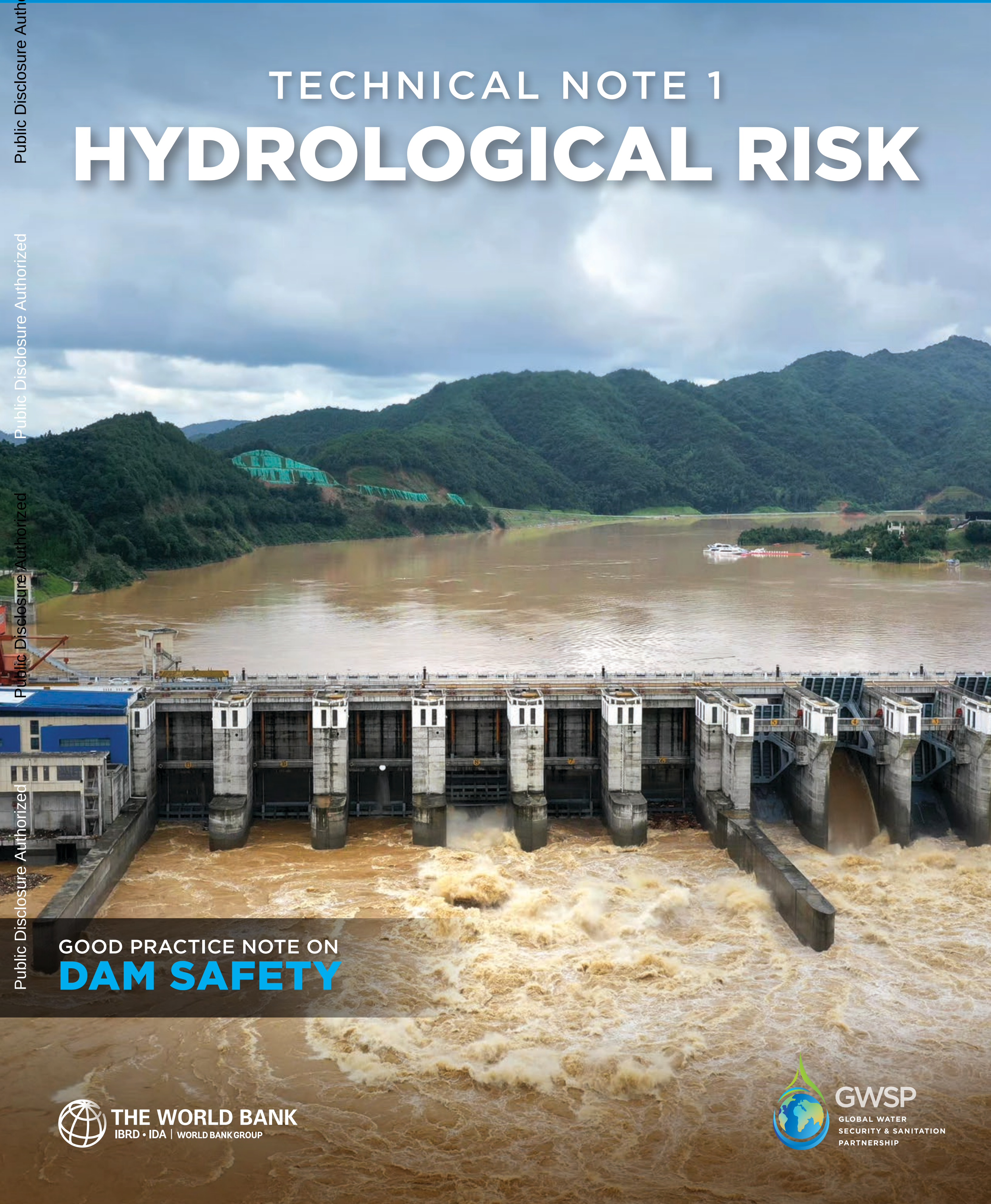
SAFETY OF DAMS AND DOWNSTREAM COMMUNITIES

TECHNICAL NOTE 1

HYDROLOGICAL RISK



GOOD PRACTICE NOTE ON

DAM SAFETY

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Technical Note 1: Hydrological Risk

Contents

Objective and Scope of This Note

This Technical Note contains a level of technical detail that nonspecialists can use for guidance in addressing the hydrological aspects of dam projects early in the project preparation. It is intended to raise awareness and inform specific studies and investigations, as appropriate, during project preparation and implementation. The material presented should be used to prepare terms of reference on such studies and to assess the adequacy of methodology proposed by consultants in response to tenders for advisory services. It is recommended that, reading the Note, the client and the World Bank project teams will assess the required level of hydrological expertise in the teams.

The hydrological subjects this Note covers are typical in World Bank-supported operations. There are several other subjects pertaining to hydrology that it does not cover. Enlarging the scope to those subjects would defeat the objective and turn the Note into a handbook on the vast discipline of hydrology. The same selective effort has been applied in choosing the references that the reader can consult to focus on specific subjects. For that reason, the list has been limited to essential references that provide general guidance on required hydrology studies, whereas the additional sources complement the general guidance with references dealing with specific aspects of the project hydrology.

Hydrology and dam safety management are dynamic subjects featuring continuing advances. The readers of this Note are encouraged to provide the World Bank with feedback and suggestions that the organization can consider for a future update.

Background

The term *hydrological risk* may have different interpretations depending on the type of project being considered and the reasons for the assessment of risk. For example, in a hydropower project, hydrological risk is often understood as the risk of having inflow that is insufficient to support the desired level of electricity generation during the operations phase of the station life cycle.

In the **design** phase of the dam life cycle, hydrological risk guides the considerations related to the sizing of discharge capacity of the dam, ensuring that the dam will not fail during the multidecadal operations phase.

During the **construction** phase, the principal hydrological risk being considered is the magnitude and likelihood of inflow that cannot be safely passed through or around the construction site by the flood diversion facility and may cause breach of the cofferdam and downstream flooding, as well as delay of the works and/or increase their cost.

A similar aspect of hydrological risk is of concern during the operations phase of the dam life cycle. Inability of flow control equipment to pass the inflow, either because of the insufficient installed discharge capacity or because equipment failures may lead to dam overtopping, which may cause structural failure of the dam and uncontrolled catastrophic release of water stored behind it. This Technical Note discusses these aspects of hydrological risk that may affect the dam's safety.

