoir is released or depleted for meeting various water demands. This period lies outside the filling period of a year.

2.5 Design Flood/Reservoir Design Flood — The magnitude of flood adopted for design purpose is called design flood. It may be the probable maximum flood (PMF) or the standard project flood (SPF) or a flood corresponding to some desired frequency of occurrence, depending on the type of structure and the extent of calculated risk the designer is prepared to accept.

2.6 Dry (Bad) Year — A year during which the precipitation or stream flow is less than that in the normal year.

2.7 Filling Period — The period during which inflow into the reservoir is likely to be more than the water demand and the surplus flow is impounded to build up the storage.

2.8 Flood Control Storage — Storage space provided in the reservoir for storing flood water temporarily in order to reduce peak discharge and to minimize flooding of downstream locations.

2.9 Full Reservoir Level (FRL) — The highest reservoir level which can be maintained without spillway discharge or without passing water through under sluices. This level is also called highest controlled water level.

2.10 Induced Surcharge Envelope Curve — This is a curve representing the maximum water level that would be allowed in a reservoir, at different rates of spillway discharges, when operating under the induced surcharge plan. This curve is drawn from a point, corresponding to the maximum permissible flood control release at the FRL, to a point corresponding to the elevation when all spillway gates are fully opened.

2.11 Induced Surcharge Storage — The storage between the full reservoir level (FRL) and the maximum water level (MWL) of a reservoir, which may be induced by regulating the outflow rates, after the reservoir is filled up to the FRL.

2.12 Live Storage — Storage capacity between the lowest outlet level of reservoir or minimum drawdown level (MDDL) to the highest controlled water level or full reservoir level (FRL). This storage is also called Live Capacity.

2.13 Maximum Water Level (MWL) — The level likely to be attained in a reservoir at the dam face, while negotiating the adopted design flood. The level is also called highest flood level, spillway design flood level or maximum water surface elevation.

2.14 Minimum Draw-Down Level (MDDL) — It is the lowest level up to which the reservoir may be depleted for meeting various needs. In power projects, releases are allowable up to MDDL only; instead of dead storage level, so as to maintain the minimum head required for power generation.

2.15 Normal (Average) Year — A year during which the precipitation or stream flow are within ± 20 percent of the long period average value.

2.16 Reservoir Routing — Flood routing is a process of determining theoretically the outflow pattern from reservoirs, for any given pattern of inflow, storage and tail water condition.

2.17 Rule Curve — Rule curve is the target level planned to be achieved in a reservoir, under different conditions of probabilities of inflows and/or demands, during various time period in a year.

2.18 Wet (Good) Year — A year during which the precipitation or stream flow is more than that in the normal year.

3 CLASSIFICATION OF RESERVOIRS

3.1 For the purpose of regulation, reservoirs are classified into following types:

3.1.1 *Single Purpose Reservoirs*

These reservoirs are developed to serve only one purpose, which may be flood control or any of the conservation uses such as irrigation, power generation, navigation, industrial use, municipal water supply, etc.

3.1.2 *Multi-purpose Reservoirs*

These reservoirs are developed to serve more than one purpose which may be a combination of any of the conservation uses with or without flood control.

3.1.3 *System of Reservoirs*

These consist of a group of single/ multiple purpose reservoirs, which may be operated in an integrated manner for optimum utilization of the water resources of the river system.

4 METHODS OF OPERATION OF RESERVOIRS

4.1 Following are some of the common methods of reservoir operation.

4.1.1 *Single Purpose Reservoirs*

a) *Flood control* — Operation of flood control reservoirs is primarily governed by the available flood storage capacity, discharge capacity of outlets, their location and nature of damage centers to be protected, flood characteristics, ability and accuracy of flood/storm forecast and size of the uncontrolled drainage area. A regulation plan to cover all the complicated situations may be difficult to evolve, but generally it should be possible according to one of the following methods:

   1) *Effective use of available flood control storage* — Operation under this method aims at reducing flood damages of the locations to be protected to the maximum extent possible, by effective use of flood control storage capacity available at the time of each flood event. Since the release under this plan would obviously be lower than those required for controlling the reservoir design flood, there is distinct possibility of having a portion of the

flood control space occupied during the occurrence of a subsequent heavy flood. In order to reduce this element of risk, maintenance of an adequate network of flood forecasting stations both in the upstream and downstream areas would be absolutely necessary.

2) *Control of reservoir design flood* — According to this method, releases from flood control reservoirs operated on this concept are made on the same hypothesis as adopted for controlling the reservoir design flood that is the full storage capacity would be utilized only when the flood develops into the reservoir design flood. However, as the design flood is usually an extreme event, regulation of minor and major floods, which occur more often, is less satisfactory when this method is applied.

3) *Combination of methods (1) and (2)* — In this method, a combination of the methods (1) and (2) is followed. The method (1) is followed for the lower portion of the flood reserve to achieve the maximum benefits by controlling the earlier part of the flood. Thereafter releases are made as scheduled for the reservoir design flood as in method (2). In most cases this plan will result in the best overall regulation, as it combines the good points of both the methods.

4) *Flood control in emergencies* — It is advisable to prepare an emergency release schedule that uses information on reservoir data immediately available to the operator. Such schedule should be available with the operator to enable him to comply with necessary precautions under extreme flood conditions.

b) *Conservation* — Reservoirs meant for augmentation of supplies during lean period should usually be operated to fill as early as possible during filling period, while meeting the requirements. All water in excess of the requirements of the filling period shall be impounded. No spilling of water over the spillway will normally be permitted until the FRL is reached. If any flood occurs; when the reservoir is at or near the FRL, release of flood waters should be affected, so as not to exceed the discharge that would have occurred when there been no reservoir. In case the year happens to be dry, the draft for filling period should be curtailed by applying suitable factors. The depletion period should begin thereafter. However, in case the reservoir is planned with carry-over capacity, it is necessary to ensure that the regulation will provide the required carry-over capacity at the end of the depletion period.

c) *Hydropower* — Reservoirs created for hydropower projects are typically small and designed primarily for power generation. They have sufficient pondage to supply water and accommodate diurnal or weekly demand fluctuations. For effective flood and sediment management, reservoir water levels are maintained near the Minimum Drawdown Level (MDDL) during high-flow periods, such as the monsoon season. Although this approach results in some loss of head, it significantly enhances sediment management, thereby extending the reservoir's useful life. This method is particularly beneficial for reservoirs located in the Himalayan region. During low-flow periods, reservoir water levels fluctuate between the Full Reservoir Level (FRL) and the MDDL, depending on inflow and power demand.

