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Catalogue of Hydrologic Analysis for Asia and the Pacific

Volume 2

Dam reservoir operation for addressing water related disasters, water scarcity and quality

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Dam reservoir operation for addressing water related disasters, water scarcity and quality

The UNESCO-IHP Regional Steering Committee for Asia and the Pacific

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October 2021

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Preface

It is our great pleasure to present the second volume of the Catalogue of Hydrologic Analysis for Asia and the Pacific. This volume focuses on the topic “Dam reservoir operation for addressing water related disasters, water scarcity and quality in Asia and the Pacific”. It contains seven documents from China, Indonesia, Japan, Republic of Korea, Malaysia, Philippines, and Viet Nam. It is the outcome of the international cooperation of the member countries of the Regional Steering Committee for Asia and the Pacific (RSC) under the auspices of the UNESCO Intergovernmental Hydrological Program Phase VIII (IHP-VIII, 2014-2021). It follows the 2020 publication of the Catalogue of Hydrologic Analysis (CHA) Volume 1.

The objectives of the publication of the Catalogue of Hydrologic Analysis are:

- To promote mutual understanding of hydrology and water resources of the region and of the neighboring countries.
- To promote information exchange among different organizations in each country.
- To share information on water-related issues such as disaster preparedness, water environment conservation, and water resources management in Asia and the Pacific.

In Asia and the Pacific, various hydrologic analysis methods have been applied for designing hydraulic structures and river improvement works for rainfall-runoff predictions, flood inundation mapping and other purposes. These hydrologic analysis methods and experiences have different characteristics in terms of climate, topography, and development history of the catchments in which they are applied. Developing a platform to share these experiences and hydrologic analysis methods strengthen risk estimation and water-related hazard damage reduction; especially for researchers and engineers in the region who have limited knowledge of and experiences with them.

To improve this situation and enhance risk estimation ability in research and engineering communities, meetings of the IHP Regional Steering Committee for Asia and the Pacific (RSC-AP) discussed the formation of a research team and the development of a hydro-informatics platform for Asia and the Pacific with the objective of realizing a hydro-hazard resilient region. With the objective enhancing regional capacity for evaluating water-related disaster risks, the RSC-AP decided to develop a Catalogue of Hydrologic Analysis (CHA) as a collaboration among researchers and engineers in Asia and the Pacific. The Catalogue collects documents including experiences and hydrologic analysis methods from practical use to advanced studies for short-term rainfall prediction, rainfall-runoff prediction, flood inundation mapping, hydrologic frequency analysis, eco-hydrology, and more.

In this volume, we focus on dam reservoir operation in Asia and the Pacific. Since ancient times, dam reservoirs have aimed at securing water resources for living and agricultural production. Since then, industrial use and hydroelectric power generation were added – and most recently, securing the water environment and mitigating damage caused by floods. Dam operation methods are being studied and operated in each country to meet different objectives and to reduce the impact of flow control on the natural environment. This report summarizes the operation and water resource management of dams in China, Indonesia, Japan, Republic of Korea, Malaysia, Philippines, and Viet Nam.

By developing and sharing knowledge through CHA, RSC-AP provides a platform to improve the ability for evaluating water-related disaster risks, which in turn will strengthen cooperation among researchers, governmental agencies and private sectors; serve to reduce the damage of water-related disasters; and stand as a regional contribution to achieve the targets of SDGs, UNESCO IHP-VIII (2014-2021) and UNESCO IHP-IX (2022-2029).

We would like herewith to express our sincere appreciation and due respect to all the individual contributors towards this volume from across the region. We also express our sincere gratitude to institutes, agencies and other organizations who have carried out the work reflected in its contents. In particular, we would like to thank the following organizations for providing the necessary support:

- UNESCO Regional Bureau for Sciences, Jakarta, Indonesia
- The Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, which provides funds to support UNESCO IHP activities in Asia and the Pacific

The editors hope that this volume may serve in various ways to further fulfill related national and regional objectives. Finally, we invite readers to provide critical comments and ideas to improve future volumes of the Catalogue of Hydrologic Analysis.

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The Operation of Three Gorges Reservoir at Yangtze River Basin in China – A System Dynamics View

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Abstract

The history of reservoir operation presents a shift from maximizing its operation benefits to balancing both economic and environmental concerns. Currently, almost all of the research aims to lower the environmental impacts, focusing only on one specific aspect of the research target, such as incorporating environmental flow into existing reservoir operation rules. A System Dynamics-based Simulation Approach (SDSA_TGR) was developed for the Three Gorges Reservoir (TGR) in China to address restoring a healthy downstream riverine ecosystem and maintaining a stable reservoir riverbank system and sustainable water use of the reservoir itself - sediment evacuation. The SDSA_TGR explicitly considers the interactions among the TGR system's components such as power production, sediment flushing, landslide stability, and downstream flow regime. Four operation scenarios were proposed to investigate the synergies and tradeoffs between power generation and alleviation of environmental impacts of reservoir operation. The main findings of our research include: (i) ensuring landslide stability can generate the most energy production during the first 50 years of operation; (ii) allowing sediment flushing to evacuate reservoir sediment may come at a high cost; (iii) the release of an extra amount of water to meet the sturgeon spawning flow improves the flow conditions for sturgeon spawning substantially, however also at a high cost of a reduction in electricity generation. The insights gained from this research can assist in the environmentally friendly operation of the TGR system. This paper also presented some recommendations for the TGR operation.

Key Words*: *Three Gorges Reservoir, Yangtze river basin, System dynamics simulation, environmental impacts

1. Introduction

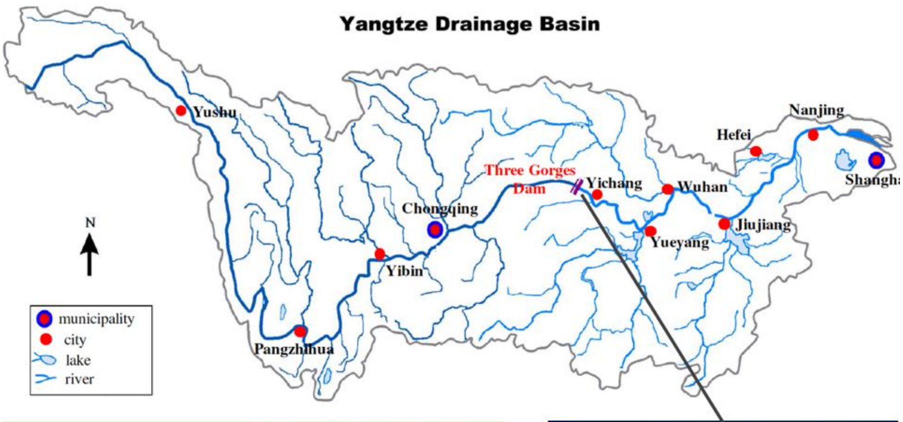
Dams and reservoirs have played important roles in managing floods, generating electricity, irrigating farmland, providing water supply, to name but a few. There are currently over 59,000 registered dams, and the number is still increasing. Dams, however, block the transportation of sediment and create barriers to the movement of nutrients. Well acknowledged environmental impacts of reservoirs and dams include: the change of natural flow and sediment regime, potential reservoir-induced landslides, water pollution, dam breach, and many others.

The past decades have seen numerous efforts devoted in investigating and mitigating those negative environmental impacts of reservoir operation. For example, Tennant (1976), Bovee (1982, 1986), and Stalnaker (1994) investigated the relationship between streamflow and aquatic habitats. Suen and Eheart (2006), Shiau and Wu (2010), Wang et al. (2015), and Rheinheimer et al. (2016) incorporated environmental flow into reservoir operation rules. Shokri et al. (2012), Peng et al. (2014), Bai et al. (2019), and Huang et al. (2019) developed multi-objective analysis models for water-sediment joint regulation. Most of the previous researches aiming at lowering the environmental impacts focus mostly on one specific aspect of research target, like the incorporation of minimum environmental flow targets into existing reservoir operation rules, the restoring of natural flow regime, and the regulation of reservoir sediment, ignoring other environmental impacts such as sedimentation, erosion, and potential geo-disasters induced by reservoir operation.

Multi-purpose reservoir operation system is a complex, interrelated system covering both socio-economic and eco-environmental subsystems, usually with conflicting targets (Jiang et al. 2020a). However, minimal research considers the interactions and feedback among power generation, environmental release, sediment flushing, and reservoir-induced landslides. In this study, a system dynamics based simulation model was developed to establish an environmentally friendly operation of the Three Gorges Reservoir (TGR) aimed at addressing the restoring of a healthy downstream riverine ecosystem, the maintaining of a stable reservoir riverbank system, and the sustainable use of the reservoir itself (sediment evacuation).

2. Three Gorges Reservoir and its concerning environmental impacts

Yangtze river, originating from the southwest of the Geladandong in the Tanggula Mountains of the Tibet Plateau, has a main stream length of about 6,300 km and a catchment area of about 1.8 million km^2. The Three Gorges Dam (TGD) is built on the middle reach of the Yangtze river (see Figure 1). Made of concrete and steel, the dam is 2.335-kilometer-long and 185 meters above sea level and took 17 years to complete. When the reservoir is filled to its maximum height, 175 meters (abs), a nearly 600-kilometer huge reservoir with total storage of 393×10^8 m^3 will be created. Of all the storage, 221.5×108 m^3 is used for flood control, improving downstream flood prevention standards from once every 10 years to once every 100 years. Besides its main purpose as flood control, the nearly 600-kilometre huge reservoir created by the TGD is also used for hydropower generation and navigation. TGR has the world's biggest hydropower station in terms of installed capacity, 22500 MW. An estimate of nearly 100 TWh of electricity shall be generated annually and transmitted to China's mega-cities, including Shanghai and Guangdong, reducing coal consumption by 31 million tonnes per year and avoiding 100 million tonnes of greenhouse gas emissions. By deepening the channel and slowing the flow, TGR also improves the navigability and increases the trade capacity of the river as the Yangtze is the largest water transportation network in China. The TGR has played an important role in preventing floods and generating electricity since its first impoundment in 2003 (Jiang et al. 2020b).