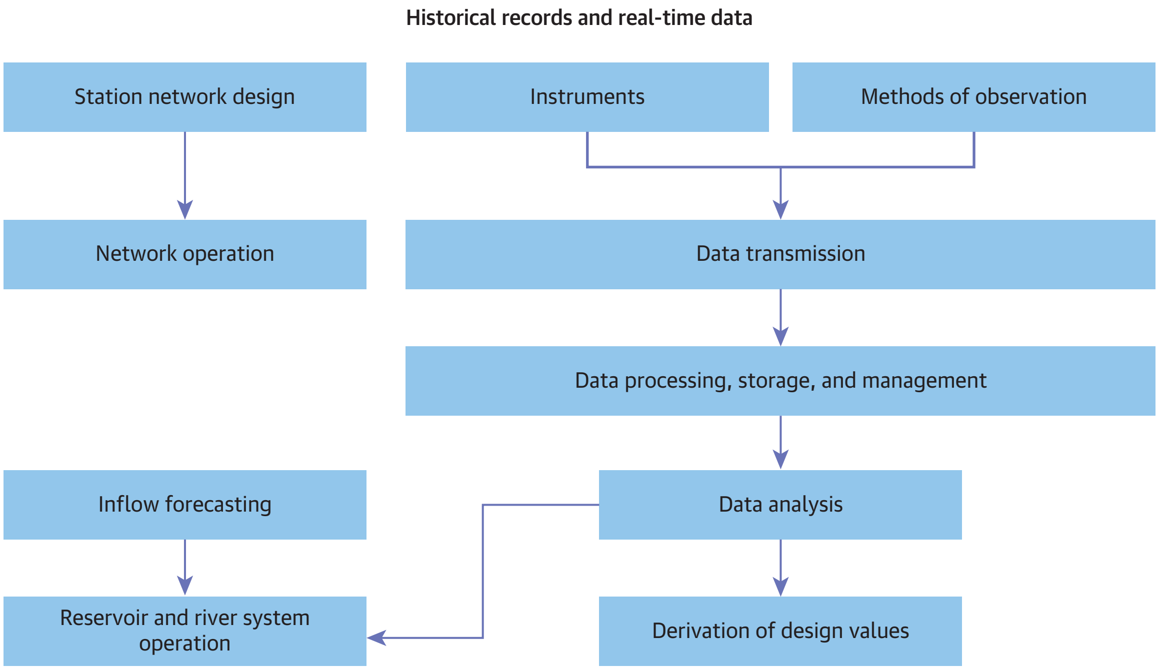
In general, dam safety aspects regarding hydrological risks relate to (a) establishment of key characteristics of extreme hydrological events, (b) establishment of discharge facilities' design and capacity of the reservoir, and (c) establishment of the operating strategy and plans.

Hydrology and the related discipline of water resources management, both of which are involved in characterization of dam safety, have a long tradition of developing methods, models, and other supporting tools characterizing hydrological hazard. Because of the breadth and depth of available methods and computer models supporting these considerations, this Technical Note cannot explain contemporary hydrological modeling in detail. The references provide general information on both basic and advanced methods and techniques.

Data Management

Climatological and hydrological data are essential in planning for any potential dam or hydropower project and for the operation of the existing projects. Collecting, processing, and maintaining the data organized as a hydrological information system provides the sound basis and necessary inputs for various hydrological studies supporting dam safety and risk assessments. Figure 1 depicts a blueprint proposed by the World Meteorological Organization (WMO 2008) for hydrological systems and modified for the purpose of dam safety assessments. The diagram illustrates activities and interrelationships involved in developing the information system capable of supporting hydrological studies carried out for operations and design purposes.

FIGURE 1. Hydrological Information System Historical Records and Real-Time Data



Source: WMO 2008.

Depending on the national economic and social circumstances, not all components of this model are present or can be easily developed and implemented. Even if the basic components exist, the frequency of readings (hourly, daily, and so on), the length of the available records, and the location of information collected as predetermined by the existing historical data sets may not be sufficient. The quality and reliability of such records and data may also be questionable because of limited or no quality control. Therefore, without collecting additional information, the extent and the completeness of the existing records may restrict the choices of modeling methods and approaches in hydrological studies necessary in developing and operating the project.

Data records should include the following observations.

Hydrometric observations:

- River/stream stage
- Lake/reservoir stage
- Sediment yield
- Sedimentation
- Ice

Climatological observations:

- Precipitation
- Snow survey[1]
- Solar radiation
- Evaporation
- Minimum and maximum temperature
- Humidity
- Wind speed and direction

If the existing data (type of data, record length, and so on) are insufficient or if the project is in the planning phase and more data needs to be collected before the project moves into the operations phase, the expansion of the existing observation network should be considered for long-term operation and suitable adjustments in the future. When data from the relevant catchment are available for only a short period[2], regional data should be used to improve the assessments. The regional data may provide the storm characteristics, such as storm depth, shape, orientation, spatial variability, etc. in the region, but its homogeneity and applicability to a particular site/catchment area needs to be checked. Table 1 provides guidance on this exercise.[3]

When hydrological data, and flow data in particular, are scarce and unreliable, with extended gaps, the ERA5 database can represent a useful starting point. Such hydrological data are made available by ECMWF from 1979 to date, at a 30*30 kilometers resolution.[4] They also include rainfall and potential evapotranspiration. Data are freely available online, from which mass balances can be made and possibly adapted based on the few direct data available. Remote sensing data can also be used as a source of alternative or additional information.[5]

Guide to Hydrological Practices, Volume I Hydrology: From Measurement to Hydrological Information (WMO 2008) provides all necessary technical and organizational support in conducting such activities.

1 Snow cover survey is important in estimating seasonal precipitation and forecasting river flow in spring in the mountainous areas where thawing/melting of accumulated snow provides a large portion of river flow water and even causes flooding.

2 As the length of record increases, the reliability of the estimate for probabilities of occurrence of a hydrological phenomenon increases. Approximate values of reliability (percent chance) can be calculated for different exceedance probabilities (recurrence intervals). An example is shown for small return periods from 2-100 years in which approximate reliabilities (% chance) is estimated as a function of confidence limit, return period and record length. The risk to have a flood with a return period greater than 2-100 years during the lifetime of the project (30-50 years) is also shown in the same manner (ICOLD 2012).

3 The limited size of available historical data requires the use of additional techniques to extend the database, such as regional analysis. Regardless, one must adopt an assumed probability relationship to extrapolate the database to the design frequency, in the range of 1000- to 10 000-year recurrence interval. There are many probability relationships to choose from for this exercise. It will be up to the dam design professionals to select the most appropriate one for the sample data on hand. One must recognize that regardless of the appropriateness of the probability relationship used, the extrapolation of data to the 1,000- to 10,000-year range from even 100 years of data is a “stretched” (complex, delicate and risky) exercise (ICOLD 2012).

4 www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5

5 Refer to Garcia (2016) for available climatological and hydrological data by remote sensing that can be used to fill the gap where ground data is scarce.

TABLE 1. Regional Data Use

Regional data availability	Data years in the catchment		
	Fewer than 20 years	20 to 50 years	More than 50 years
Good	Infer from regional data	Use catchment data and check with regional data	Primarily use catchment data
Fair	Use regional data and compare with empirical formulae[a]	Use catchment data and compare with regional data	
Poor	Use empirical approaches		

Source: Original table for this publication.

a. The empirical flood formula is typically expressed as a flood discharge envelope curve to provide a rough estimate of the upper limit of discharge for a region/area. A common type formula indicates the peak discharge (m^3/s) as a power function of the catchment area (km^2).

In addition, if the watershed upstream of the project is prone to significant erosion, assessment of sediment yield into the reservoir is essential before initiation of a detailed design phase. Topography, geology, geomorphology, and land use pattern of the watershed should be examined as part of sediment assessment. More-detailed assessments, including appreciation of suspended and bed-load material yields, may be necessary during detailed design.

The primary data processing task should include adjustment of collected data for known errors, aggregation, and interpolation of data and calculation of derived variables; for example, discharge amounts calculated from stage observations with the help of rating curves. It is prudent to check the gauging stage condition, which could be affected by malfunctions, changes in river bed condition, frequency of measurement during flooding periods, and so on; calibrate the rating curve; and examine the accuracy and reliability of the data and analyses. A secondary data processing step should include estimating and inserting missing data and general validation and quality control of all records. This is important because inadequate skills and experience often lead to neglect such critical process. When performing these tasks, the guidance provided by WMO 2008 should be followed to the extent permitted by local conditions.