4.1.2 *Multi-purpose Reservoirs*

4.1.2.1 Operation of a multi-purpose reservoir should be governed by the manner in which various uses of the reservoir have been combined. While operating the reservoirs to meet the demands of end users, the priorities for allocation may be used as a guideline. In general five basic zones of reservoir space may be used in operating a reservoir for various functions. Typical storage allocations for various uses are indicated in Fig. 1. The various storage zones often identified are:

a) *Spill zone* — Storage space above the flood control zone between FRL and MWL is generally referred to as spill zone. This space is occupied mostly during high floods and the releases from this zone are trade-off between structural safety and downstream flood damages.

b) *Flood control zone* — This storage space is designated for temporarily holding excess water to mitigate downstream flood damage. It should be emptied as quickly as possible to accommodate the next flood event. This zone typically lies between the Full Reservoir Level (FRL) and a predefined level between the FRL and the Minimum Drawdown Level (MDDL) or Dead Storage Level (DSL).

c) *Conservation zone* — This storage space is used for conservation of water for meeting various future demands. This zone is generally between FRL and dead storage level.

d) *Buffer zone* — This is the storage space above dead storage level which is used to satisfy only very essential water needs in case of extreme situations.

e) *Dead Storage zone* — This is also called inactive zone. This is the lowest zone in which the storage is meant to absorb some of the sediments entering into the reservoir. The storage in this zone is not susceptible to release by the in-built outlet means.

4.1.2.2 The general methods of operation of reservoirs with these multiple storage spaces are described below:

a) *Separate allocation of capacities* — When separate allocations of capacity have been made for each of the conservational uses, in addition to that required for flood control, operation for each of the function shall follow the methods of respective functions. The storage available for flood control could, however, is utilized for generation of secondary power to the extent possible. Allocation of specific storage space to several purposes within the conservation zone may sometimes be impossible or very costly to provide water for the various purposes in the quantities needed and at the time they are needed.

b) *Joint use of storage space* — In multipurpose reservoir where joint use of some of the storage space or storage water has been envisaged, operation becomes complicated due to competing and conflicting demands. While flood control requires low reservoir level, conservation interests require as high a level as is attainable. Thus, the objectives of these functions are not compatible and a compromise will have to be effected in flood control operations by sacrificing the requirements of these functions. In some cases parts of the conservational storage space is utilized for flood moderation, during the earlier stages of the monsoon. This space has to be filled up for conservation purposes towards the end of monsoon progressively, as it might not be possible to fill up this space during the post-monsoon periods, when the flows are insufficient even to meet the current requirements. This will naturally involve some sacrifice of the flood control interests towards the end of the monsoon.