Items	Water level (m)	Storage (billion m³)
Check flood level	180.4	45.044
Design flood level	175	39.3
Normal water level	175	39.3
Flood limiting water level	145	171.5

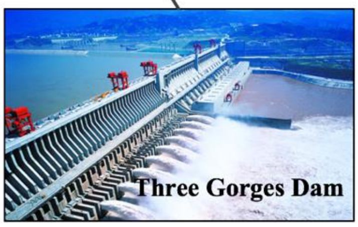


Figure 1 Yangtze river basin and the Three Gorges Dam

However, like most dams and reservoirs in the world, the building of the TGD and the operation of the TGR cause significant and far-reaching environmental impacts, including the sedimentation problem, the alteration of flow regime, the reservoir-induced landslides, the algal bloom (Fu et al. 2010). The TGD blocks the transportation of a huge amount of gravel, sands, and silts down to the Yangtze Delta every year. Yang et al. (2007) indicated that the TGR retains 151 million tons of sediment per year on average since its early operation in 2003-2005. With the control of soil erosion and dam construction in the upper reaches, the sedimentation rate in the TGR in recent years has decreased significantly (91 million tons on average from 2009-2019). The operation of the TGR is also characterized by fast ascent and drop of water level, especially during the flood season. The nearly 30 m water level fluctuations (reservoir water level drops from 175 m to 145 m) put great risk on the landslides' stability within the TGR area. In 2003, the Qianjiangping landslide failed shortly after the impoundment of the TGR and killed 24 lives (Wang et al. 2008). The TGD and the Gezhouba dam cut off the migration route of the Chinese sturgeon, among many other spawning migration fishes. Millions of artificially-bred Chinese sturgeon fry have been released into the Yangtze to revive the river. River fragmentation caused by dam construction and the changed flow and thermal regimes caused by reservoir operation are reported as major contributing factors for the decline of the Yangtze Chinese carps during the last decade (Zhang et al. 2020).

3. Methodology and data

The method (SDSA_TGR) used for analysis of the interactions between TGR's various purposes including those for human purposes such as hydropower generation and those for environmental protections such as fish habitats, sediment flushing, and landslide stability, was developed based on the SDSA model from Jiang et al. (2020a). For more details about the SDSA model, please refer to Jiang et al. (2020a). The significant difference between SDSA and SDSA_TGR is the discharge of sediment. In the SDSA model, sediment can only be released from *sediment release*. In contrast, in the SDSA_TGR model, sediment can be released from *sediment release*, *flood release*, and *power release* in flood season. In non-flood season it is assumed that the discharge from power release contains only pure water and no sediment. Figure 2 presents the schematic operation of the TGR both in flood season (Figure 2(a)) and non-flood season (Figure 2(b)). In the figure, *total reservoir volume* is made up of *water volume* and *total sediment volume*. *Total sediment volume* consists of *river sediment* transported from upstream and landslide deposit, which is the amount of landmass that slides into the reservoir when a landslide fails. *Sediment release* is the release through scouring sluices, *flood release* is the release through spillway and sluices, and *power release* is the release through power plants.

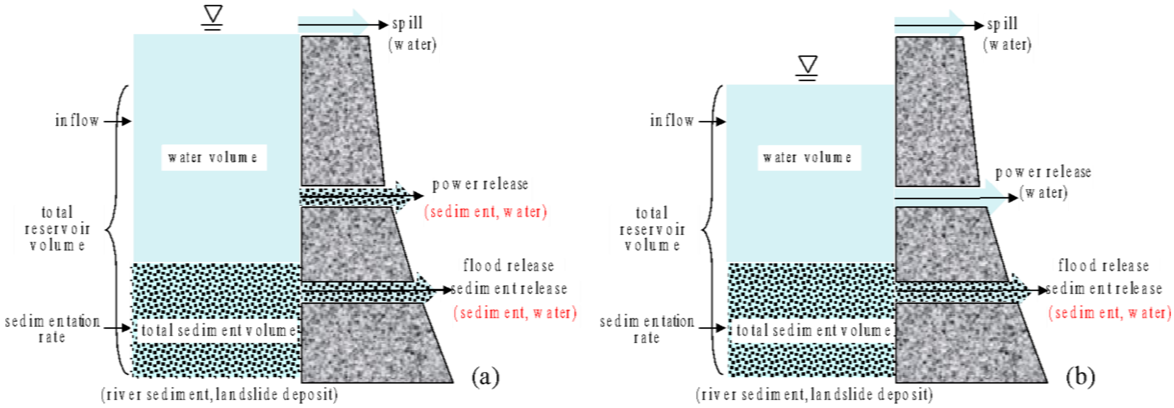


Figure 2 Schematic presentation of the TGR operation in flood season (a) and non-flood season (b)

Historical daily inflow series from 1910-01-01 to 2010-12-31 (shown in Figure 3) were used as inputs to drive the SDSA_TGR model.

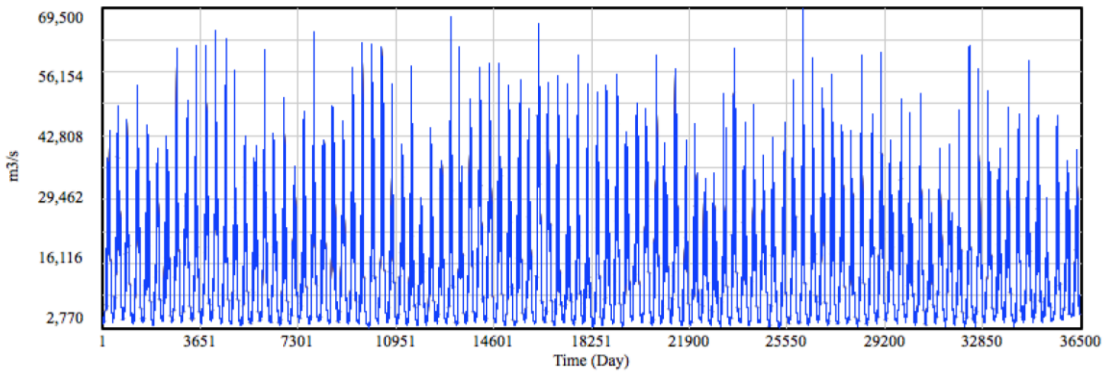


Figure 3 Historical daily inflow series from 1910 to 2010

4. Results

Four operation scenarios are proposed to test the impacts of placing different economic and environmental priorities on the TGR system performance. The S_power scenario, which serves as a baseline, focuses on maximizing power generation. The S_fish scenario ensures ideal flow for sturgeon spawning and the S_sediment scenario allows for sediment flushing. Furthermore, the S_landslide scenario focuses on ensuring landslide stability. Table 1 describes each of the scenarios in detail.

Table 1 Description of reservoir operation scenarios

Operation scenario	Scenario descriptions
S_power	Five power production transition zones: 6,300 MW, 8,400 MW, 10,500 MW, 12,600 MW, and 14,700 MW are set to maximize power production during the periods of reservoir filling-up and draining-down.
S_fish	During the sturgeon spawning season, from October to November, a minimum reservoir release to provide the ideal fish flow for sturgeon spawning is ensured.
S_sediment	During the reservoir drawdown period (from 1 May to 10 June), open the scouring sluice gates fully to allow for sediment flushing when the reservoir water level is between 150 m and 145 m.
S_landslide	Maintain a maximum water level drop rate of 0.6 m/d during the non-flood season.

In this study, eighteen large-scale landslides located in the TGR area are taken into account. For details of each landslide and the main model variables and their corresponding values, please refer to Tale A1 in reference Jiang et al. (2020a). The dynamic behaviour of reservoir water level under four operation scenarios is as shown in Figure 4. The bottom picture shows the whole simulation period (time = 1~36500). The upper picture is for the first 10 years (time = 1~3650). The blue line shows the S_power scenario, the red line for the S_fish scenario, the green line for the S_sediment scenario, and the grey line for the S_landslide scenario. The system behaviours of energy production, total sediment (river sediment and landslide deposit), and fish flow deficit are presented in the following paragraphs.

The dynamic behaviour of energy production under four operating scenarios is shown in Figure 5. The left picture in the lower part shows the energy production by the end of the first ten years (time = 3650). At this time, the S_landslide scenario generates much more electricity when compared to the base run. S_fish and S_sediment scenarios generate much less electricity. And the S_sediment scenario value is slightly higher than the S_fish scenario value. However, by the middle of simulation (time = 18250), the S_fish scenario generates more electricity than the S_sediment scenario. By the end of the simulation (time = 36500), the base run S_power scenario generates the most electricity, followed by the S_landslide and S_fish scenarios. S_sediment scenario generates the least electricity.