When data availability is adequate, management of the processed data should be carried out through development of a computerized database that should archive the data in a secure and accessible way and with the provision for possible integration with other data sets (for example, GIS-based information). When data availability is poor or the amount of collected data is limited, simpler data management tools can be appropriate and still meaningful.

Watershed and River System Models

The key to the analysis and characterization of hydrological hazard and risk is the development of the watershed hydrological and river system models.

Watershed hydrological models developed through hydrological modeling (Singh and Frevert 2002 a and b) permit the assessment of how climate and weather affect the streamflow. Watershed hydrological models may range from simple empirical formulas to conceptual or complex physically based computer models. Both conceptual and physically based models can be of lumped parameters or distributed parameters. Todini (2007) provides an informative discussion of features, advantages, and limitations of different hydrological models. Selection of the modeling techniques depends on the complexity of the project, available technical capacity, and availability of the data for modeling. What is important when making the decision about the appropriate modeling technique is to maintain the proper balance among the available data and the analytic method considered. It is important to note that the increased complexity of the analytic methods without sufficient data does not improve the accuracy of results. The complexity of the model should also be adapted in line with the purpose and scope of the required analyses.

Availability of software, which the practitioners have extensively used and validated, is a dominant way of analysis. Consultants from different countries use various models and software, and the quality of hydrology assessment reports greatly vary from project to project. It is important to judge suitability and adequacy of the proposed mathematical tool for each case. Critical assessment of the results is also essential because one could be overconfident of nicely presented graphical results by sophisticated models. General characterization of contemporary watershed modeling approaches that include metric, conceptual, and physically based methods is outlined in Hartford et al. (2016).

Most of the contemporary hydrological models include the capability of modeling the watershed as a collection of subwatersheds using hydrological routing methods for modeling the movement of water between the subwatersheds. If such an option is not available, the streamflow routing can be carried out using well-known hydraulic routing methods. Streamflow, or flood routing, is a process used to describe temporal and spatial variation of a (flood) hydrograph as it moves through the river channel. This tracing of the dynamic movement of water downstream through the river reach has a well-established theoretical background in computational fluid mechanics and an abundant literature (ASCE 1996; Chow 1959; Maidment 1993; Singh 2004; Weinman and Laurenson 1979). Widely used methods include kinematic wave, diffusion wave, quasisteady, and full dynamic wave. Standalone hydrological routing methods, which can be used as an alternative, include linear reservoir, modified pulse, Muskingum, and Muskingum-Cunge models (Hartford et al. 2016).

Table 2 provides a list of widely used watershed models of varying complexity. A more detailed list of available hydrological models can be found in Edsel et al. (2011), Singh (1995), and Sitterson et al. (2017). Existing models cover the entire spectrum of possible modeling approaches, so the wide variety of available watershed models makes the idea of developing a new model specifically for the project cost-inefficient, unnecessary, and impractical.

The following should be established when selecting a model for the project:

- General hydrological modeling knowledge and experience of the engineer or team that carries out the selection and is later responsible for implementation of the selected model
- Experience in applying the selected model

- Identification of the watershed area to be modeled. Often, for design purposes, only the area upstream of dam location needs to be included. However, when the operation of the dam is considered, a downstream portion of the watershed should also be included.[6]
- Ability of the selected model to include all relevant hydrological processes occurring in the watershed
- Quality check of the data
- Ability of the existing data to support implementation of the selected hydrological model (and separate routing model if necessary, for the watershed of interest)
- Models calibration and validation process requirements

Reference to the information contained in table 2 should consider the following:

- Some experts may propose to use software models not included in table 2; that does not mean that those methods are inadequate and special advice should be sought in the assessment.
- Reference to specific software products, some of which are commercial, should not be considered a preference or endorsement for the same.

River system models represent useful tools in dam safety management because they can be used to assess how hydrological hazards, especially floods, affect the risk posed by engineering structures (dams and reservoirs). A well-developed simulation model is also a relevant tool for testing policies, plans, development options, and operating strategies for projects proposed or in place in a basin. The objective in developing a river system model is to describe the key hydrological and hydraulic characteristics of the basin, and through simulations of a range of development scenarios or policy interventions, to evaluate the potential effects that may occur on the water resources.

The purposes of basic modeling include analysis of options for dam sites, possible reservoir capacities, reliable water supply/hydropower output yields, and integrated flood management. Simple spreadsheet models are adequate at the prefeasibility level and can be adequate for simple or small-scale water resources development projects.

Further stages of development of more-complex and large-scale projects require more-accurate river system models. Development of watershed hydrological models and river system models is a complicated, time-consuming, and often costly task requiring advanced technical skills and computer modeling experience. Table 3 contains a list of interactive programs that help in formulating water resources alternatives, analyzing their effects, and interpreting and selecting appropriate options for implementation.

6 Results of modeling of the downstream portion of the watershed are necessary for river system modeling and system simulation purposes. Moreover, adequate assessment of impacts from dam failure requires this information.

TABLE 2. Hydrological Models

Model	Type	Description	Access	Source
GR4J	Catchment	Empirical general, efficient, and robust model using significantly less data than conceptual or physics-based models	Free	eWater, Australia
HBV	Catchment	Empirical general, efficient, and robust model using significantly less data than conceptual or physics-based models	Unknown	SMHI-Sweden
IHACRES	Catchment/stream	Empirical general catchment model using unit hydrographs to hydrologically route runoff	Free	Integrated Catchment Assessment and Management Centre (ICAM), Australia
HEC-HMS	Catchment/stream	Hydrological modeling system simulating a complete set of hydrological processes and hydraulic routing; input data in HEC format compatible with other USACE software packages	Free	U.S. Army Corps of Engineers (USACE)
Mike 11	Catchment/stream	Empirical catchment model that simulates runoff production and hydraulic routing; can be linked to other DHI modelling systems	Purchase	DHI, Denmark
TOPKAPI-X	Distributed physically meaningful catchment model and simplified hydraulic routing	Advanced watershed model that simulates all the processes using kinematic flow equations	Free	Idrologia & Ambiente
MIKE-SHE	Distributed physically meaningful catchment model and hydraulic routing	Advanced watershed model that simulates all the processes with appropriate hydraulic equations	Purchase	DHI

Note: DHI = Danish Hydraulic Institute; HEC = Hydrologic Engineering Center; SMHI = Swedish Meteorological and Hydrological Institute.