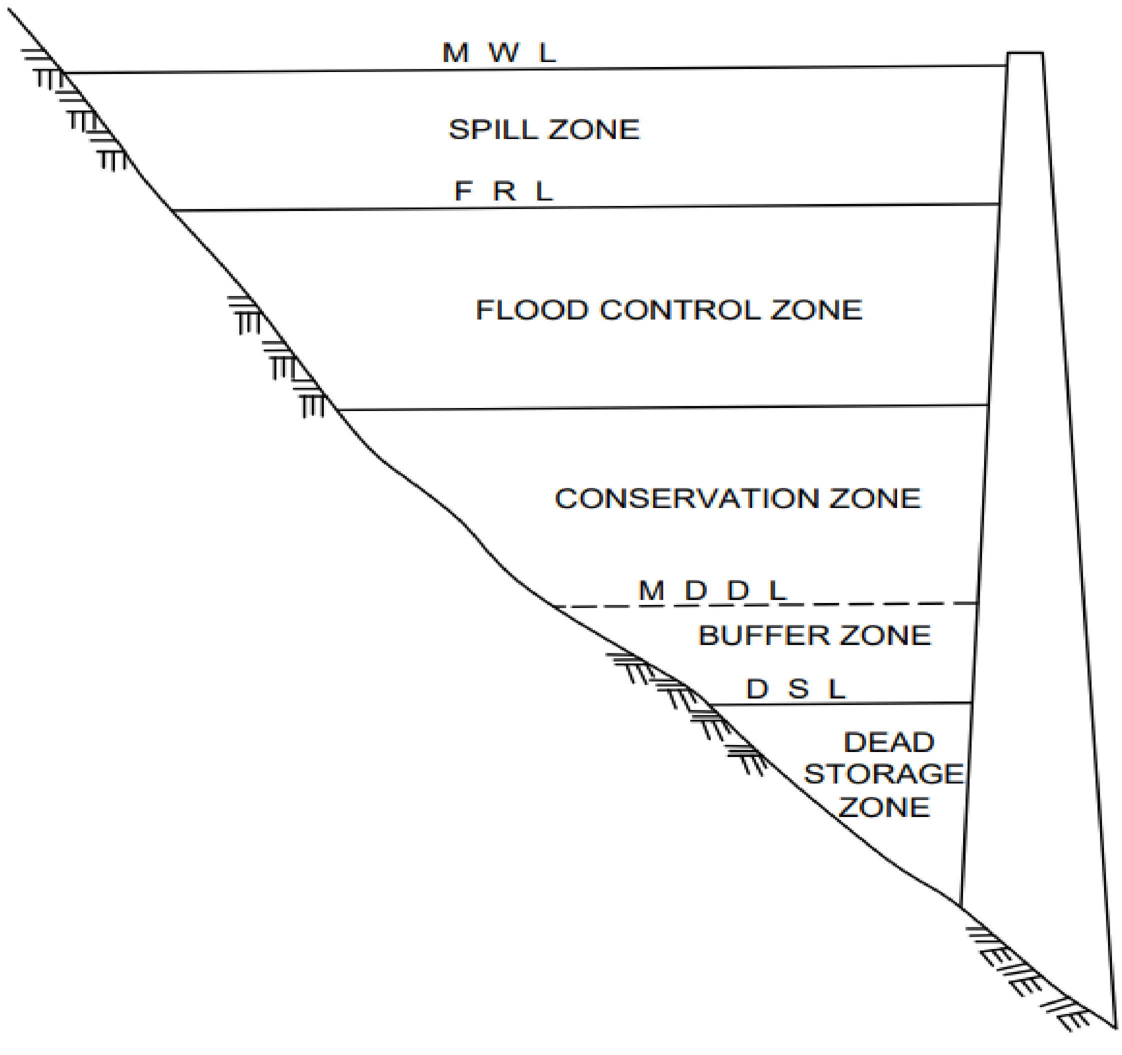

FIG. 1 RESERVOIR STORAGE ALLOCATION ZONES

4.1.2.3 The concept of joint use of storage space, with operational criteria to maximize the complementary effects and to minimize the competitive effects requires careful design. Such concepts, if designed properly, are easier to manage and will provide better service for all requirements. With the advancement of system analysis techniques, it is easy now to carefully design the joint use in a multi-purpose reservoir.

4.1.3 *System of Reservoirs*

In case of system of reservoirs, it is necessary to adopt a strategy for integrated operation of reservoirs to achieve optimum utilization of the water resources available and to benefit best out of the reservoir system.

4.1.3.1 In the preparation of regulation plans for an integrated operation of system of reservoirs, methods applicable to separate units are first applied to the individual reservoirs. Modifications of schedules so developed should then be considered by working out several alternative plans. In these studies optimization and simulation techniques may be extensively used with the application of computers in water resources development. The method features usually considered for integrated operation of, reservoirs are given below:

a) *Flood control regulation* — The basin-wise flood conditions are considered, rather than the condition of the individual sub-basins. The occupancy of flood reserves in each of the reservoirs, distribution of releases among the reservoirs and bank-full stages at critical locations should be considered simultaneously. For instance, if a reduction in outflows is required, it should be made from the reservoir having the least capacity occupied or has the smaller flood run-off from its drainage area. If an increase in release is possible, it should be made from the reservoir where the percentage occupancy is the highest or relatively a higher of flood run-off is occurring. Higher releases from reservoirs receiving excessive flood run-off may be thus counter balanced, particularly in cases of isolated storms, by reducing releases from reservoirs receiving relatively less run-off.

b) *Conservation regulation* — The current water demands for various purposes, the available conservation storage in individual reservoirs and the distribution of releases among the reservoirs, should be considered to develop a co-ordinated plan to produce the optimum benefits and minimize water losses due to evaporation and transmission.

5 PREPARATION OF RULE CURVES

A rule curve is generally based on detailed sequential analysis of various critical combinations of hydrological conditions and water demands. These should be prepared in accordance with the methods described in **4** and should indicate reservoir levels and releases during different times of the year, including operational policies. Rule curves once prepared should be constantly reviewed and, if necessary, modified so as to have the best operation of the reservoirs.

The operational decisions are based on the current state of the system and time of the year, which account for the seasonal variation of the reservoir inflows. A simple rule curve should base the release of the next time period solely on the current storage level and the current time period of the year. A more complex rule curve should consider storages in other reservoirs, specific downstream control points and the forecasted inflows into the reservoir.

5.1 Single-Purpose Reservoirs

a) *Flood Control* — When the protected area lies immediately downstream of the reservoir, the flood control schedules would consist of releasing all inflows up to the safe channel capacity. The methods followed in all cases are the same as given in **4.1.1** (a) and are detailed below:

1) *Method (1) of* ***4.1.1*** *(a)* — When there is appreciable uncontrolled drainage area between the dam and the locations to be protected, operation under method (1) of **4.1.1** (a) should consist of keeping the discharge at the damage centre within the highest permissible stage or to ensure only a minimum contribution from the controlled area when above this stage. Operation under this method aims at reducing the damaging flood stages at the location to be protected to the maximum extent possible with the flood control storage capacity available at the time of each flood event. In order to accomplish this result, it is essential to have an accurate forecast of flood flows into the reservoir and the local inflows into the stream below it for a period of time sufficient to fill an empty reservoir. This is obviously an ideal case. It is difficult to forecast reliably and precisely in quantitative terms the rainfall. Thus, there is always the risk of facing difficulty in regulation of run-off from subsequent storms. In order to reduce this element of risk, maintenance of an adequate network of flood forecasting stations both in the upstream and downstream area of the project becomes absolutely necessary. To account for the uncertainly in forecasting the flows, the forecasted flows may be multiplied by a contingency factor for arriving at release decision. The contingency allowance should be greater than one for flood control and less than one in case of conservation.

2) *Method (2) of* ***4.1.1*** *(a)* — The operation schedules based on method (2) of **4.1.1** (a) should consist of releases assumed for design flood conditions, so that design flood could be controlled without exceeding the flood control capacity. The operation consists of discharging a fixed amount, which may be subject to associated flood, storage and outflow conditions, such that all excessive inflows are stored as long as flooding continues at specified locations.

3) *Combination of Methods* — When both local and remote locations are to be protected, schedules based on the combination of methods (1) and (2) are usually more satisfactory. In this method, method (1) that is, ‘ideal operation’, may be followed to control the earlier part of the flood to achieve the maximum damage reduction during moderate flood. After the lower portion of the flood reservoir is filled, the regulation may be based on the method (2) that is, ‘based on control of design flood’, so as to ensure more control of major floods. In most cases such a combination of methods (1)

and (2) would result in the best overall regulation as it combines the good points of both the methods.

In all cases, procedure for releasing the stored water after the flood has passed would also be laid down in the schedule, in order to vacate the reservoir as quickly as possible for routing subsequent floods. In this way, variation in releases may be made depending on the prevailing, as well as the anticipated conditions of storm/rainfall and run-off.

b) *Conservation* — The operational schedule of a conservation reservoir would usually consist of two parts, one for filling period and the other for the depletion period. For each project it will be necessary to prepare rule curves separately for the filling period and for the depletion period. The rule curves for filling period may be developed from a study of the stream flow records over a long period. These will show the limits up to which reservoir levels are to be maintained during different times of the filling period for meeting the conservational commitments. The most critical release schedule, which provides for only minimum required flow, is specified by the rule curve, in order to provide for acceptable storage or desired contingency allowances during that critical period. When regulation is guided by such curves, it' would be apparent when restrictions are to be imposed on utilization.