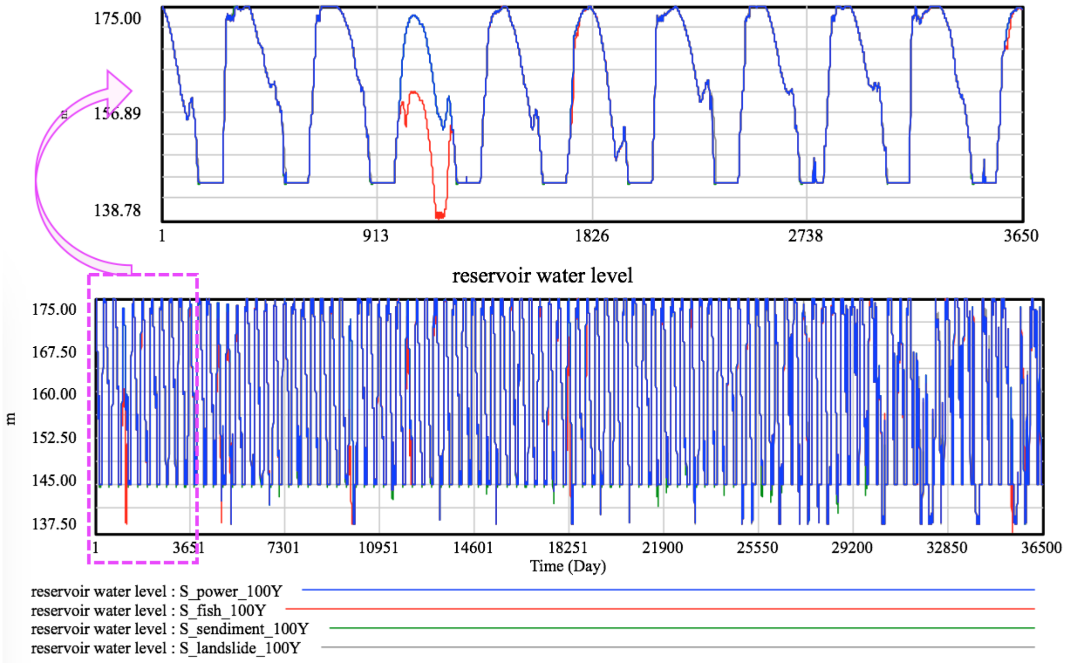


Figure 4 System behaviour of TGR water level under four operation scenarios

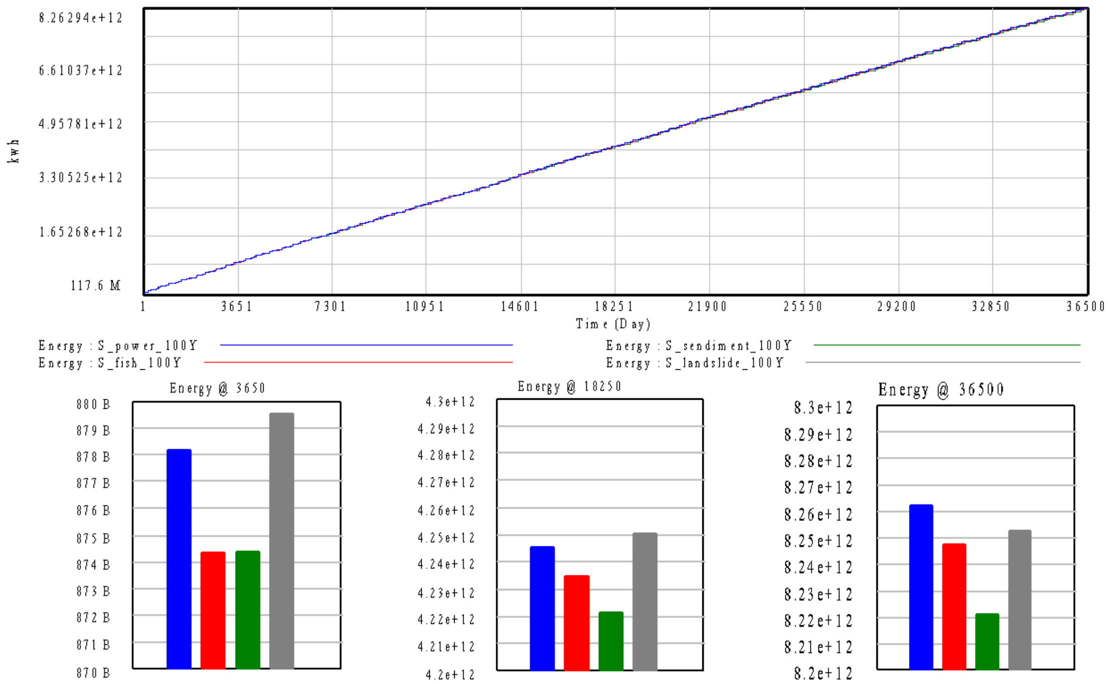


Figure 5 System behaviour of energy production under four operation scenarios

The dynamic behaviour of river sediment under four operating scenarios is as shown in Figure 6. As can be seen, the dynamic behaviour of river sediment under the four operation scenarios didn't change over time. S_sediment scenario significantly lowers reservoir sediment. The river sediment under the S_fish scenario is the highest.

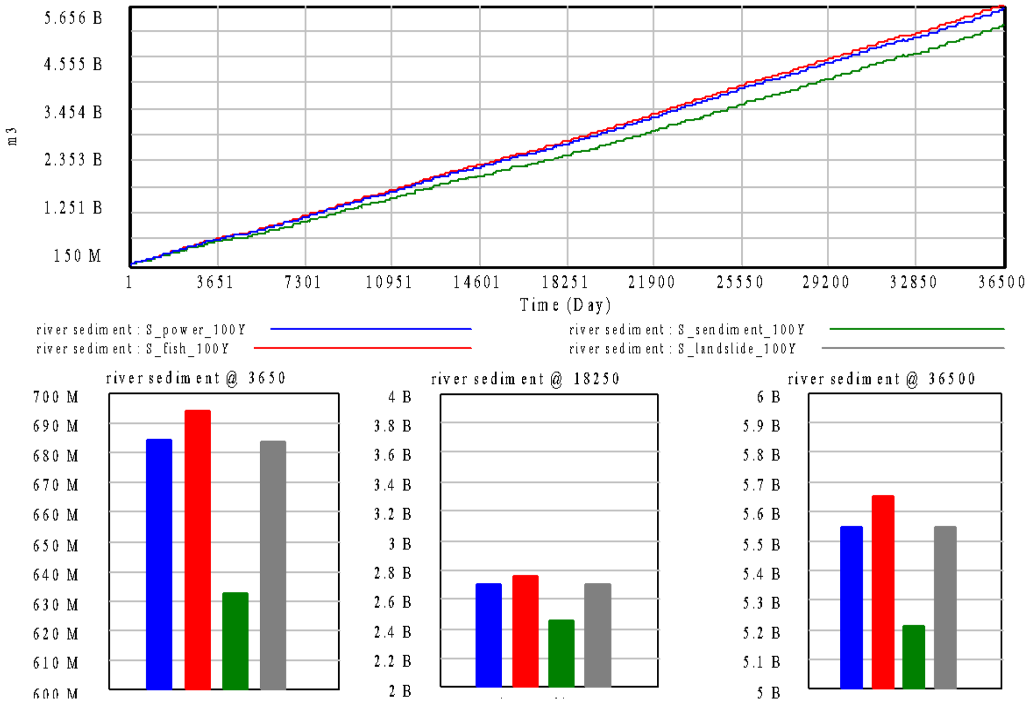


Figure 6 System behavior of river sediment under four operation scenarios

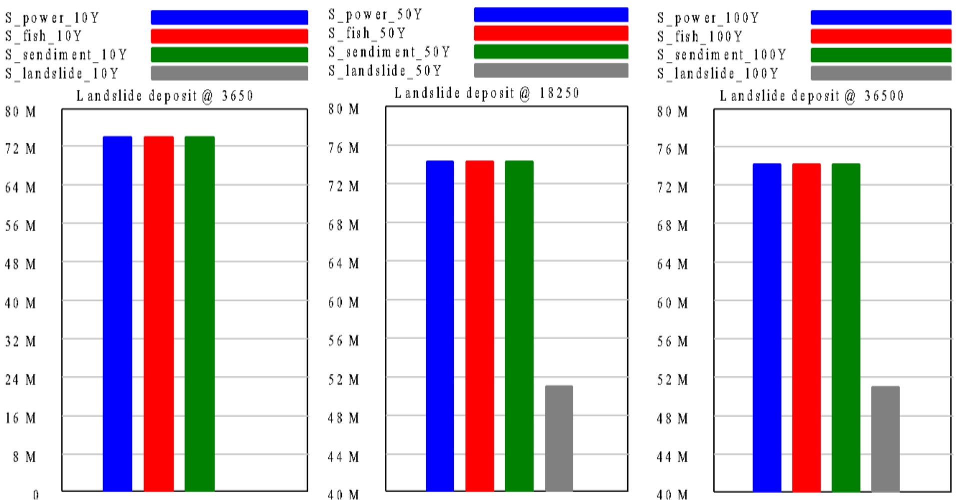


Figure 7 System behavior of landslide deposit under four operation scenarios

The dynamic behavior of landslide deposit under four operating scenarios is shown in Figure 7. By the end of the first 10 years (time = 3650), all of the considered 18 landslides failed under the S_power, S_fish, and S_sediment scenarios if no prevention measures were employed. By the end of the simulation, only a small portion of landslides failed under S_landslide scenario.

The dynamic behaviour of total sediment volume (the sum of river sediment and landslide deposit) under four operating scenarios is as shown in Figure 8. As can be seen, the total sediment volume under the S_fish scenario is slightly higher than the base run value. Total sediment volume under the S_landslide scenario is much lower than the base run during the beginning 50 years (time = 1~18250), then gradually approaches the base run value afterwards. The total sediment under the S_sediment scenario is much lower when compared to the base run value. Another interesting finding is the relationship between the S_sediment scenario and the S_landslide scenario. During the first ten years (time = 1~3650), the total sediment volume under the S_sediment scenario is much higher than the S_landslide scenario. But after that, the total sediment is much lower than the S_landslide scenario. Overall, the total sediment volume under the S_sediment scenario is the lowest by the end of the simulation, indicating that allowing for sediment flushing can significantly reduce the reservoir sediment in the long run.

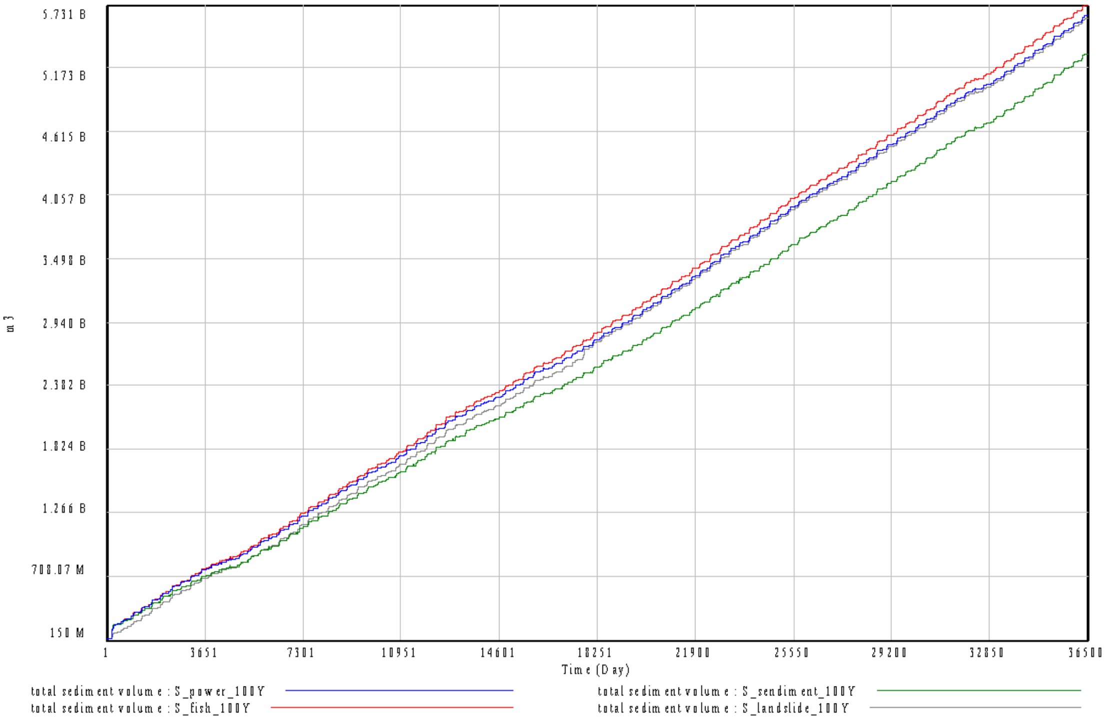


Figure 8 System behaviour of total sediment under four operation scenarios

The dynamic behaviour of the total fish flow deficit under four operating scenarios is as shown in Figure 9. The fish flow deficit under the S_power, S_sediment and S_landslide scenarios share the same system behaviour. Ensuring ideal flow for sturgeon spawning can significantly improve the flow condition for the Chinese sturgeon.