TABLE 3. River System Models

Model	Description	Access	Source
RiverWare	Reservoir and river system operation and planning model	Purchase	http://www.riverware.org/
	Reservoir and river system operation and planning model—older versions	Free	CADSW University of Colorado, Boulder
ModSim	Generalized river basin Decision Support System and network flow model developed at Colorado State University with capability of incorporating physical, hydrological, and institutional/administrative aspects of river basin management	Free	Colorado State University
HEC-ResSim	Software modeling reservoir operations at one or more reservoirs for a variety of operational goals and constraints; it simulates reservoir operations for flood management, low flow augmentation and water supply for planning studies, detailed reservoir regulation plan investigations, and real-time decision support	Free	U.S. Army Corps of Engineers (USACE)
HEC-WAT	Software supporting the planning process by allowing the user to intuitively and collaboratively perform an alternative analysis	Free	USACE
GOLDSIM	Simulation package that uses an object-oriented programming environment and builds the model from stocks, flows, modifiers, and connectors	Purchase	https://www.goldsim.com
WEAP	Decision simulation software based on optimization and user priorities to allocate water and simulate effect of user-constructed scenarios	Free	Stockholm Environment Institute
MIKE-BASIN	Models water availability, water demands, multipurpose reservoir operation, transfer/diversion schemes, and possible environmental constraints in a river basin	Purchase	DHI

Note: DHI = Danish Hydraulic Institute

Reference to the information contained in table 3 should consider the following:

- Experts may propose and use software models not included in table 3; that does not mean that those methods are inadequate, and special advice should be sought in the assessment.
- Reference to specific software products, some of which are commercial, should not be considered a preference or endorsement for the same.

Probabilistic Characterization of Floods

Simple probabilistic characterization of hydrological hazards can be carried out with the help of flood frequency analysis. Flood frequency analysis is conducted by fitting a probability distribution to the data using either on-site statistical parameters or regional parameters. Table 4 provides a list of software that is often used for flood frequency analysis. Single-site frequency is easier to carry out and may be sufficient for estimating large floods at a site with a long record of streamflow observations. When that record is inadequately short (see the Data Management section), regional analysis is a powerful tool to carry out a meaningful flood characterization. A regional frequency analysis is particularly suitable for estimating rare and extreme floods. Hosking (1997), ICOLD (2014 and 2016b), and WMO (2009) provide extensive, up-to-date guidance on regional and single-station flood frequency analysis. A regional analysis is generally complex and time demanding because it uses data from other sites in a hydrologically similar region. It is particularly important that the team conducting the analysis has the knowledge and experience in applying statistical procedures for data pooling (advanced methods of testing for homogeneity, stationarity, and independence). As such, the application of regional analyses requires specialist input, and independent review is advisable.

Reference to the information contained in table 4 should consider the following:

- Several experts may propose or use software models not included in table 4; that does not mean that those methods are inadequate, and special advice should be sought in the assessment.

TABLE 4. Flood Frequency Analysis Software

Model	Description	Access	Source
HYFRAN-Plus	Software used to fit statistical distributions. It includes several powerful, flexible, user-friendly mathematical tools that can be used for the statistical analysis of extreme events. It can also, more generally, perform basic analysis of any time series of IID data.	Purchase	Water Resources Publications, LLC
HEC-SSP	Specialized analysis of hydrological data (flow frequency analysis, general frequency analysis, volume frequency analysis)	Free	U.S. Army Corps of Engineers (USACE)
peakfqSA	Implementation of the Expected Moments Algorithm (EMA) for flood frequency analysis	Free	http://www.timcohn.com/TAC_Software/PeakfqSA
CumFreq	Software for calculation of frequency and for fitting probability distribution of data series	Free	https://www.waterlog.info/cumfreq.htm

Note: IID = Identically Distributed Data

- Reference to specific software products, some of which are commercial, should not be considered a preference or endorsement for the same.
- One cannot overstress the importance of quality control of data, data availability and collection period, accuracy of the fit, and so on for any analyses.

The focus of a recently emerging approach in flood frequency analyses is on changing climate and resulting nonstationarity of hydroclimatic time series. Adjustments to the traditional methods of flood frequency analyses are discussed in Mondal and Denzil (2018) and Volpi (2018).

With the progress in the probabilistic characterization of extreme meteorological events (Koutsoyiannis 1999; Papalexiou and Koutsoyiannis 2006; Singh, Singh, and Byrd 2018), an alternative indirect approach applies the watershed model to generate response to the PMP characterized in probabilistic terms. Combined with uncertainty characterization of other inputs and parameters, simulation of watershed response can provide the probabilistic characterization of extreme flood events.

Probable Maximum Precipitation and Probable Maximum Flood

In addition to flood frequency analyses, the main characteristics (peak flow, flood volume, and flood duration) of extremely large floods can be obtained from the application of watershed simulation modeling that provides probable maximum flood (PMF) as the response of the watershed to an extreme meteorological event called the probable maximum precipitation (PMP). The characteristics of a reservoir—its routing effects, discharge facilities, antecedent conditions before PMP, and so on—are also important. WMO (2009a) defines PMP as the "theoretical maximum precipitation for a given duration under modern meteorological conditions. Such a precipitation is likely to happen over a design watershed, or a storm area of a given size, at a certain time of year." WMO (2009a) provides detailed guidance on derivation of the PMP. The Hershfield method is one of the most practical methods to calculate the PMP as recommended by WMO (2009a).

Glacial Lake Outburst Flood

For catchments in high mountains that contain glaciers and glacial lakes, glacial lake outburst flood (GLOF)[7] is one of the phenomena causing extreme floods. GLOF is a sudden release of water by the failure of glacial lakes that has been formed by moraine complexes, glacial ice, or even bedrock, causing catastrophic damage in high mountain areas. As glaciers recede in response to climatic warming, the number and volume of potentially hazardous moraine-dammed lakes is likely to increase. In such areas, qualified experts should undertake an initial glacial hazard assessment to prepare an inventory of glacial lakes and assess their current and future hazards. For high-risk or -consequence dams, a multiphase assessment would be recommended, possibly including satellite image studies, more-detailed and frequent high-resolution studies, helicopter flyover study, and so on.[8]

7 GLOFs present an important issue to consider in dams located in high mountain environments. Global warming has an incremental effect on hydrological risk associated with GLOFs. See Section for Probabilistic Characterization of Floods for more information on required assessment and data collection.

8 The website www.reynolds-international.co.uk/dfid provides rich information on glacial hazards and useful publications.

Other Methods for Flood Characterization

When the available data to be used in supporting watershed modeling or formal frequency analyses is scarce or lacking entirely, an approximate characterization of floods can be carried out with the help of simple, deterministic methods. The basic characteristics of floods (peak inflow, peak volume, and so on) in a river may be determined by the following methods.

Empirical Formulas and Curves

Empirical models (often called *data-driven* or *black-box models*) apply statistical relationships between inputs (rainfall) and outputs (runoff at a specific location). The models are observation-oriented, and no information or knowledge about physical processes that control runoff are used in developing the models. Simplicity of implementation, negligible computational times, and low cost are advantages for empirical models to be chosen for modeling over more-complex models. However, it is important to check the context and limitation of applicability with due consideration to the region, catchment area, and so on.

The Curve Number (CN) models were initially developed as design tools to estimate runoff from rainfall events on agricultural fields, but they are now also used for computing peak runoff rates and volumes for urban hydrology. The CN models are essentially the coefficients that reduce the total precipitation to runoff potential after losses (evaporation, absorption, transpiration, and surface storage). Curve numbers (available in hydrology texts) are defined in terms of land use, soil types, watershed wetness, and surface cover conditions. Curve number is typically defined as an index of watershed runoff potential, and its value ranges from 0 for no runoff to 100 when all rainfall is converted to runoff.

Rational Method

The rational method is a simple approach based on a formula that relates runoff-producing potential of the watershed to the average intensity of rainfall for a particular length of time (the time of concentration) and the watershed drainage area. It provides not the complete hydrograph, but the peak inflow instead.