5.2 Multi-purpose Reservoirs

5.2.1 When separate space allocations for different uses, including flood control are made, preparation of schedules will rarely pose any special problems as the operation for specific uses will usually be independent of each other and will follow the schedules of single purpose operation for respective functions.

5.2.2 In multi-purpose reservoirs, which have flood control as main purpose besides other conservational demands, operation should be done in two ways as discussed below:

a) *Permanent allocation for flood space* — Permanent allocation of space for flood control at the top of conservation pool may be kept in the regions where flood can occur at any time of the year. A study based on historical or generated flood would indicate the storage space required during different periods.

b) *Seasonal allocation for flood space* — Seasonal allocation of flood control space during flood season depends upon magnitude of flood likely to occur. Thereafter, this space should be utilized for storing inflows for conservation uses. The operation plan to this effect should be prepared based on study of historic and/or generated floods.

c) *Joint use of storage space* — For projects envisaging joint use of some of the space for flood control as well as conservational needs, flood control operation should usually be carried out by using part of the conservational storage, which shall be progressively reduced as the season advances. The regulation schedule for the conservation phase should then consist of an additional rule curve, indicating levels which may not be exceeded at any particular time of the monsoon season, except for the purpose of storing flood water temporarily. Normal filling and dry weather release curves for the conservation use should be drawn as in the case of single purpose reservoir.

5.3 System of Reservoirs

5.3.1 Regulation schedules for reservoirs operated as part of system should be prepared separately for each reservoir, based on an integrated plan of operation and considerations discussed in **4.1.3**. When determining rule curves among the various reservoirs in the system, it should, however, be noted that critical conditions may not be attained in all projects in the system at the same time. In addition, when considering two reservoirs in series, the upstream reservoir release schedule will bias the development of a rule curve at the downstream one. For parallel reservoirs, the best rule curve may require apportionment of releases from two or more reservoirs, based on available storage capacity or other relevant criteria.

Because of the complex interdependence of system operating rules, it is usually necessary to simulate the system operation to determine a workable regulating schedule. After initial curves are estimated, these independent estimates should then be simulated with a hypothetical operation of the system, to ensure that system targets are satisfied, project objectives are maximized and an equitable distribution of water within the system is maintained. Thus an iterative procedure would be required for establishing operation rules that attain these goals. The following points are generally kept in view, while developing rule curves for a system of reservoirs.

a) *Balancing of reservoir* — As the balancing of reservoirs is an important consideration, the concept of ‘index levels’ may be employed, as an aid to making release decisions to keep the reservoir system in a balanced state. The reservoir storage allocation may be subdivided into flood control, conservation, and one or more buffer zones. The top of each of these zones has a corresponding reservoir level, which is assigned an integer or index level. When the index levels in all the reservoirs coincide, the system is in balance. In reservoirs operation, if the current index levels are unbalanced, the releases for the subsequent interval are adjusted as far as possible to restore equilibrium. The index levels are also useful in the regulation of parallel reservoirs with the equivalent reservoir concept.

b) *Apportioning of storage and releases* — For an explicit reservoir operation rule that specifies releases of each reservoir as a function of storage volumes, time period and inflows, there are three basic characteristic components for an operation policy. These involve apportioning of storage and release of water among purposes, among time periods and among reservoirs. The governing rules for apportionment are generally as follows:

1) *The space rule* — The release among parallel reservoirs be planned in such a way that the ratio of space available in each reservoir to that in all reservoirs equals, as far as possible, the ratio of predicted inflow into each reservoir in the remaining period of drawdown refill cycle to that in all reservoirs. Hence, the probability of some reservoirs being spilled while others being empty are minimized.

2) *The pack rule* — It is a flexible rule that specifies useful releases in excess of current demand, perhaps to generate clump energy instead of possible future spills.

3) *The hedging rule* — It accepts current shortage to avoid large shortages in future and is to be adopted when cost functions for shortages are nonlinear.

5.4 System Engineering Techniques

System engineering may be defined as the art and science of selecting from a large number of feasible alternatives, involving substantial engineering content, that particular set of actions which will best accomplish the overall objectives of the decision makers, within the constraints of law, morality, economics, resources, and loss governing the physical life and other natural sciences. Since system engineering techniques have the potential of significantly improving the water resources planning and management process, use of these techniques is increasing rapidly. A variety of these techniques, computational algorithms and increased computer capabilities together with the knowledge of hydrology, hydraulics, economics and environmental engineering could be used for evaluating the performance of a water resource system and problems associated with operation of reservoirs. Various system engineering techniques are available for solving problems associated with reservoir operation. Among these simulation and optimization are the most commonly used techniques.

5.4.1 *Simulation*

5.4.1.1 Simulation is perhaps the most widely used method for evaluating alternatives due to its mathematical simplicity and versatility. Simulation is a surrogate for asking ‘what if’ and thereby providing a rapid means for evaluating the anticipated performance of the system. The advent of high speed computers has enabled development of detailed simulation programs to describe the operation of a water resource system, Simulation methods do not identify the optimal design and operating policy but they are excellent means of evaluating the expected performance resulting from any design and operating policy.

5.4.1.2 Simulation may be deterministic or stochastic. If the system is subject to random input events, or generates them internally, the model is said to be stochastic. If no random components are involved, the model is said to be deterministic. The stochastic simulation is a powerful tool for reservoir operation studies. For example, in reservoir operation studies, the reservoir may be empty, hall filled or full in the beginning, the stream flow and rainfall are random and so are the demands and, therefore, stochastic simulation is better suited for reservoir operation problems.

5.4.1.3 Simulation is time sequenced or event sequenced. In a simulation model a fixed time interval is selected and it examines the state of the system (flows, storage volumes, demands, etc,) at successive time intervals. The increment should be small enough so that no significant information is lost. But the smaller the time increment, larger will be the computation time; on the other hand, if the time increment large, the chance of missing an event of interest increases. Thus a judicious choice of time increment is necessary in time sequenced models.