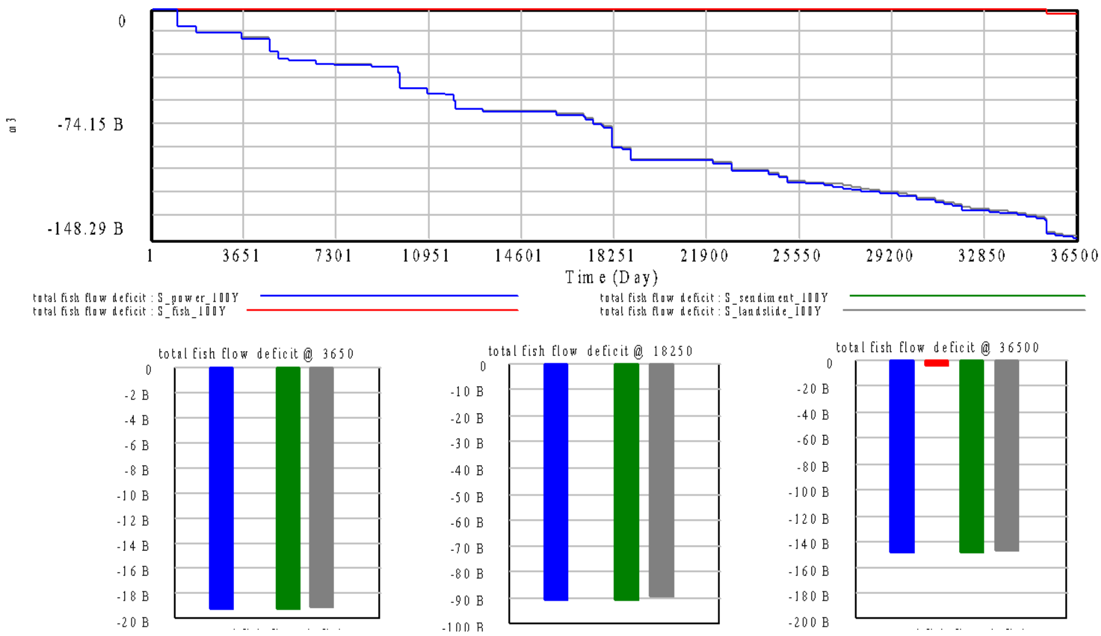


Figure 9 System behavior of total fish flow deficit under four operation scenarios

5. Conclusion and discussion

In recent years, the China Three Gorges Corporation has been seeking environmentally-friendly operating rules for the TGR. As the multi-purpose TGR operation system is a complex, interrelated system, a system view of the interactions between hydropower production and environmental impacts is a prerequisite to attain the full benefits of its operation. To better understand the dynamic behaviour of the TGR system, we developed a SDSA_TGR simulation model that considers the interactions and feedbacks among the reservoir various systems function. The system behaviour of the TGR under different operating policies with priorities focusing on maximizing power production and lowering negative environmental impacts respectively are investigated. The interesting findings are concluded in the following paragraphs.

Finding 1: Ensuring landslide stability can generate the most energy production during the first 50 years of operation. In the S_landslide scenario, ensuring a maximum allowable water level drop rate to guarantee landslide stability results in a significant decrease in landslide deposit and correspondingly a reduction in total sediment volume. A lower level of sedimentation means more active storage capacity is preserved, resulting in the highest power generation after 50 years of operation, indicating that pursuing the maximum production of hydropower like in the S_power scenario does not always guarantee the maximum energy production. However, after 100 years of operation, the S_power scenario finally generates the most electricity.

Finding 2: Allowing sediment flushing to evacuate reservoir sediment may come at a great cost. Sediment flushing aims to maintain a high active reservoir storage capacity to store more water for power generation, water supply, and many other uses. However, our research finds that for the operating rules we proposed here under the S_sediment scenario, the effect of evacuating sediment to maintain active storage capacity is outpaced by the impact of discharging significant amounts of additional water along with the process of sediment flushing. It explains the results shown in Figure 5 that the S_sediment scenario generates the least electricity.

Finding 3: The release of an extra amount of water to meet the sturgeon spawning flow improves the flow conditions for sturgeon spawning substantially, however also at a high cost of a reduction in electricity generation. During sturgeon spawning in October to November and the TGR filling-up period from September to October, it is crucial ensuring sturgeon spawning flow fill up to its designed normal water level of 175 m in dry years (see the red line in Figure 4).

The simulation results presented and discussed in previous sections offer us a better understanding of the potential synergies and trade-offs among the reservoir's different operation priorities. Based on the simulation results, the following recommendations for the operation of the TGR and future research are made: (i) avoiding abrupt reservoir water level fluctuations while operating the reservoir; (ii) more in-depth researches on sediment flushing operating rules are needed to achieve the goal of sediment evacuation at no or less cost of a reduction in electricity generation; (iii) further studies on balancing the needs of reservoir filling-up and releasing of fish flow during the sturgeon spawning season.

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6. References

Bai, T., Wei, J., Chang, F.J., Yang, W., Huang, Q., 2019. Optimize multi-objective transformation rules of water-sediment regulation for cascade reservoirs in the Upper Yellow River of China. J. Hydrol. 577, 123987.

Bovee, K.D., 1982. A guide to stream habitat analysis using the instream flow incremental methodology. US Department of Fisheries and Wildlife Services.

Bovee, K.D., 1986. Development and evaluation of habitat suitability criteria for use in the instream flow incremental methodology. US Department of Fisheries and Wildlife Services.

Fu, B., Wu, B., Lü, Y., et al., 2010. Three Gorges Project: Efforts and challenges for the environment. Prog. Phys. Geog. 34(6), 741-754.

Huang, L., Li, X., Fang, H., Yin, D., Si, Y., Wei, J., Liu, J., Hu, X., Zhang, L., 2019. Balancing social, economic and ecological benefits of reservoir operation during the flood season: A case study of the Three Gorges Project, China. J. Hydrol. 572, 422-434.

Jiang, H., Simonovic, S.P., Yu, Z., Wang, W., 2020a. A system dynamics simulation approach for environmentally friendly operation of a reservoir system. J. Hydrol. 587, 124971.

Jiang, H., Simonovic, S.P., Yu, Z., Wang, W., 2020b. System dynamics simulation model for flood management of the Three Gorges Reservoir. J. Water Res. Plan. Man. 146(7), 05020009.

Peng, Y., Ji, C., Gu, R., 2014. A multi-objective optimization model for coordinated regulation

of flow and sediment in cascade reservoirs. Water Resour. Manage. 28, 4019-4033.
Rheinheimer, D.E., Liu, P., Guo, S., 2016. Re-operating the Three Gorges Reservoir for environmental flows: A preliminary assessment of tradeoffs. River Res. Appl. 32, 257-66.
Shiau, J.T., Wu, F.C., 2010. A dual active-restrictive approach to incorporating environmental flow targets into existing reservoir operation rules. Water Resour. Res. 46, W08515.
Shokri, A., Haddad, O.B., Mariño, M.A., 2012. Reservoir operation for simultaneously meeting water demand and sediment flushing: stochastic dynamic programming approach with two uncertainties. J. Water Res. Plan. Man. 139, 277-289.
Suen, J., Eheart, J.W., 2006. Reservoir management to balance ecosystem and human needs: Incorporating the paradigm of the ecological flow regime. Water Resour. Res. 42, W03417.
Stalnaker, C.B., 1994. The instream flow incremental methodology: A primer for IFIM (Vol. 29). National Ecology Research Center, National Biological Survey.
Tennant, D.L., 1976. Instream flow regimens for fish, wildlife, recreation and related environmental resources. Fisheries. 1, 6-10.
Wang, F., Zhang, Y., Huo, Z., Peng, X., Wang, S., Yamasaki S., 2008. Mechanism for the rapid motion of the Qianjiangping landslide during reactivation by the first impoundment of the Three Gorges Dam reservoir, China. Landslides. 5(4), 379-386.
Wang, H., Brill, E.D., Ranjithan, R.S., Sankarasubramanian, A., 2015. A framework for incorporating ecological releases in single reservoir operation. Adv. Water Resour. 78, 9-21.
Yang, S.L., Zhang, J., Xu, X.J., 2007. Influence of the Three Gorges Dam on downstream delivery of sediment and its environmental implications, Yangtze River. Geophys. Res. Lett. 34 (10), L10401.
Zhang et al. 2020. Rapid change in Yangtze fisheries and its implications for global freshwater ecosystem management. Fish and Fish. 21(3), 601-620.

Saguling Reservoir Operation at Citarum River Basin in West Java – Indonesia: Opportunities and Challenges

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Abstract

Saguling reservoir is one of three large multi-purpose cascade reservoirs constructed along the Citarum river basin. These reservoirs and its river basins play important roles to provide water needs for agriculture irrigation, domestic, hydropower plant and industrial activities in West Java and DKI Jakarta Provinces. Several environmental problems have increased in the last two decades in this region related to flood, soil erosion, land use change, water pollution, and fluctuations of water supply. Similar conditions were experienced in Saguling reservoir in terms of environmental degradation consisting of sedimentation and water pollution. Despite equipment, tools and efforts engaged so far, this dam has experienced a decline in capacity and potential functions. USLE method was used to estimate erosion level around Saguling reservoir catchment areas. These catchment areas showed a very high erosion index up to 491 tons/ha/year and with total erosion of 112 million tons/year. Citarum, Ciwidey and Cisangkuy sub-catchments had very high erosion levels with 661, 567 and 540 ton/ha/year respectively and classified as very bad erosion index. Efforts and concerns should be enhanced in order to ensure Saguling reservoir functions and operation for a long-time by controlling and improving water quality entering this dam. Ecohydrology concept gives alternative ways to restore river basins and reservoir ecosystems for the reason of its capability to trap pollutants and sediment and provide habitats for demersal and pelagic species. Low-cost technology through ecohydrology implementation will help to reduce anthropogenic impact on river basins throughout coastal zones by using the natural capacity.