Envelope Curves

The approach (ICOLD 1992, 2016c) establishing the relationship between the flood peak inflow and the watershed area was originally introduced by Rodier and Roche (1984) and later updated by Nathan, Weinman, and Gato (1994) and Herschy (2003).

Unit Hydrograph

Different forms of unit hydrograph (UH) models are common in that they convert a rainfall input to a flow output using a deterministic model of catchment response. These deterministic models may vary in details but all have three common elements: (a) the unit hydrograph itself, (b) loss model, and (c) baseflow. Model parameters are usually estimated from recorded rainfall-runoff events, but in the absence of observed data may be derived from physical characteristics of the watershed and the model is then called synthetic unit hydrograph (SUH). Traditional methods of deriving parameters of UH and

SUH models (Snyder, TS, and SCS) developed in the mid-twentieth century are now being replaced by probability distribution function-based SUH methods.

When possible, different methods should be used that are independent of one another. The limits of applicability for each method should be considered.

References supporting the developments of these methods together with the recommendations for selecting model parameters for different climate regimes (tropical, semiarid, and arid), different types and characteristics of watersheds, and so on are available in Amiry and Mohammadi (2019); Bhunya, Panda, and Goel (2011); Biondić, Barbalić, and Petraš (2007); Chaves et al. (2017); Ewea et al. (2018); Hayes and Young (2005); IHP (2001); Kansal and Thakur (2000); Kovacs (1988); Nathan, Weinmann, and Gato (1994); Rakhecha and Singh (2017); Saha (2002); Salami et al. (2009); Soliman (2010); and Weaver (2003).

Sedimentation

Although not the component of common characterization of hydrological risk, the services provided by hydropower facilities and dams are at risk from the sedimentation process. The process of reservoir sedimentation reduces the storage capacity of the reservoir, causes damage to hydromechanical equipment, and has significant adverse downstream effects. Reservoir sedimentation occurs worldwide at a rate close to 1 percent per year, but the sedimentation rate varies extensively around that average in different regions (ICOLD 2009).

Trapping of sediment in a reservoir behind the dam may affect the safety of the structure in the following ways:

- Reduction of available storage capacity leading to increased likelihood of overtopping caused by floods
- Reduction of spillway discharge capacity by loss of approach depth
- Blockage of low-level outlets

Design of the dam has to not only incorporate effective sediment management measures, such as sediment sluicing/flushing through bottom outlets, periodic excavation/dredging, catching sediments in upstream check dams, etc. but also consider, when feasible, the means of reducing amounts of incoming sediment from upstream through erosion control in watershed/catchment areas and/or bypassing.

ICOLD (2007) provides guidance on modeling and quantitative assessment of sedimentation together with the presentation of case studies. ANEEL (2000) is a practical guiding document to reservoir sedimentation assessment (measurement methods, data collection and analysis, and assessment of secondary effects).

Annandale, Morris, and Karki (2016);[9] Efthymiou et al. (2017); Morris, G. (1998), and Palmieri, Shah, Annandale, and Dinar. (2003 a and b) provide advice on treatment of sediment issues that includes a comprehensive overview of sedimentation issues, sediment transport and deposition, sediment monitoring, and sediment management techniques.

Ecological Flows

An ecological or environmental flow is the amount of water flowing down a river that is necessary to maintain the river in a desired environmental condition. In general, determination of ecological flow is part of a wider assessment framework within the integrated water resources management.

Important reference documents explaining the concept of ecological flows and discussing the broad range of approaches to determine the amount of ecological flows, ranging from prescriptive methods to interactive approaches, are European Union (2015), Horne et al. (2017), World Bank (2003), and IFC (2018).

With respect to the effects of dam operation, both intake/diversion volume and ecological in-stream flow should be determined at the onset of planning. Dam design should consider that ecological releases need to be secured at all stages of the project, not only during reservoir operation. Appropriate release facilities, of temporary or permanent nature, should be provided during construction and reservoir filling periods. The ecological flow should be monitored during operation of the dams.

Design Flood Criteria

In most instances, the design flood[9] is selected based on the dam classification system considering its size, downstream consequence, etc. This classification helps to secure a consistent safety level against floods and potential overtopping risk. The magnitude of the selected design flood can vary significantly, from a 100- or 200-year flood for low-class dams to a 1,000-year flood, 10,000-year flood, or PMF for high-class dams.

Different countries have adopted a wide range of hydrological safety criteria along a continuum.[10] These criteria reflect the individual country characteristics, informed by the socioeconomic realities and public expectations of safety; technical aspects, such as adequacy and reliability of hydrometeorological data; and other design features, such as freeboard requirements (the vertical distance between the top of the dam and the full supply level or surcharge flood level). It is important for client countries to discuss and agree on suitable hydrological safety level considering potential risk or consequence and its economic, social, and other conditions.

9 The term *inflow design flood* is used in North America instead of *design flood*.

10 Wishart, et al. (2020) provides detailed information on various dam classification systems and hydrological safety design criteria. ICOLD 1992, 2012, and 2016 provide information on hydrological safety design and useful examples. In particular, information on the design flood selection in 28 countries (ICOLD 2016c) illustrates substantial differences among the countries with the design flood range from the floods with 10^{-3} AEP to PMF.

One of the most important recommendations by the ICOLD Bulletin 82 (1992) is to examine the hydrological safety of dams against the following two floods:

- Safety check flood (often PMF); structure on verge of failure but exhibits marginally safe performance characteristics during flood
- Design flood (represents required flood discharge under normal conditions with a safety margin provided by freeboard)

It is also recommended to check the hydrological safety considering that some gates will not be available during a design flood. Access to the site, maintenance of some gates, or any other issues could affect the spillway capacity. The number of gates available during the design flood would depend on the total number of gates and scenarios. Although all gates may be considered available during design floods, it is recommended to ensure that the dam would be able to handle a lower flood if some gates are unavailable (ICOLD 2016c).

The hydrological safety should also be considered for the construction phase involving temporary flood diversion facilities. The construction design floods are typically much smaller events than the design flood. The maximum design flood selected for the construction periods typically reflects a balance between cost of accommodating floods and the risk of larger floods occurring during this period. Typical values range from floods with annual exceedance probability (AEP) of 4×10^{-2} (25-year flood) to 10^{-2} (100-year flood), with the latter value used infrequently and usually when the incremental cost is small. Special cases involving flood management by upstream reservoirs and use of concrete cofferdam, which can resist overtopping, may allow return periods shorter than 25 years.

Impacts of Climate Change

There is extensive writing about climate change, mostly aimed at raising awareness of the issue. Most publications on the effects of changing climate on water resources point to the general potential effects but rarely describe methodology that can be reliably applied to make probabilistic predictions on future hydroclimatic processes or water flows. Climate change projections are affected by high uncertainty when assessing future average behaviors such as average temperature or precipitation. Uncertainty becomes high for projections about extreme events, with a consequent expected low reliability of results.

However, the lack of quantitative, probabilistic characterization of hydrological risk does not necessarily mean that hydrological risk cannot be successfully managed. Relevant and recent information can be found in IHA (2019) and Ray and Brown (2015), which, in terms of substance, offer the same guidance contained in the following text. Annex 1 to this Technical Note articulates the reasons for such substantial alignment.