5.4.1.4 A number of general purpose simulation programs are available at present, which may be used to analyse virtually any configuration and purpose for evaluating various strategies for the operation of a reservoir or system of reservoirs. Most of the reservoir simulation programs have been developed in other countries where geographical, economic and social conditions considerably differ from those encountered in India. Hence direct adoption of these models without a critical assessment of the hypotheses or simplifying assumption is to be discouraged. These may, however, be advantageously used with suitable modifications to suit local conditions.

5.4.2 *Optimization*

Optimization is the science of choosing the best solution based on mathematical logic for finding the best operation policies (decision set) without having to evaluate all possible alternatives. Optimization implies use of an optimisation model in conjunction with an appropriate optimization algorithm.

5.4.2.1 The choice of objective function is a very important decision in an optimization formulation which is governed by the nature of problem and the computational facilities available. For example, the objective for flood control operation may be to minimize the flood damage or to minimize the flows which are greater than the safe carrying capacity of the channel. Similarly for conservation operation the objective function may be to minimize the deviations from the demands or to maximize the reservoir attainable water level for maximization of firm power.

5.4.2.2 Out of the various optimization techniques, linear programming and dynamic programming have been most commonly solving reservoir operation problems.

a) *Linear programming* — Linear used for programming (LP) is concerned with solving special type of problems where all the constraints and objective function to be optimized are linear. Since most of the constraints involved in solving reservoir operation problems are non-linear, considerable care should be taken for linearization of these functions. Linearization of a non-linear function over a wide range with a single constant may result in a significant error. Therefore, adequate number of adjustments (iterations) should be made to ensure that the linearized coefficients are adjusted until they are essentially equal to the derivatives of the non-linear functions they represent at the point of optimality.

b) *Dynamic programming* — Dynamic programming technique has been widely accepted for formulation of reservoir operation policies mainly because of its ability to accommodate non-linear functions. This technique is based on multi-stage decision process. For example, in a reservoir operation problem, the reservoir storage at any time is a typical choice of state variable, the release from the reservoir may be the decision variable and the time is a natural choice of control variable. Therefore, knowing the benefit or cost function the recursive equation may be established.

NOTE — Discrete differential dynamic programming (DDDP) has been found more suitable for reservoir operation problem because it is an iterative procedure in which the recursive equation of dynamic programming is solved within a restricted set of quantified values of the state variables. The initial solution of the problem is assumed known. To obtain good convergence, the increment to the state variable should be chosen so that entire feasible region could be inspected, if required. Several iterations with a small increment may be allowed at the end of each computation cycle to improve the value of objective function.

5.5 Spillway Gate Regulation Schedules

5.5.1 In the operation of gated spillways the reservoir is sometimes maintained at its FRL until all gates are opened, after which outflow would be uncontrolled as long as the inflow flood exceeds the capacity of the spillway at FRL. Under this plan of operation when the reservoir is at FRL or near it, the spillway releases may be larger than the inflows, since the dampening effect of valley storage within the reservoir reach is practically non-existent and the flood waves originating from the upstream areas travelling faster may synchronize with those from the local areas around the reservoir to produce higher peak discharges.

5.5.2 In order to mitigate damage that may occur under this mode of operation, reservoirs, when full or nearly full, should be so operated that (a) peak outflow rates during damaging floods do not exceed inflow rates of the corresponding floods that would have occurred at the reservoir site before construction of the dam and (b) the rate of increase in outflow does not constitute a major hazard to downstream interests. The above objectives may be accomplished by one or both of the following procedures:

a) When the anticipated inflow is likely to raise the reservoir level above FRL, the opening of spillway gates will be initiated before the reservoir attains this level and the outflow will be gradual and limited to acceptable rate of increase. This method of operation achieves the objectives but with some risk of not attaining the FRL subsequently.

b) In the other method, the induced surcharge storage space above the FRL will be utilized to effect partial control over outflow rates after the reservoir has attained the FRL. This is done by raising all gates initially by small increments thus forcing all inflows in excess of the spillway capacity at the selected gate opening into surcharge storage which will of course be evacuated as rapidly as the prevailing conditions warrant. Upon completion of drawdown to the FRL, the regular schedule for release of stored water should be followed.

NOTE — In projects, where water level is not permitted to rise above FRL, the method (a) is the only applicable.

5.5.3 Development of spillway gate regulation schedules for reservoirs, both with and without induced surcharge storage space, are given in Annex A.

5.5.4 It is of utmost importance that the schedules so developed are used to route the spillway design flood for determining the adequacy of the MWL which may often be based on old operation plans.

5.6 Ungated Spillway

There is no possibility of any regulation in reservoirs having ungated spillways except some adjustments that can be brought out by the outlets operations.

6 REAL TIME OPERATION OF RESERVOIRS

6.1 The operation of reservoirs based on fixed operation rules, which are developed taking into account the demands and historic/synthetic time series data, often poses difficulties in making appropriate reservoir release decisions due to the uncertainty in the probability of occurrence of the flood event exactly similar to the past event, though the demands could be fairly stable. Operation of reservoirs, therefore, becomes an operation in real time in which water control decisions have to be taken at each instant of time.

6.2 In real time reservoir operation control decisions are made quickly, for a finite future condition of the system at that instant of time and the forecast of the likely inputs over this time horizon depending on the purpose of the reservoir operation that is flood control, conservation, irrigation and/or power releases.

6.3 Use of systems engineering techniques using computer technology should be employed and a computer model be developed for real time operation. Some of the important aspects of real time reservoir operation are listed below:

a) Collection of catchment hydrological data and water demand data and transmission of the data to the operation manager at the control station through suitable logistics such as hydrological sensors, data loggers and telemetry network;

b) Availability of a computer system at the control station;

c) A real time data base management system; and

d) A computer model having capability of flow forecast, control decisions forecast with flexibility for modified data entry and updating, preferably in an interactive mode, in shortest possible execution time.

e) Downstream warning system to issue alert for locations vulnerable to large releases from the project.

f) Flood simulation studies for the downstream locations corresponding to different releases (regulated / un-regulated / dam break) from the project.

g) Inundation mapping for downstream locations to identify vulnerable locations corresponding to different releases (regulated / un-regulated / dam break) from the project.

h) Himalayan regions are most vulnerable to multiple kinds of disasters such as Landslides, Cloudbursts, Flash floods, Earthquakes, Avalanches, Glacial Lake Outburst Flood (GLOF), and Landslide Lake Outburst Flood (LLOF) etc. To reduce the risk to the life and property due to such disasters a comprehensive Early Warning System (EWS) need to be implemented.