***Key Words**: ecohydrology, ecosystem services, hydropower, multipurpose dam, sedimentation, water quality*

1. Introduction

Indonesia is an archipelagic country with abundant natural resources located in the equator area. Around 13.85 million ha of inland water resources spread across the archipelago consisting of: rivers, swamps, flood exposures, lakes, lakes, lakes, and dams [Kartamiharja et al., 2009]. Beside ecology and social functions, these water ecosystems also have other important functions in the economic sector. It closely supports almost all human activities and economic value chains including industry, energy, transportation, water and sanitation, fisheries, agriculture, forestry, and tourism [Sutapa, 2019]. The potential economic values of inland water resources in Indonesia is estimated to reach thousands of trillions IDR per year, some items among others: 143 trillion IDR/year for providing 100% safe drinking water access; US$ 9,935 million/year for agricultural irrigation systems and 1.92 billion US$/year for hydroelectric power plants development of 7,358,400 MWh/year [Sutapa, 2021].

The huge potential contribution of inland water resources to the national economy attracts higher attention of various parties and stakeholders to manage them in a comprehensive and sustainable approach. It can be noted that geographical position on the equator makes Indonesia very sensitive to changes and tends to decrease environmental conditions or degradation in terms of quality and quantity. Global climate change contributes to ecosystems and their environment deterioration in addition to human pressure through anthropogenic activities such as pollution, land use changes and natural resources exploitation. This condition is often exacerbated by increasing disaster frequency such as floods, landslides, earthquakes and very extreme weather. The National Agency of Disasters Mitigation (BNPB) recorded 1,441 water related disaster events from January to June 2021 consisting of: 599 floods, 398 tornadoes, 293 landslides and 108 forest fires [BNPB, 2021].

In accordance with Act No.17/2019 on Water Resources Management, water management should be implemented from central to a local level and organized based on several principles including: public benefit, fairness, affordability, independence, local wisdom, balance, insight into the environment, sustainability, conservation, integrity, accountability, transparency and harmony [Zalewski, M, 2015; Sutapa, 2018]. Regulation on water resources, as mentioned in Article 3 Act No.17/2019, has purposes: protect and ensure people water gain; safeguard sustainable water availability for society equitable benefits provision; guarantee water preservation; ensure legal certainty creation for public participation implementation; ensure communities protection and empowerment including indigenous peoples in water and water sources conservation; and control water destructive power including prevention, mitigation, and recovery [MPWH, 2019]. In general, water management policy in Indonesia aims to ensure people rights to water access in line with sustainable development achievements through environmentally friendly manner.

Surface water is one of the main raw water sources to fulfill national water needs even though its sensitivity to seasons and climate change [Yusuf et al., 2009]. Artificial lakes and reservoirs are often built in order to support water resources management and utilization for a certain period of time. Saguling reservoir built in 1981 is one of man-made dams constructed along Citarum river. This reservoir, combined with two other Cirata and Jatiluhur reservoirs, has several important functions covering water supply for agriculture, domestic, hydropower plant and industrial activities from West Java to DKI Jakarta Provinces. Despite its significant roles so far, Saguling reservoir has experienced a decline in capacity and potential functions in the last two decades due to pollution, sedimentation and siltation. Sutapa et al. reported that implementation of the ecohydrology concept in the upper Citarum river basin by introducing an ecohydrology demonstration site on Cibitung catchment area permits to improve water quality entering Saguling reservoir [Sutapa et al., 2021]. This paper aims to describe Saguling reservoir characteristics consisting of functions, operations, legal frameworks, obstacles and future challenges in accordance with national policy to support sustainable water resources management.

2. General Reservoir Operation Method in Indonesia

Construction of dams and its reservoirs is part of government policies follow-up in supporting water supply, food and energy securities. Upgrading, improvement and maintenance of existing reservoirs and dams are important to be noticed in addition to development of new dams including its functionality, sustainability, and safety in order to guarantee the effective continuation and achievement of national targets. Good understanding of dam characteristics and functions will help to predict constraints and failure risks of its potential operation in the long term.

2.1 Purpose of Dam Reservoir Operation

In general, constructed reservoirs are called multipurpose reservoirs for the reason of its consistency and reliability to fulfill stakeholders' diverse needs. A such multipurpose project should deliver quantifiable benefits of each purpose. According to Bonet, six categories of data are used to create a multipurpose benefits framework representing reservoir operations and services culmination. Assessment of collective and interdependent relationships are basically founded on these associated categories [Bonet et al., 2015] consisting of:

- Water supply: water withdrawals by public and private for municipal, industrial and consumption needs.
- Irrigation: water withdrawal and use to meet crop and plant requirements for growth and production.
- Hydropower: water use and operation facilities and/or equipment to produce electricity power.
- Flood control: use of dam facilities and equipment to prevent and/or lessen flood damage severity to valuable resources within a flood basin.
- Navigation: locks operation and control to facilitate goods transportation through inland waterways.
- Recreation: use of reservoirs or river water bodies for physical and recreational activities.

Based on the National Strategic Plan 2020 – 2024, several future challenges should be understood related to dam's construction and management in Indonesia. Five major issues of these challenges include increasing demands of: services for raw water, drinking water, agriculture irrigation, and hydropower as a renewable energy source; dam and safety performance from disaster risk; OP management improvement, upstream dam areas conservation and new technologies application to get optimized benefits and safety; integrated development and utilization of multi-purpose water reservoirs for cities, agriculture, and electricity; economic zones and smelter industries support [Idris et al., 2019]. **Table 1** shows potential benefits and loss calculation related to dam construction. It is important to note that avoided benefits loss up to 1,004,742,859 USD may be saved covering: irrigation, hydropower benefits, household property and assets, dam replacement or rehabilitation expenditure and emergency response cost [AIIB, 2017]. One of efforts carried out by government in order to strengthen dam's operational improvement and the safety was establishment of Dam Operational Improvement and Safety Project (DOISP) was established. This project was implemented in several steps within a six years period of activities. The 2nd phase of DOISP starting from the middle of 2017 to the end of 2022 aims to complete previous program targets not being able to be achieved, particularly emphasizing the dam's physical rehabilitation and further operational and safety improvement. Main concerns of this project cover: strengthening dam management units and safety assurance institutions; development of national expertise in engineering and management; remedial works design improvement and quality assurance construction; dam safety assurance expansion to mine tailings and privately-owned dams; deferred maintenance cost reduction related to inadequate budgets; hydrology and flood design resolution; emergency action plans implementation; sedimentation problem and risks reduction; and portfolio assessment for remedial works [MPWH, 2010].

Table 1. Potential averted benefit and loss related to dam construction (AIIB, 2017)

Category	**Avoided Benefit Loss (USD)**	**Proportion of Total Benefits Loss (%)**
Irrigation	98,101,854	9.8
Hydropower benefits	30,723,561	3.0
Household property and assets	463,550,024	46.1
Dam replacement or rehabilitation expenditure	281,112,376	28.0
Emergency response cost	131,255,043	13.1
Total	1,004,742,859	100

2.2 Basic Method & Rule for Dam Reservoir Operation

Saguling reservoir is part of three cascade dams with Cirata and Jatiluhur reservoirs [**Figure 1**]. Equal sharing principle is the basic method of distribution for these reservoirs in total live water storage fixed during each month. Downstream water demand and water level requirements will be taken into account in determining water distribution between three reservoirs. Several important elements include: water level, elevation and volume/surface area relation, water demand, evaporation and local inflow. Reservoir operation rules consist of three hydrological periods: normal, wet and dry year, starting at its levels on 1st January. A dry year corresponds to a year with average local inflow of 10% and 40% dry month. Meanwhile, the values 50% and 60% to 90% of average represent normal and wet years respectively [Barus et al, 2017].

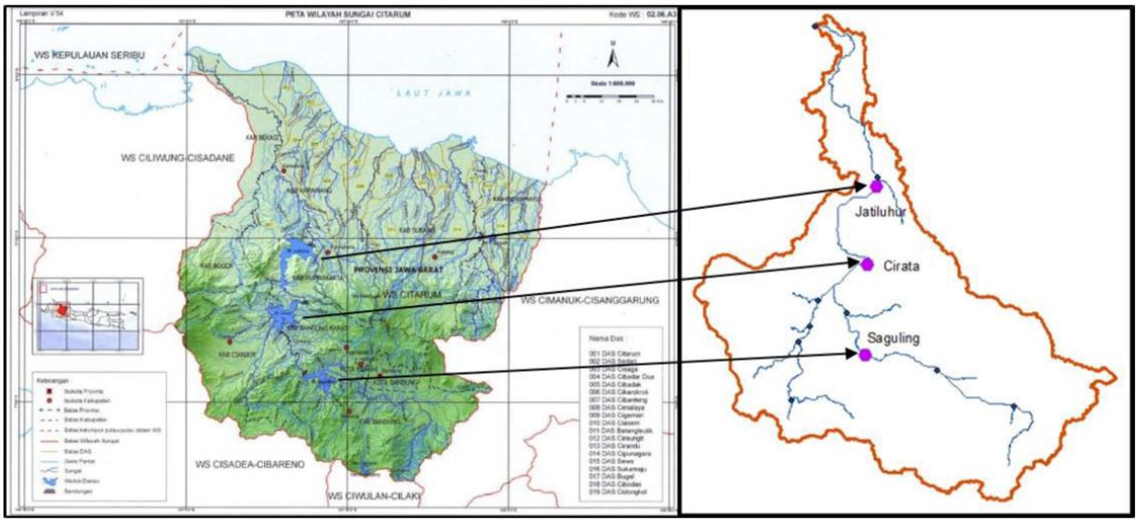


Figure 1. Three Dams location along Citarum River Basin based on Presidential Decree 12 Year 2012 [Barus et al, 2017]

In general operation, Saguling reservoir water level should be maintained between 625.0 and 642.5 m + MSL. For a normal and dry year, maximum levels of 642.5 m with spilling at 643.0 m and flood storage 25 Mcm are taken into account for every month of the year. Total mandatory flood storage space in these periods amounts to 95 Mcm. This value is equivalent to 3.6% of combined live storage capacity of 2,653 Mcm. In case of wet year period, maximum levels of 642.0 m with spilling at 643.0 m and flood storage 50 Mcm) will be noticed [Mayasari et al., 2015]. Flood storage space in a wet year is spared to 120 Mcm, corresponding to 4.5% of live storage capacity. Flood control seems to have a minor role in the method of standard operation with only 0.5 m for maintaining flood control space and needs to be re-considered in the future. Technical data of Saguling dam is summarized in **Table 2**.

3. Dam Reservoir Operation in Citarum River

3.1 Overview of the Citarum River

Citarum river is one of major rivers on Java island in Indonesia. This river basin located in West Java Province, has 269 km of length and flows from Wayang mountain foothills with 1,700 masl in the south to river mouth in the north Java sea coast. Tropical monsoonal characterized by different rainy and dry seasons is the main climate in the Citarum river basin with relatively constant humidity and temperature throughout the year. November to April is generally the rainy season period and May to October corresponds to the dry season period.