The References listed at the end of this Technical Note and experience from the World Bank operations point out the following observations:

- Climate model results are not predictions or forecasts. Because of the presence of large and undetermined uncertainties at all scales of climate modelling (global, regional, and watershed), they are referred to as "projections."

- The projections' uncertainty is caused primarily by (a) significant uncertainty about the values of key physical parameters, (b) the fact that local and global climate and the effects of climate change are strongly influenced by unpredictable human actions over the coming century, and (c) inherent, chaotic variation in weather not only daily but also on annual and decadal scales.

- Although temperature projections are relatively reliable, precipitation projections, which are the most important for hydrological modeling, are much less reliable at all time and geographical scales. It is not even always possible to determine whether mean precipitation is increasing or decreasing, and both outcomes are possible.

- Changes in precipitation projections (IPCC 2014) will not be uniform. Under the scenario with very high greenhouse gas emissions, the high latitudes, many midlatitude wet regions, and the equatorial Pacific are likely to experience an increase in annual mean precipitation. In many midlatitude and subtropical dry regions, mean precipitation will likely decrease. Intense precipitation events over most of the midlatitude land masses and over wet tropical regions will likely become more intense and frequent.

- All climate models show continued warming of surface air temperatures in the future. However, for rainfall, which shows much greater variations across space and through time, there is less agreement among climate models. Although precipitation intensification is emerging in the observed record across many regions of the world (Fischer 2016; Prein et al. 2016), in many cases the models do not agree on whether a place will become drier or wetter (Sippel et al. 2017). Downscaled climate models are so far of limited operational use for planning except, possibly, in the case of very large-scale water resources and hydropower projects.

- For time horizons of 30 years or less, internal climate variability is the main source of uncertainty about precipitation, and relative uncertainty is higher for smaller geographic areas and for seasonal versus annual means.

ICOLD (2016c) confirms these observations, stating that "projected impacts of climate change in water resources and floods and droughts are uncertain, and cannot provide exact information of the rate of future changes to decision-makers, but they can offer very useful general information, and they could serve as preliminary and initial assessment." Though credible assessment of uncertainty with respect to quantitative characterization of effects on streamflow from future extreme climate events is at the present unavailable, information obtained through downscaling of global climate models results can provide a basis for sensitivity analyses. McSweeney and Jones (2016) provide general guidance on conducting such sensitivity analyses. The findings from analyses can subsequently be applied as valuable inputs for adaptive river system and reservoir management.

Many attempts have already been made around the world to assess the influence of changing climate on water resources. The preferred methodology is based on ensemble approach, which is supported by Kundzewicz et al. (2018). The paper concluded that "since model-based projections of climate impact on water resources can largely differ, adaptation procedures need to be developed which do not need crisp, quantitative, projections of changes in hydrological variables, such as river flow, lake level, soil moisture, etc., but rather on projected ranges of values." Adaptive planning should be based on ensembles and multimodel probabilistic approaches rather than on an individual scenario and a single-value projection for the future. The approach uses future climate projections indicating a range of potential shifts in temperature and precipitation based on the results from a collection of global climate model runs from the World Climate Research Programme's Coupled Model Intercomparison Project Phase 5 (CMIP5) multimodel data set that informed the IPCC Fifth Assessment along with regional downscaling techniques. Representative scenarios constructed from a selected number of projections can then be chosen to represent different combinations of the potential changes in temperature and precipitation under future climate projections.

It should be noted that the approach:

- Requires extensive computational effort and may be impractical for smaller projects. Alternative, less costly, but sufficiently credible approaches are not available.
- Provides only sensitivity indicators (a range of possible future values) and is incapable of determining their likelihoods.

In view of the high uncertainty of combined climate and hydrological models (Hattermann et al. 2018), until models are improved beyond current limitations, the most promising way forward is to incorporate adaptive river system management, especially in the planning of new projects. Sensitivity indicators developed through ensemble modeling may provide sufficient guidance for adaptive and resilient design and adaptive management of the dam system to mitigate the potential effects of climate change. Adaptive management would entail regular monitoring, evaluations, and reviews, with possible redesign of the management program, as necessary. Most important, adaptive management needs to be based on a solid set of indicators.

Although it is not the subject of this Technical Note, increasing awareness of the possible presence of hydrological nonstationarity (with almost certainty of nonstationarity emerging during the lifetime of river systems with dams) leads to the development of novel approaches to decision making under uncertainty (Brown et al. 2011) and management of hydrological risk.

Managing Hydrological Risk and Enhancing Resilience

When dealing with hydrological risk, the immediate link is to the assessment of the discharge capacity of a dam's spillway and outlet works. Another recurrent discussion point is the selection of the appropriate flood level. Such selection, which is *de facto* a selection of a required level of safety, has political, economic, and social implications and depends on many factors and local conditions. Therefore, a general rule to ensure adequate safety cannot be expected to come only from adopting very high flood levels (for example, PMF). Because of the stochastic nature of floods, application of design standards is necessary, but not sufficient to manage hydrological risks. It is recommended to widen the assessment to topics such as:

- Hydrological data and information acquired during operation, in addition to and integration of those used at the design stage
- Evolution, in time, of social and hydraulic conditions upstream and downstream of the dam
- Awareness and preparation of competent authorities and communities to respond to emergency situations
- Evolution of national regulations and guidelines
- Resilience of dam and appurtenant works to extreme hydrological events

Table 5 analyzes selected topics that have relevant and recurrent application in the World Bank operations. They all pertain to the subject of hydrological risk and infrastructure resilience.

The following paragraphs provide further details for hydrological risk management in terms of: (a) adaptive and resilient dam design, (b) adaptive dam system management, (c) adaptive dam operation, and (d) enhancing community resilience. Hydrological risk can be reduced and managed through incorporation of principles of adaptive and resilient design and principles of adaptive management (Sayers et al. 2012).

Adaptive and Resilient Dam Design

Standard planning and design for hydrological safety should include:

- Selection of dam type, favoring overtopping-resilient types when uncertainty in flood hydrology is high
- Design of the dam and spillway large enough to ensure that the dam will not be overtopped by floods ("design flood" and "check flood") or design flood determined by a comprehensive risk assessment
- Design of the dam and appurtenances ensuring that the structure can be overtopped without failing and without suffering serious damage
- Design of the dam and appurtenances ensuring that breaching of the structure caused by overtopping will occur (a) gradually permitting full implementation of emergency management system, and (b) with damage to the dam located where it could be repaired timely and most economically
- Definition of ordinary and exceptional freeboards
- Appropriate selection of types of service spillway/outlet gates, introducing redundancy when uncertainty in flood hydrology is too high[11]