7 DATA COLLECTION AND ANALYSIS

7.1 An adequate plan for collection and analysis of hydrological data should be developed and adopted in order to ensure efficient operation of reservoirs, particularly during the monsoon period.

7.2 A suitable network of rainfall and river gauging stations should be established according to relevant Indian Standards in the project area at the investigation stage. This would provide sufficient basic data to evolve a reliable programme of flood forecasting for use in the reservoir operation.

The instrumentation for the purpose should include hydrological sensors with capability of in-situ recording and compatibility with telemetry network for real time operation of reservoirs.

7.3 The number and distribution of ordinary and self-recording raingauge station should be decided based on the storm characteristics and topography of the region and the requirements of flood forecasting.

7.4 An adequate number of river gauging stations should be set at key locations according to relevant Indian Standards to provide satisfactory information on current river stages/flows upstream and an index to the total inflow to the reservoir. In case of flood control reservoirs, a sufficient number of river gauging stations should be set up below the dam to provide data at the locations to be protected. All stream gauging stations should also be equipped with instruments for measuring rainfall.

7.5 Manual and/or automatic reservoir gauges should be installed for obtaining current reservoir levels. Reservoir levels should be recorded at regular intervals, say every 24 hours or as required. During flood times, reservoir gauges should be observed at closer intervals, say once in 3 hours or even more frequently.

7.6 A close co-operation should be maintained with the nearest office of the Indian Meteorological Department to obtain the data on current weather situation and its expected development. In case of major projects it would be necessary to have a separate meteorological unit which will collect the necessary data and interpret them to the engineer-in-charge of operations.

7.7 The mode and frequency of communication of basic data recorded by reporting stations should be decided based on the requirements of such data at the given time. During flood periods, reports at shorter interval (usually 6 hourly or less) are required. Manually based and/or semi-automatic data handling systems are generally adequate for the single project system or relatively small multi-project systems. Installation of automatic data handling system in addition to manual or semi-automatic system may be necessary for reducing the transmission and processing time of vast data from various sources. The data transmission media such as telephones, mobiles, telemetry, GSM/GPRS communication, Radio Wave communication, VSAT communication system etc. should be used for communication of data. All these types of transmission media may be used either singularly or in combination. Planning and design of a particular system should consider each of these alternatives prior to selecting the one or combination of these that best meets the overall requirement of the reliable data system, particularly in the storm period.

7.8 The hydro-meteorological data collected during storm periods should be analyzed by suitably trained personnel. Use of computer at the analyzing centre may be useful in providing accurate information on prevailing and anticipated flood stage/flows at all the locations of interest. Forecast of inflow into the reservoir and the regulation plans during storm period should be developed usually every six hours or as required using the advancements in techniques. Based on the results of this analysis, the operations should be determined by the engineer-in-charge of the reservoir system operation taking into consideration the operation schedule. In case of real-time data collection, computers are essential for data handling, manipulation and analyzing project regulation schemes.

7.9 During non-monsoon period, reservoir operation usually consists of release of water from conservation storage for various uses, considering actual requirements and storage conditions. As such, it requires less attention. This period, therefore, should be devoted to investigating possible technical improvements in the hydro-meteorological data collection and transmission network, application of modern technical know-how such as system engineering techniques, development of computer models and training of personnel to facilitate reliable and optimum system regulation in addition to the normal works pertaining to reservoir regulation.

7.10 Capacity surveys should be done to compute the actual storage capacities at various levels at regular intervals depending on the rate of sedimentation. The higher the rate of sedimentation, the greater will be the frequency of survey. Capacity survey of reservoirs may be carried out once in 3 to 5 years or when the loss of capacity is 5 percent, whichever is earlier.

7.11 In order to facilitate and to keep up-to-date information for the operation of reservoirs, a proper record of all data pertaining to reservoir operation should be maintained. For large reservoir systems a suitable computerized data base management system is essential for storage retrieval of data/information. Data received from the data collection network should be stored in the data base. The data base should also include flow forecast and project operation data and should be designed for providing both graphical and tabular displays. Various proformas for data compilation as per the requirements of system operation may be designed. Three sample proformae for compiling information are given in this standard. Proforma 1 deals with collection of rainfall and stream flow data. Proforma 2 deals with the computations of forecasting inflows based on rainfall-runoff correlation and unit hydrograph. Proforma 3 contains data relating to daily reservoir operations.

ANNEX A

(*Clause* 5.5.3)

DEVELOPMENT OF SPILLWAY GATE REGULATION SCHEDULES

A-1 GENERAL

A-1.1 In many earlier projects where the FRL and MWL are the same and even in projects with provision for induced surcharge operation, it may be imperative to utilize a portion of the storage space below the FRL in order to meet the requirements of 5.5 under operating conditions. The volume of inflow, however, must be predicted before releases can be determined. Although forecasting of runoff from reports of rainfall and river stages/discharges provides a sound basis for operation, schedules for use in spillway design and by operational staff under emergency conditions require a more conservative approach. During very severe floods communications may fail and the only information available at the dam may be reservoir water levels and the rate of rise. The minimum volume of inflow to be expected during flood at any instant may be predicted by assuming that the inflow has crested for computing the volume under the recession curve of the hydrograph. The assumed recession curve should, however, be steeper than the normal observed recession for conservative results and may usually be patterned after the spillway design flood recession. Once the minimum volume expected with a given inflow is known, the outflow required to limit storage to the capacity available may be readily determined.