Almost 70% of annual rainfall occurs during the rainy season, with average annual rainfall in the range of 1,000 mm in coastal areas and 4,000 mm in the mountainous areas. Highland and mountainous areas have average temperature of 15 – 16 °C while lowland areas have around 27° C in average temperature [Mayasari et al., 2015]. **Figure 2** shows daily inflow in the Saguling, Cirata and Djuanda reservoirs (m3/s) during the period of 1st January to 28th June 2010.

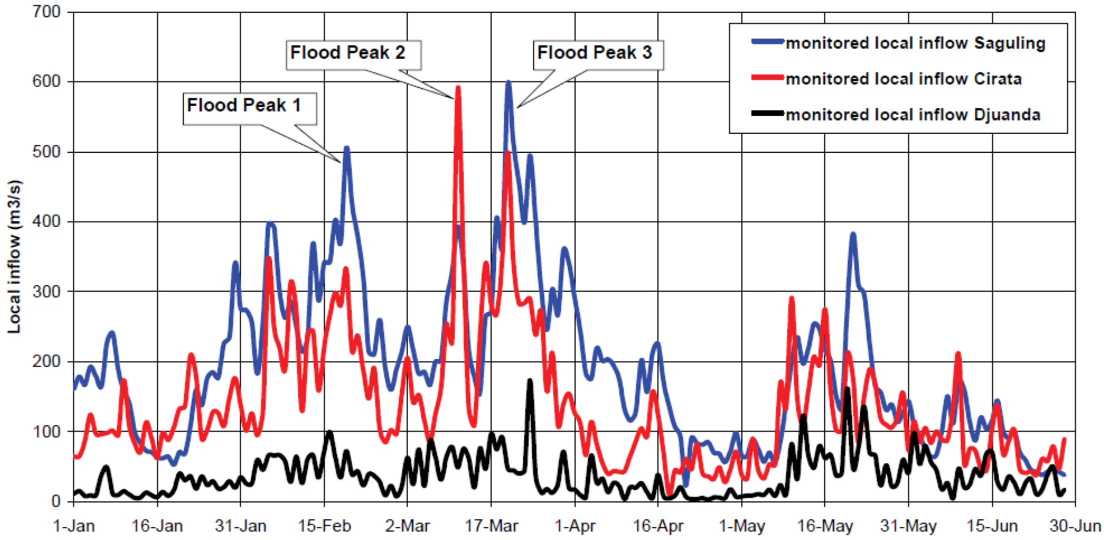


Figure 2. Daily local inflow in the Saguling, Cirata and Djuanda reservoirs (m^3/s) during the period of 1st January to 28th June 2010 [MPWH, 2010]

Citarum river basin topographically consists of upper, middle, and downstream sections. Bandung Basin is a giant basin located in the upper section mostly covered by forest with elevations of 625 – 2,600 meters above sea level (masl). Middle and downstream sections are located in the range of 200 - 2.600 masl and 200 - 1,200 masl respectively. Agricultural and settlement areas cover the middle and lower part of this river basin. Water from Citarum river flows to support three cascades dam's operation including Saguling, Cirata, and Jatiluhur from the upper to the downstream. Mayasari et al. reported that these dams have important roles in Indonesia economic development among others as hydropower reservoirs to generate up to 1,973 MW for providing electricity in Java and Bali islands, as source of water to irrigate 240,000 ha of paddy fields and crops, and as raw water for domestic and industrial activities in West java and DKI Jakarta provinces [Mayasari et al., 2015].

Table 2. Saguling Dam Technical Data [BBWSC, 2008]

Characteristic	Notice		Characteristic		Notice
Beginning construction	1981		Capacity	Flood elevation	645 m
Dam type	Embankment, rock-fill with watertight core			Highest elevation	643 m
Height above riverbed	97 m			Lowest elevation	623 m
Height	99 m			Flood surface area	53,432 km^2
Length	301.4 m			Widest surface area	48,695 km^2
Width	10 m			Narrowest surface area	17,407 km^2

Elevation of crest	650.5 m			Dam volume during flood	982 million m^3
Total capacity	2.79 million m^3			Maximum dam volume	875 million m^3
Provision	Irrigation, hydropower 700 MW			Dam volume at dry river	163 million m^3
Catchment area	2,283 km^2			Effective dam volume	609 million m^3
Average annual rainfall	1,321 mm		Tributaries	Ciminyak, Cijeruk	Small river
Rainfall by design	2,322 mm/year			Cibitung	Small river
Average Annual Discharge	80.85 m^3/sec			Cipatik, Cilanang	Small river
Preventive Discharge by Design	3,200 m^3/sec			Cihaur, Cijambu	Small river

3.2 Characteristics of Saguling Dam Reservoir

Saguling dam is an artificial lake or reservoir constructed in 1981. This reservoir is one of the big dams along the Citarum river basin. Besides other purposes, Saguling reservoir was built to provide hydropower electricity up to 700 MW at the first phase and expandable to 1,400 MW following future different customers' demand. Based on geo-topography conditions, Saguling dam has numerous bays and irregular shapes with a lot of water springs coming from the surrounding hilly environment [MPWH, 2015]. **Figure 3** shows Saguling reservoir and power house for electrical generation.

Several equipment was engaged to manage the reservoir and powerhouse generator [**Table 3**]. Advanced technology is also planned to be installed for drawing on digital systems synergized with existing platforms such as real time monitoring data, flood forecasting, warning and preparedness systems. Telemetry system is used to facilitate real time data connecting dam site, relay station and office within basin organization and central dam management unit [**Table 4**]. Basic Dam Safety Facilities (BDSF) were considered to be improved to strengthen dam basic safety consisting of: access and mobility, communication facilities, surveillance and monitoring equipment, inspections and emergency repair, power supply, water borne transportation etc [AAIB].

Table 3. Instrument and Facilities in Saguling Reservoir [AIIB, 2017]

Instrumentation	Facilities	Related equipment
V-Notch Weirs	CCTV Cameras	Monument Surveys
Water level	Toe lead-away drains	Settlement Surveys
Seismographs	Stand by Generators	Dip Meters
Piezometers		Pressure Gauges
Inclinometers		Readout Units
Extensometers		

Table 4. Flood forecasting and preparedness system [AIIB, 2017]

Risk	Monitoring System	Communication	Response Capacity
Hazard	Rainfall	Radio	Evacuation center
Risk elements	River level	Telephone	Search and rescue
	Water reservoir	Household warning	
	Dam condition		

(a)

(b)

Figure 3. Saguling reservoir (a) and hydropower house (b) [IP, 2018]

3.3 Future Challenges of Saguling Dam Management

Several environmental issues attracted national attention in the last two decades including: water quality deterioration, flood, soil erosion, land use change and climate change. Saguling is one of reservoirs subjected to environmental decrease mostly related to sedimentation and water pollution. These main problems tend to shorten the useful life of the reservoir. Wardani et al. reported that water quality in Saguling reservoir deteriorated significantly due to polluting substances coming from domestic, industry, agricultural activities [Wardhani et al., 2018; Sutapa et al., 2019]. **Figure 4** shows Saguling reservoir silting due to aquatic plants blooming.

Figure 4. Saguling reservoir silting due to aquatic plants blooming [IP, 2018]

Turbidity generally represents sediment content of river water reflecting erosion level of related watershed area. Monitoring of river water turbidity will be important information and tool to support reservoir management as sedimentation closely affects dam functions. Universal Soil Loss Equation (USLE) is a commonly used method to predict erosion rates for the reason of simplicity where rain and runoff are the main factors causing erosion [Arifandi F. and Ikhsan C. 2019]. Based on this method, Risdiyanto estimated erosion levels around Saguling reservoir catchment areas. It was indicated that these catchment areas had a very high erosion index up to 491 tons/ha/year and with total erosion of 112 million tons/year [Risdiyanto, 2009]. **Table 6** summarizes erosion level and index on Saguling catchment areas. Citarum, Ciwidey and Cisangkuy sub-catchments showed very high erosion levels with 661, 567 and 540 ton/ha/year respectively and classified as very bad erosion index. Meanwhile, other sub-catchments were categorized as bad erosion index with quite high erosion level close to threshold value >480 tons/ha/year. **Figure 5** represents erosion index map distribution of Saguling catchment areas, while **Figure 6** indicates its sediment deposition areas. Field observation noticed that high erosion level of sub-catchments seems to be closely related to type of land cover in the form of vegetable and open land [Risdiyanto, 2009]. Efforts to control and improve water quality entering this dam must be the concern of managers and stakeholders in the future.

Table 6. Level and index of erosion on Saguling catchment areas [Risdiyanto, 2009]

Sub-catchment		**Land erosion**		
Name	**Area (ha)**	**Ton/year**	**Ton/ha/year**	**Erosion index**
Cikapundung-Cipamokolan	30,442.2	13,698,610	450	Bad
Cikeruh	18,641.3	6,659,086	357	Bad
Cisangkuy	34,092.1	18,403,774	540	Very bad
Citarik	21,816.5	9,441,560	433	Bad
Upper Citarum	37,745.2	24,930,983	661	Very bad
Ciwidey	22,138.9	12,556,520	567	Very bad
Southern part of Saguling dam	32,540.9	15,443,496	475	Bad
Northern part of Saguling Dam	27,959.6	11,212,448	401	Bad
Total	228,757.0	112,346,477.0	491.1	Very bad

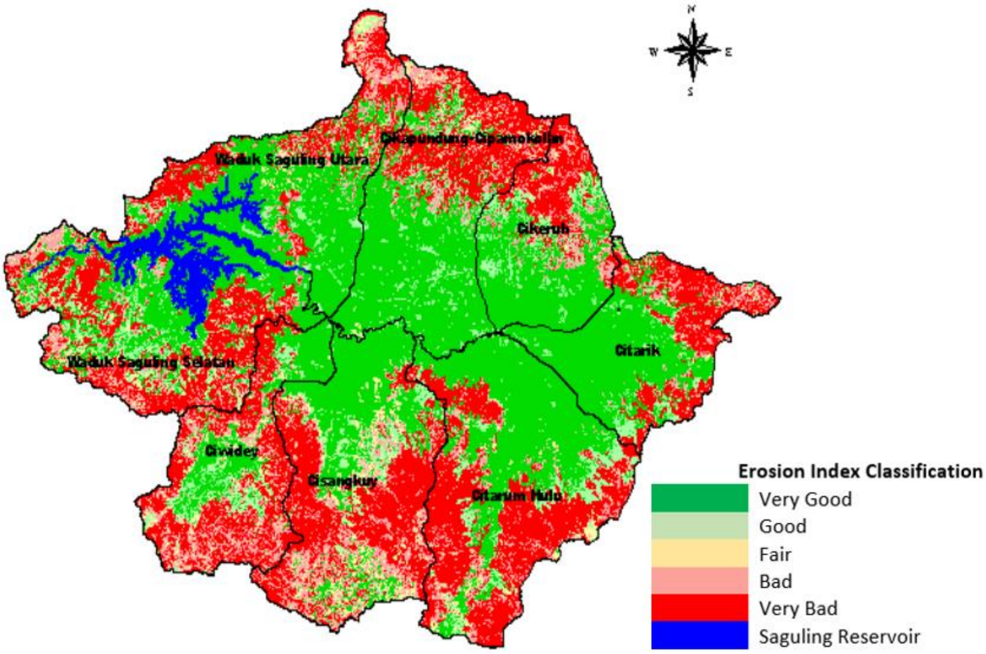


Figure 5. Erosion Index Class on Saguling Dam Catchment Area [Risdiyanto, 2009]