11 Discussion of recent advances in spillway design can be found in ICOLD (2016d).

TABLE 5. Hydrological Risk and Resilience Enhancement Measures

Topic	Remarks	What to do
Update of hydrological database	Hydrological data gathered during dam/reservoir operation include rainfall and snowpack, inflow to reservoir, reservoir sedimentation, and water quality. Adaptive management: The database used at the design stage should be periodically updated with information acquired during operation. Operational rules should be revisited, as necessary, at least every 10 years.	Include provisions for hydrological data update and adaptive management in the O&M plan
Adaptive dam system management	Advanced hydro-met monitoring and flood forecasting system should be incorporated to enable reservoirs to be drawdown for increasing flood control capacity and ensure dam safety prior to peak flood arrival. During the operation of dams, there may be instances when large discharges will have to be released, often in anticipation of large floods. Adequate downstream warning and training is needed for dams operation and water releases under exceptional situations in particular for densely populated areas.	Include dam operational system and procedures on flood forecast, increased water releases, and downstream warning system in the O&M plan and in the EPP.
Resilient infrastructure design	Many regions of the world are experiencing significant stress on water resources, and global warming might exacerbate this stress. Even though many elements to be considered in planning and operation are specific to any projects involving dams, three key elements are usually present: (1) water availability, (2) hydrological extremes (floods and droughts), and (3) seasonal and interannual flow variability. In addition to using adaptive management, in the face of uncertainty, good design requires the adoption of measures that enhance infrastructure resilience. Resilience of a system determines how quickly it recovers from crisis. The Good Practice Note (GPN) lists several measures for enhancing infrastructure resilience. Both structural and nonstructural measures should be considered, along with their desirable time of implementation during the project life cycle including: (a) structural measures such as suitable types of spillway / outlet works, operational system, installation of fuse plugs/gates, hard fill type dams to resist overtopping, etc. and (b) non-structural measures, such as optimal reservoir operation, early warning, emergency preparedness plans, and so on. There should be no bias toward structural or nonstructural solutions; in fact, good solutions inevitably involve an intelligent combination of both.	Consider options for enhancing infrastructure's resilience throughout the life cycle of the dam as shown in the main GPN.
Sustainable sediment management	Reservoir sedimentation has dam safety implications in terms of: • Clogging of water control /discharge facilities • Reduction of flood regulation capacity • Ultimately, severe damages to surface spillways if the process is left to develop without control and long-term sediment management measures are not implemented Adequate sediment assessment including sufficient data collection and analyses should be undertaken, based on which a comprehensive sediment management plan, including sediment dredging/excavation in reservoirs, flushing /sluicing through bottom outlets, check dams, catchment conservation, etc. should be prepared and incorporated into the project during preparation period. It is important to adopt the "life-cycle" approach rather than the traditional cost benefit analysis and inclusion of "dead storage" alone in order to ensure the long-term sustainability of the reservoirs.[a]	Undertake adequate sediment assessment and prepare and incorporate a comprehensive sediment management into the project design. Apply the life cycle approach to enhance sustainable reservoir operations.

Source: Original figure for this publication

Note: EPP = Emergency Preparedness Plan; O&M = operation and maintenance.

a. The World Bank developed the RESCON (Reservoir Conservation) concept that modified the economic analysis of storage reservoirs using the "life-cycle" approach instead of the "dead storage" practice (Palmieri et al. 2003 a). A World Bank follow-up reports (Annandale et al. 2016) and (Efthymiou et al. 2017) has enhanced the mathematical model at the base of the life-cycle approach and added 20 years of experience in the application of the RESCON method worldwide. ICOLD (2007) and ANEEL (2000) also provides useful guidance on sediment assessment and management.

- Consideration of auxiliary and emergency spillways
- Consideration of fuse plugs and fuse gates/stoplogs as means of available additional discharge capacity, if needed
- Consideration of a spillway diversion channel to allow safe passage of flood around the dam
- Consideration of a means of preventing gated spillways blockage by debris
- Feasibility, ease, and cost efficiency in raising the embankment height
- Feasibility, ease, and cost efficiency in adding service spillway bays
- Introduction of adequate flood forecasting (equipment and computer models)
- Downstream warning system

Beyond these considerations, emerging principles of adaptive design include:

- Design resistant to a wide range of threats, including those that were not necessarily foreseen during the design process
- Design ensuring that provisions accommodating future modifications, when necessary, during the project life cycle are considered and implemented during the planning and design process. The provisions should enable the most cost-effective implementation of modifications for the entire life cycle of the dam.
- The performance of a resilient design that does not decay catastrophically when exposed to events more severe than design levels
- Design critical components (valves, gates, and so on) for maximum operational reliability

ICOLD (2012) discusses this subject in more detail and provides advice on implementation of these principles.

Adaptive Reservoirs System Management

Specific principles of adaptive river system management include:

- Design of effective and accurate inflow forecasting system (as the tool supporting effective decision making in operation and flood management) that includes (a) a clear definition of the forecasting system purpose; (b) specification of the modeling content; (c) review of required and available information (real-time hydrometeorological data acquisition, satellite imagery, upstream dams and river flow gauges, and so on) and development of data sharing protocol; (d) selection of model features and structure; (e) selection of performance criteria; (f) model calibration, testing, and validation; and (g) uncertainty quantification
- Operation of the forecasting system: coordination with hydrometeorological and other relevant agencies; and periodic review of data sharing mechanism and protocol

- Optimization of river system operating strategy by considering coordinated, systemwide prereleases (that is, preflood reservoirs drawdowns) that can support improved management of extreme flood events. Prerelease in this context is the strategic release of stored water to proactively drawdown the reservoir water level before rainfall and inflow increase based on hydro-met and flood forecasting information. The timing and amount of prerelease can be guided by carrying out simulations along with hydro-met monitoring and forecasting information.

Prereleases and surcharge actions should follow a policy established in coordination with political (in case of transboundary river systems) and all institutional stakeholders. The process of implementing prereleases and surcharges in operational decision making must be defined and explained in an operation and maintenance manual or separate flood operational manual.

Adaptive Dam Reservoir Operation

Specific principles of adaptive dam reservoir operation include:

- Modification of operating rules to surcharge the reservoir for a limited time
- Temporary or permanent lowering of normal operating reservoir water level to increase available storage for flood attenuation

Ouranos (2015) details the advantages and disadvantages of actions implementing the principles outlined earlier.

Enhancing Downstream Community Resilience

Despite all efforts to reduce and control the hydrological risk, residual risks of varying magnitudes may remain in place. The effective way of managing these risks is through establishment of an effective emergency management program based on three pillars: preparedness, response, and recovery. Some guidelines, such as *Technical Bulletin: Emergency Management for Dam Safety* (CDA 2018) and *Federal Guidelines for Dam Safety: Emergency Action Planning for Dams* (FEMA 2013), can serve as valuable reference documents providing detailed information necessary in developing Emergency Preparedness Plans (EPPs).

Also, public safety has become an important subject because we have seen several flooding incidents and casualties in downstream rivers of dams resulting from failure or mishandling of spillway gates and outlet works without proper discharge procedure and downstream warning. Some documents, such as *Guidelines for Public Safety Around Dams* (CDA 2011) are quite useful.[12]

Implementing a Risk Management Approach

Properly conducted risk assessment is an invaluable tool in assessing the safety of a dam. It provides the dam owners, design engineers, and operators with a better understanding of the site-specific flood risk.

12 Wishart, et al. (2020) summarizes the global trends of the EPP/EAP regulations and guidelines in Chapter 7: Emergency Preparedness and Public Safety.

The information about risk allows for better identification of potential deficiencies and prioritization of risk reduction measures.

In recent decades, advances in formal risk analysis of hydrological hazards affecting dam safety has led to the development of methods and techniques capable of comprehensively addressing the hydrological risk. These developments recognize that the overtopping failures of dams are caused not always by extreme floods exceeding the design discharge capacity, but often by equipment failures, and human errors in planning and implementing the operation can also lead to overtopping during more-frequent and smaller events.[13] This kind of comprehensive risk assessment method is covered in more detail by the main Good Practice Note on Dam Safety.