A-2 PROCEDURE

A-2.1 A complete schedule of releases in the form of a chart may be developed that will allow the outflow to be regulated on the basis of the current inflow and storage space available by making a series of computations with various assumed values of inflows and amounts of storage available as below:

a) Calculate a constant T_s (in days), that is the time required for the discharge to recede to $1/2.7$ of its initial value, by reading from the assumed recession curve.

b) Compute $\frac{S_A}{Q_2}$ values for the project, by multiplying T_S with the $\frac{S_A}{Q_2}$ values derived by assuming T_S = 1. The $\frac{S_A}{Q_2}$ values corresponding to T_S = 1 for a set of $\frac{Q_1}{Q_2}$ ratios are given below:

$\frac{Q_1}{Q_2}$	$\frac{S_A}{Q_2}$ $(for\ T_s = 1)$
1.2	1363
1.6	10023
2.0	23657
2.5	45006
3.5	96163
10.0	548856

Where S_A is the amount of storage required in cubic metres to impound a flood inflow of Q_1 (in cumecs) with Q_2 (in cumecs) as the constant release from the reservoir.

c) For an assumed range of inflows Q_1 (for example 3000 m^3/s to spillway design flood peak) compute a set of Q_2 for the entire set of $\frac{Q_1}{Q_2}$ ratios by dividing Q_1 by $\frac{Q_1}{Q_2}$.

d) Lastly compute a set of S_A values for each selected value of Q_1 by multiplying the project $\frac{S_A}{Q_2}$ values by Q_2.

A convenient computational form is given in Table 1.

A family of curves S_A versus Q_2 such as in Fig. 2 may be then plotted for each assumed values of inflow Q_1.

Table 1 Computation for Spillway Gate Regulation Schedule

[*Clause* A-2.1 (d)]

$\frac{Q_1}{Q_2}$	Project $\frac{S_A}{Q_2}$	$Q_1 = 3000\ m^3/s$ $Q_2 = \frac{Q_1}{col\ (1)}$	$S_A = col\ (2) \times col\ (3)$	$Q_1 = 6000\ m^3/s$ $Q_2 = \frac{Q_1}{col\ (1)}$	$S_A = col\ (2) \times col\ (3)$
(1)	(2)	(3)	(4)	(5)	(6)

NOTE — Columns will extend with various values of Q_1 considered.

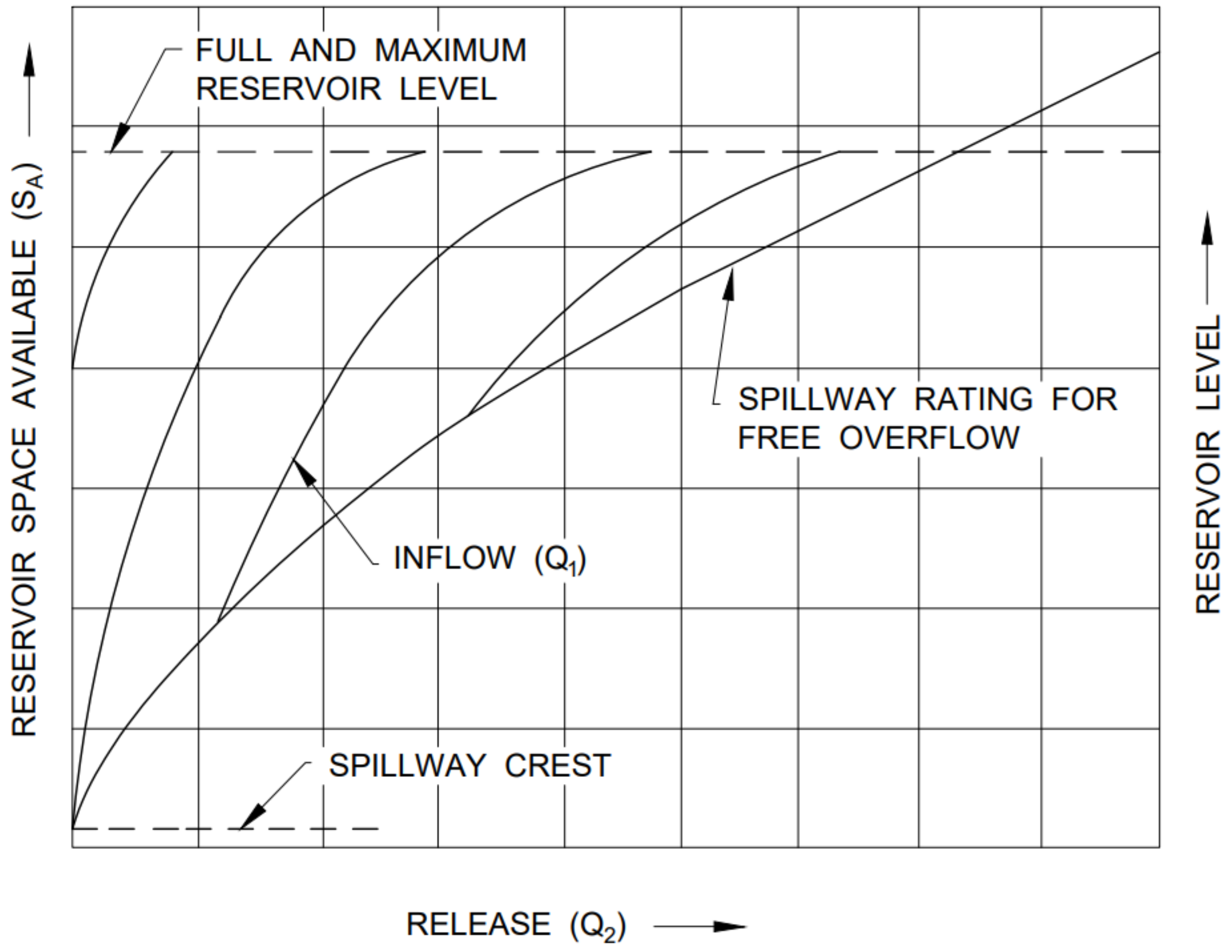

FIG. 2 SPILLWAY GATE REGULATION SCHEDULE WITHOUT INDUCED SURCHARGE

For reservoirs having no induced surcharge storage provision, S_A values can be transformed into reservoir elevations by subtracting S_A values from the storage capacity at FRL and reading corresponding elevation values from the elevation-capacity curves.

In case of reservoir with induced surcharge provision, the points located as above may be raised vertically by the amount of surcharge storage permissible at the particular outflow as shown in Fig. 3. Thus the point b corresponding to the schedule with induced storage will be obtained by raising point a of the dotted curves (without induced storage) by an amount cd, the amount of surcharge storage at the given outflow.