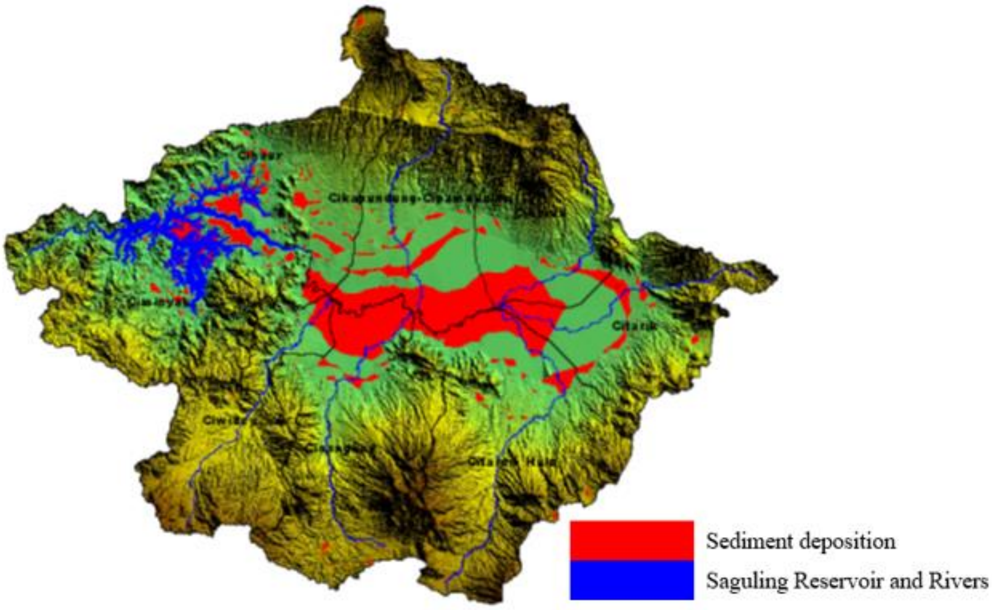
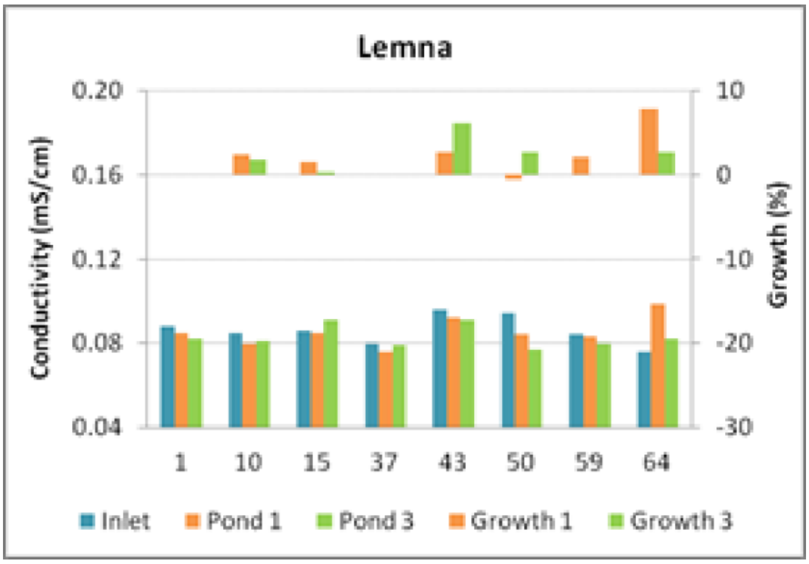


Figure 6. Sediment deposition in Saguling dam catchment area [Risdiyanto, 2009]

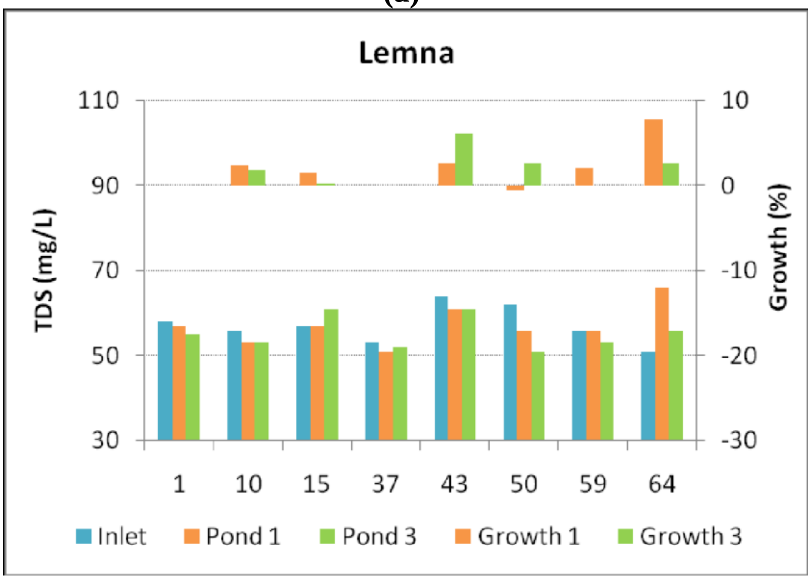
3.4. Ecohydrology Demonstration Site as a Tool to Strengthen Ecosystem Services

Ecohydrology concept may be used to restore and create wetlands, mangroves, salt marshes and mudflats for the reason of their ability in pollutants and sediment trapping and providing habitats for demersal and pelagic species. Low-cost technology through ecohydrology implementation gives an alternative in anthropogenic impact mitigation on river basins throughout coastal zones by using the natural capacity [Wolanski et al., 2004]. Sutapa et al.

reported the capability of aquatic plants in Saguling demo site such as *Lemna minor*, *Ceratophyllum demersum*, and *Eichhornia crassipes* to trap nutrients excess of pollutants and sediments and convert them into plant biomass [**Figure 7**]. In this case, it permits the restoration of the water ecosystem and its environment on the ponds or reservoirs by providing habitats for demersal and pelagic species. It was also noted that ecohydrology can mitigate climate variability and human activity impact on Lacar lake in Argentina [Sutapa et al., 2021]. Based on ecohydrology implementation in three different demonstration sites, there was an alternative solution to restore and improve lake and river ecosystem services. Tools development integrating hydrological cycles with basin-wide human activities should be comprehensively considered.



(a)



(b)

Figure 7. Conductivity (a) and TDS (b) levels in Lemna ponds [Sutapa et al., 2021].

4. National Development Plan and Legal Framework

The Ministry of Public Work and Housing RI noted that the national government has 192 government-owned dams with 7 dams newly constructed within the “new 65 dams’ program”. With ten other new dams constructed in the 2017-2018 period, the number of government dams will become 202. In addition to government-owned dams, there are 32 non-government dams, owned by private companies or state-owned companies [MPWH, 2015].

Most of the dams in Indonesia are quite old in the age range of 20-50 years and a large number of dams are getting old over 50 years. Among 234 dams there are: 7 dams more than 100 years old; 36 dams 50-100 years old; 117 dams 20-50 years old; and 73 dams less than 20 years old. This condition requires attention from different stakeholders related to operations and maintenance in order to ensure safety of the dams and its functions. In general, implementation of dam operations is carried out based on dam operation permits issued by the Minister of Public Works and Housing in accordance with Regulation No.27/PUPR/2015. Only 16 of 202 government-owned dams have operating licenses in 2018 [MPWH, 2015].

5. Good Practice and Lesson Learned

Saguling reservoir and Citarum river basin have national strategic functions. These dams and rivers play important roles related to: potential water resources; population and sector; economic, social, and environmental impacts on development; and potential water damage [MPWH, 2015]. Saguling reservoir is one of three large multi-purpose cascade reservoirs constructed along the Citarum river basin. The other two reservoirs are Cirata reservoir and Jatiluhur reservoir. These reservoirs serve and provide as sources of: electricity generation for Java and Bali islands, rice fields water irrigation of 353,071 Ha area, raw water for household and industrial drinking water in West Java and Jakarta Provinces, and fish ponds of 39,292 Ha area [MPWH, 2015]. Several key environmental issues arose in the last two decades in this region. Flood, soil erosion, land use change, water pollution, and fluctuations of water supply are the major water related problems considered by different stakeholders. Saguling reservoir experienced similar conditions with two other reservoirs in terms of environmental degradation related to sedimentation and water pollution [Wardhani et al., 2018]. Based on the data from three different ecohydrology demonstration sites, Sutapa et al. reported that implementation of ecohydrology may improve and manage water quality and its ecosystem in the upper Citarum river basin [Sutapa et al., 2021]. This important finding will be a valuable tool to support Saguling dam operation in a sustainable manner.

6. Conclusions

Saguling is one of man-made dams constructed along Citarum river. This reservoir belongs to the national government, managed and operated by national company PT. Indonesia Power. Several important functions of Saguling reservoir cover water needs for agriculture irrigation, domestic, hydropower plant and industrial activities in West Java and DKI Jakarta Provinces. Equipment and tools including advanced technology are engaged to support reservoir and powerhouse generator management. In the last two decades Saguling reservoir has experienced a decline in capacity and potential functions probably closely related to sedimentation, siltation and pollution. Efforts and concerns of different stakeholders to control and improve water quality entering this dam should be enhanced in order to ensure its functions and operation for a long time. Ecohydrology concept gives alternative ways to restore river basins and reservoir ecosystems for the reason of its capability to trap pollutants and sediment and provide habitats for demersal and pelagic species. Low-cost technology through ecohydrology implementation will help to reduce anthropogenic impact on river basins throughout coastal zones by using the natural capacity.