13 The Ontario Power Generation has undertaken detailed quantitative risk assessment of two control dams and five generating stations. Dynamic simulations of the river flow system were done using stochastic flood models and detailed modeling of gates and turbine availability. Although the design-standard approach requires them to use PMF for inflow design floods, the study concluded that the overtopping failure mode is not the dominating mode of dam failure but rather a broadly acceptable risk. The far greater risks are those caused by the potential of internal erosion or slope instability of embankment structures and concrete components resulting from sliding (Source: System approach and simulation in risk assessment of dams (Zielinski et al. (2017).)

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Annex 1: Catchment Area and Probable Maximum Floods of Some Large Dams

Table A1 indicates the volume of PMF and catchment area of some large dams. Although there is no specific correlation between the PMF and catchment areas under various climate regions, the table may give some ideas for cross-checking the volume of extraordinarily large floods.

TABLE A1. **PMF and Catchment Area of Some Large Dams**

Country	Dam	Catchment area [km^2]	PMF [m^3/s]	Ratio PMF/catchment area [$m^3/s/km^2$]
China	Three Gorges	1,005,501	102,500	0.1
United States	Glen Canyon	173,772	19,737	0.1
Lao PDR	Xayaburi	272,000	47,500	0.2
Canada	Little Long	36,468	13,260	0.4
Canada	Bark Lake	2,690	1,410	0.5
Pakistan	Chakwal	4,044	3,790	0.9
Indonesia	Wonogiri	1,350	1,270	0.9
India	Sardar Sarovar	88,000	87,000	1.0
Pakistan	Talagangh	5,700	5,880	1.0
United States	Folsom	4,823	6,700	1.4
Lao PDR	Nam Ngum	5,640	9,000	1.6
Chile	Puclaro	6,582	12,000	1.8
China	Yunfeng	17,572	36,800	2.1
Thailand	Mae Sruai	434	990	2.3
India	Kol	3,595	10,000	2.8
United States	286 mile	2,563	13,671	5.3
Malaysia	Sultan Mahmud	2,600	18,890	7.3
China	Banqiao	768	14,400	18.8
Malaysia	Sultan Abu Bakar	183	4,260	23.2
Indonesia	Logung	44	1,031	23.4

Source: Original table for this publication

Note: km^2 = square kilometers; m^3 = cubic meters; PMF = probable maximum flood; s = second

Annex 2: Review of Relevant World Bank Studies

Documents Reviewed

- Ray, P. A., and C. M. Brown. 2015. *Confronting Climate Uncertainty in Water Resources Planning and Project Design*. The Decision Tree Framework. Washington, DC: World Bank.
- International Hydropower Association. 2019. *Hydropower Sector Climate Resilience Guide*. London: IHA.

The importance of the first document lies in the clear characterization of present limitations of contemporary climate modeling and very direct spelling out of what can and cannot be inferred from modeling results. The study differentiates between the *risk assessment*, understood as risk analysis and risk evaluation, and *risk management*, which deals with means of reducing and controlling the risk. It is an important distinction because these two activities are not affected by shortcomings of climate modeling in the same way and to the same extent. Only the first of these activities (risk assessment) is directly affected by the existing limitations. These major limitations are:

- Uncertainty about the general outputs from the General Circulation Models (GCMs) is not only unknown but also irreducible because of the still largely imperfect knowledge about the behavior of physical processes controlling the climate and weather.
- Even less information is provided by the GCMs outputs about these aspects of future climate, which is most important to water resources management in general and to dam safety management in particular. This refers to timing and magnitudes of extreme events resulting in unusually large intensities and amounts of precipitation, and increased spatial and temporal variability of climate inputs for hydrologic models, to name just a few.
- Inability of the current climate science and practice to provide quantitative characterization of uncertainty in probabilistic terms.

From the perspective of hydrological risk, the inability of climate projections to provide probabilistic representation of uncertainty limits its use in any formal quantitative, semiquantitative, or qualitative analysis and evaluation of such risk.

Moving to the second activity (risk management), these shortcomings of current climate and climate change modeling can be to some extent mitigated by applying a different strategy of project assessment and decision making. Moving from the ex ante or scenario-led approach to the ex post approach reduces and, in some instances, eliminates the need for complete probabilistic characterization of climate model outputs. The focus of the approach is on conditions leading to a system (or dam) failure. The potential for existence of such conditions can be assessed with the help of sensitivity analyses dealing with the effects of climate change on water resources and hydrology, which can be successfully carried out with the help of ensemble projections. Such assessment may provide sufficient information for adaptive and resilient dam design, adaptive dam system management, and adaptive dam operation (as discussed in the Managing Hydrological Risk section of this Technical Note).

Water system models using ex post scenarios test the performance of the system across a wide range of potential futures (climate and nonclimate permutations), beyond the scope of the futures suggested by the IPCC narratives and associated GCM models. Scenarios are thereby defined as those futures in which the system struggles or fails. Scenarios defined as ex post are meant to identify suboptimal system performance and are less likely to underestimate vulnerabilities. In addition, the ex post definition of scenarios may facilitate the assignment of relative or subjective probabilities to the scenarios.

The second document provides some general observations and directions:

- Collection of hydroclimatic data, its quality control, and statistical analysis informing about the trends and directions should follow the WMO guidance (as quoted in the Data Management section of this Technical Note).
- The estimation of the long-term mean values of precipitation and flow might be subject to considerable uncertainty. The document postulates that, if possible, this uncertainty in the long term mean values should be quantified. However, such an objective might be impossible to achieve. One of the comprehensive dam system risk assessment projects in eastern Canada attempted to do that and was unsuccessful. Although an extensive amount of hydroclimatic data, including individual storms, from the watershed and the neighboring region was collected, comprehensive statistical testing failed to establish the nonstationarity of the collected time series, even when testing split samples containing only the recent data. (The testing included linear regression for trend, Mann-Kendall test for trend, linear regression with change point, Mann-Kendall test for change point, two-sample t-test for equal means with common variance, two-sample test for equal L-CV (Coefficient of Variation) with unequal variance, Pettit change point test, augmented Dickey-Fuller test for nonstationarity with unit root, Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test for stationarity, and the Priestly-Subba-Rao test for nonstationarity of variance.) Therefore, existing data, contrary to common beliefs, may be insufficient to provide information necessary for developing future projections of climate and streamflow.
- Climate change projections obtained with the help of GCMs and Regional Climate Models (RCMs) can provide insight into behavioral changes that the climate might undergo in the future. However, as the authors indicate, *the climate change projections are most meaningfully consulted for questions of change relative to historical (for example, more or less total annual precipitation, slightly warmer or much warmer winters, or more or less net solar radiation) as opposed to questions requiring basic statistics of local future climate (for example, future local precipitation mean/variance or future local max daily temperature*).

Therefore, it appears that the general conclusion from both documents is that at present there is insufficient command of the climate change modeling and the modeling of its effects on hydrology and water resources to make any attempts to quantify these aspects of hydrological risk. However, what is also emerging clearly from both documents is the postulate to characterize general direction of the changes and to use such information to use the principles of adaptive design and adaptive management in the face of uncertainty. This Technical Note provides general guidance in this direction in the section of Impacts on Climate Change.

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