These curves are useful in deciding the required releases for reservoir regulation based on the inflow and available storage space at any instant.

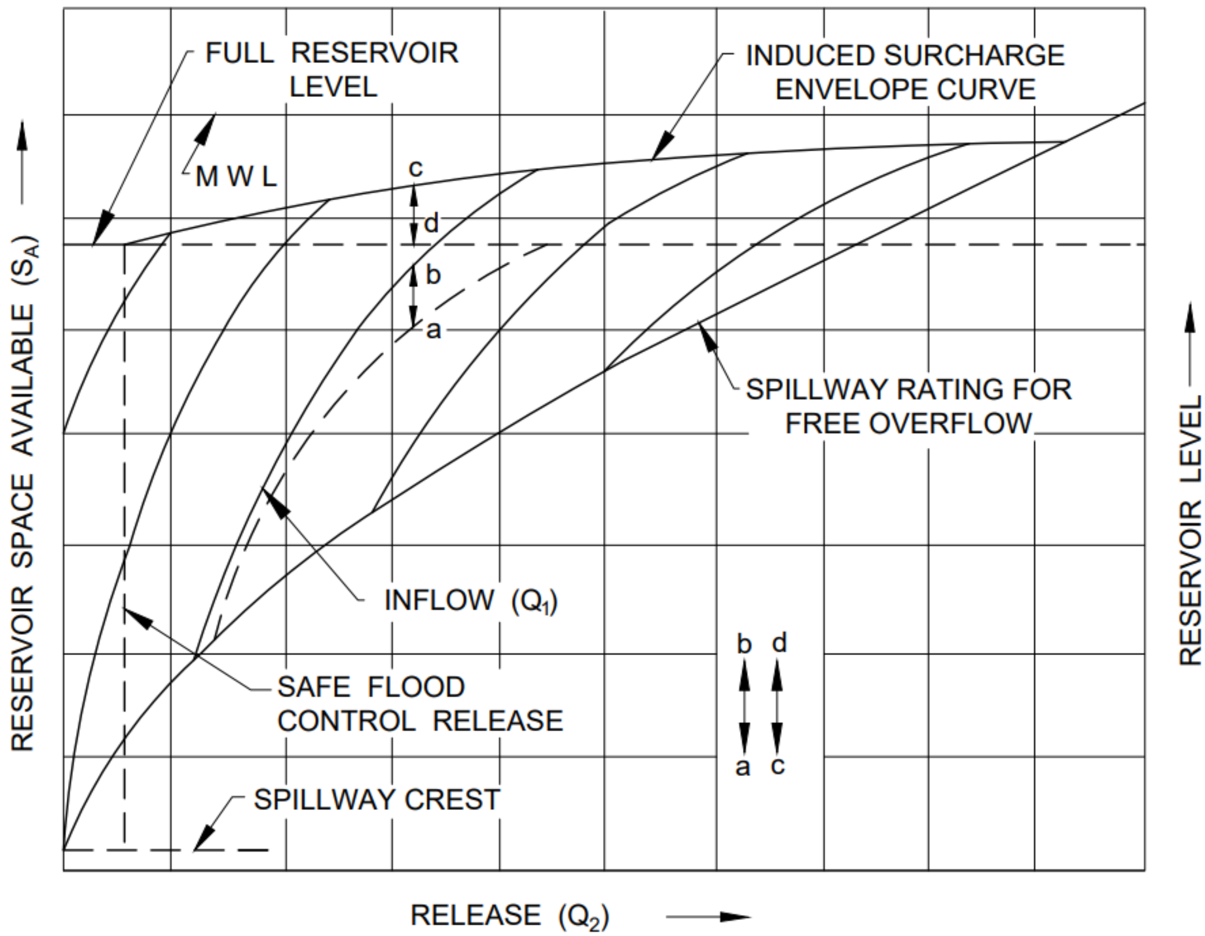

FIG. 3 SPILLWAY GATE REGULATION SCHEDULE WITH INDUCED SURCHARGE

Proforma 1 — Rainfall and Streamflow Data

(*Clause* 7.11)

Name and Location of
Raingauge . . . .
River gauge . . . .
R. L. of Zero of gauge . . . .

Date	**Time in Hours**	**Observed rainfall in mm**			**Catchment rainfall**	**Gauge in meters**	**Discharge Estimated/Observed m^3/s**	**Remarks**
		Stn. 1	Stn. 2	Stn. 3				

Proforma 2 — Forecast Computation Sheet

(*Clause* 7.11)

(Using Rainfall, runoff co-axial relations and unit hydrographs)

Stream and Station	**Runoff Computations**	**Discharge in m^3/s**													
		Date 6		7		8		9		10		11		12	
		8 AM	8 PM	8 AM	8 PM	8 AM	8 PM	8 AM	8 PM	8 AM	8 PM	8 AM	8 PM	8 AM	8 PM
Station A on river X	Antecedent precipitation …………………………….cm	Hydrograph (Previous period)													
	Total Duration ………………h	12 h unit hydrograph													
	Total rain………………… cm Total runoff ……………….cm	Direct Runoff													
	Prev. runoff………………. cm Runoff increment ………... cm	Total flow													
Local area between Station A and Station B	Antecedent precipitation ……………………………cm	Hydrograph (Previous period)													
	Total Duration ………………h	12 h unit hydrograph													
	Total rain…………………. cm Total runoff ……………….cm	Direct Runoff													
	Prev. runoff………………. cm Runoff increment ………... cm	Total flow													
Station B on river X	Routing	Routed flow from Station A													
		Local flow													
		Total flow													
		Adjusted food													
………… (Basin)	Computed …………………………… (Month) (Date) (Year)	For Storm beginning…………………… (Hour) (Month) (Date)						Computed by ………………………………………… Checked by………………Time……………………							

Proforma 3 — Daily Reservoir Operation Data

(*Clause* 7.11)

Date	**Time in h**	**Pool elevation in metres above MSL**	**Withdrawals m^3/s**	**Spillway Discharge**[1)]	**Estimated Inflow**	**Dam Site Weather**					**Remarks**
						Precipitation, mm	Temperature		Wind		
							Max	Min	Speed km/h	Direction	
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)

[1)] Sluices, crest bays and power house separately.