7. Acknowledgement

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8. References

Asian Infrastructure Investment Bank [AIIB]. 2017. Project Document of The Asian Infrastructure Investment Bank. Republic of Indonesia Dam Operational Improvement and Safety Project Phase II. PD 0017-IND February 28, 2017. 56 pages.

Arifandi F. and Ikhsan C. 2019. Pengaruh Sedimen Terhadap Umur Layanan Pada Tampungan Mati (Dead Storage) Waduk Krisak di Wonogiri Dengan Metode USLE (Universal Soil Losses Equation). e-Jurnal Matriks Teknik Sipil/ Desember 2019/430-439. https://jurnal.uns.ac.id › article › download

Balai Besar Wilayah Sungai Citarum [BBWSC]. 2008. Dinas PSDA Provinsi Jawa Barat 2008.

Barus A.S.U., Maskey S., Mclain M.E. and Marence M. 2017. Climate Change Impacts on the Reservoir Operation in the Cascade Dams in West Java, Indonesia. 85th Annual Meeting of International Commission on Large Dams, July 3-7, 2017, Prague, Czech Republic. 10 pages. https://www.researchgate.net/publication/337783597

BNPB, 2021. BNPB: There are 1,441 natural disasters that hit Indonesia until June 2021. BNPB: Ada 1.441 Bencana Alam yang Melanda Indonesia Hingga Juni 2021.

Bonnet M., Witt A., Stewart K., Hadjerioua B. and Mobley M. 2015. The Economic Benefit of Multipurpose Reservoirs in the United States-Federal Hydropower Fleet. Oak Ridge National Laboratory. September 2015. 30 pages. DOI: 10.13140/RG.2.2.15894.14400. https://databoks.katadata.co.id/datapublish/2021/06/19/bnpb-20-gempa-bumi-mengguncang-indonesia-hingga-18-juni-2021

Idris A.M.S., Permadi A.S.C., Sianturi U.M. and Hazet F.A. 2019. Strategic Issues in Dam Operation and Maintenance in Indonesia. The Indonesian Journal of Development Planning Volume III No. 2 – August 2019. 225 – 238.

Indonesia Power. 2018. Ecosystem Disaster Problems and Vulnerability in Saguling Reservoir. Problem dan Kerawanan Bencana Ekosistem Di Waduk Saguling. APCE Internal Workshop, Sentul - Bogor, Indonesia. 2018.

Kartamihardja E.S., Purnomo K. and Umar C. 2009. Indonesian Mainland Common Aquatic Fish Resources – Neglected. Sumber Daya Ikan Perairan Umum Daratan di Indonesia-Terabaikan. J. Kebijakan. Perikan. Ind. Vol.1 No.1 Mei 2009: 1-15

Mayasari R. and Gunady B. 2015. Cascade Reservoirs Optimization in Citarum River – Indonesia. Published as part of proceedings of the Symposium Hydropower 15 in Stavanger, Norway, June 2015. 10 pages.

Ministry of Public Works and Housing [MPWH]. 2010. Review of the Standard Operation Procedure for the Citarum Reservoirs July 2010. 85 pages.

Ministry of Public Works and Housing [MPWH]. 2015. Indonesian Government Act No.122/2015 on Potable Water Supply Network.

Ministry of Public Works and Housing [MPWH]. 2019. Law of the Republic of Indonesia No. 17 of 2019 concerning Water Resources. Undang-Undang Republik Indonesia No.17 Tahun 2019 tentang Sumber Daya Air. Sekretariat Negara Republik Indonesia, Jakarta, 2019.

Risdiyanto I., 2009. Kondisi Erosi dan Sedimentasi DTA Waduk Saguling. Working Paper Report. June 2009. DOI: 10.13140/RG.2.1.2108.8242. https://www.researchgate.net/publication/305520762

Sutapa I.D.A. and Fakhrudin M. 2021. Ecohydrology: A Management Tool for Aquatic Ecosystem and SDGs Implementation. IOP Conf. Series: Earth and Environmental Science 789 (2021) 012032. pp. 1-14. doi:10.1088/1755-1315/789/1/012032

Sutapa I.D.A., 2021. Inland water resources, managed or become a source of disaster?. Sumberdaya Perairan Darat, Dikelola atau Menjadi Sumber Bencana? Kompas.com, 05/08/2021, 18:11 WIB. https://www.kompas.com/sains/read/2021/08/05/181100223/sumber-daya-perairan-darat-dikelola-atau-menjadi-sumber-bencana-

Sutapa I.D.A., Prihatinningtyas, E., & Daryanta. (2019). IPAG60 as an alternative solution to provide clean water in peatland areas. IOP Conf. Series: Earth and Environmental Science, 477(012030): 1-11. doi: 10.1088/1755-1315/477/1/012030

Sutapa I.D.A. 2018. The Government's Challenge in Providing Proper water. APCE Best Learning Book on Water Resource Management. (Tantangan Pemerintah dalam Mewujudkan Air Guna Pakai. Buku APCE best learning pengelolaan sumber daya air). Yogyakarta, Indonesia: Penerbit Sekolah Pascasarjana UGM. ISBN 978-602-8683-21-0, pp. 37–51.

Sutapa I.D.A. 2019. Development of Peat Water Treatment Plant (IPAG60) as a Tool for People Basic Rights Fulfilling to Water in Peatland Areas. Research Professor Inauguration in Environmental Engineering (Pengembangan Instalasi Pengolahan Air Gambut (IPAG60) Sebagai Sarana Pemenuhan Hak Dasar Masyarakat Atas Air di Daerah Gambut). Orasi Pengukuhan Profesor Riset Bidang Teknik Lingkungan. LIPI Press. ISBN 978-602-496-064-3 (printed)/978-602-496-065-0 (e-book). 79 pages

Wardhani E., Notodarmojo S. and Roosmini D. 2018. Sediment Quality Assessment by Using Geochemical Index at Saguling Reservoir West Java Province Indonesia. Energy and Environment Research; Vol. 8, No. 2; 2018, 34-44, ISSN 1927-0569 E-ISSN 1927-0577. doi:10.5539/eer.v8n2p34

Wolanski E, Boorman LA, Chicharo L, Langlois-Saliou E, Lara R, Plater AJ, Uncles RJ and Zalewski M, 2004 Ecohydrology as a new tool for sustainable management of estuaries and coastal waters Wetlands Ecology and Management 12 pp 235–276

Yusuf A.A. and Francisco H. 2009. Climate change vulnerability mapping for Southeast Asia. Economy and Environment Program for Southeast Asia (EEPSEA), Singapore: 10-15.

Zalewski, M, 2015 Ecohydrology and Hydrologic Engineering: Regulation of Hydrology-Biota Interactions for Sustainability Journal of Hydrologic Engineering 20 (1) p 14

Current status and new challenges in operation of reservoir systems in Japan

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Abstract
This chapter aims at presenting the current status and challenges in operation of reservoir systems in Japan. Firstly, general method of dam reservoir operation in Japan is introduced. Outline of reservoir operation in the Yoshino River basin is then described including key science and techniques for robust reservoir operation under the hydrological condition in Japan. Subsequently, novel approaches to derive the capability of reservoir systems are introduced and discussed for more sustainable water resources management under changing climate. Legal frameworks, good practices and lessons learned from past disasters are finally presented to identify more effective operation of reservoir systems.

Key Words *reservoir operation, flood control, water supply, hydropower, river environment, prior release, hydrological prediction, dam upgrading, climate change, sustainability*

1. Introduction

Japan is an archipelago country located in the mid-latitude region of the Asia-Pacific. It has a long archipelago lying in the subarctic, temperate and subtropical zones. Most regions of the country have clear four seasons, which cause a large inter-seasonal variability in temperature and precipitation. Japan is affected by East Asia Monsoon, which forms seasonal frontal rainfall called the plum rain (“Baiu” or “Tsuyu” in Japanese) that typically brings a significant amount of rainfall in 1-1.5 months before summer. The country is also located in one of the major paths of typhoons coming from the northwestern Pacific, also bringing significant rainfall usually in a few days from late spring to autumn. Northern Japan receives a lot of snowfall in winter due to northwest humid wind from the Sea of Japan, providing important water resources for spring and early summer in those regions.

Due to the climatic condition described above, Japan receives relatively high precipitation. Annual mean precipitation of Japan is estimated to be around 1,700 mm/year [1], which is higher than global mean annual precipitation (818 mm/year for land [2]). However, because of the high population density, annual mean precipitation per capita is approximately 5,000 m^3/person/year in Japan, which is much less than the world average (20,000 m^3/person/year)[1]. The mountainous topography of Japanese islands further emphasizes inhomogeneity of surface water resources both in space and in time, along with fast runoff by short and steep rivers. Available surface water resources are therefore limited compared with demands for stable water use in agriculture, industry and other economic activities. On the other hand, river discharge surges dramatically in case of heavy rainfall due to active frontal systems or typhoons due to steep topography, which sometimes leads to severe flood inundation and makes land use on the plains difficult.

As construction of dam reservoirs is a very effective measure for water resources development and flood management in regions with such hydrological characteristics, many reservoirs have been constructed in the river basins in Japan. In this chapter, current status and new challenges in operation of reservoirs systems in Japan is introduced with an example for reservoir operation practices in the Yoshino River basin.

2. General dam reservoir operation method in Japan

2.1 Purpose of dam reservoir operation

There are approximately 2,800 large dams (higher than 15 meters) located across Japan [3] (**Figure 1**). They are operated for various purposes, including flood control, water supply, power generation and environmental flow. Among those dam reservoirs, approximately 860 reservoirs are operated for flood control purpose in Japan [3]. Operation of a reservoir for flood control is conducted by storing flood water flowing into the reservoir from the upstream with a designated amount of vacant storage volume (called flood control capacity) so as to mitigate water release rate from the reservoir to the downstream based on its flood control rule.

On the other hand, approximately 2,100 reservoirs [3] are operated for water supply purposes, including supply of irrigation, municipal and industrial waters. As described in the previous section, natural river discharge has significant inter-seasonal variation in Japan, which prevents stable use of surface water resources. These reservoirs are therefore operated for mitigating inter-seasonal variation in river discharge (precipitation) rather than inter-annual variation in order to meet water demands in the downstream throughout a year. Most reservoirs are requested to release a certain amount of water so that minimal water discharge required to maintain a good river environment is gained in the downstream river. Operation method of reservoirs for power generation (approximately 680 reservoirs [3]) is somehow similar with that for water supply purposes, though it is usually more dynamic and complicated in order to respond to power demands which are varying depending on weather, temperature and power supply from other generation methods (such as solar or wind power generation).

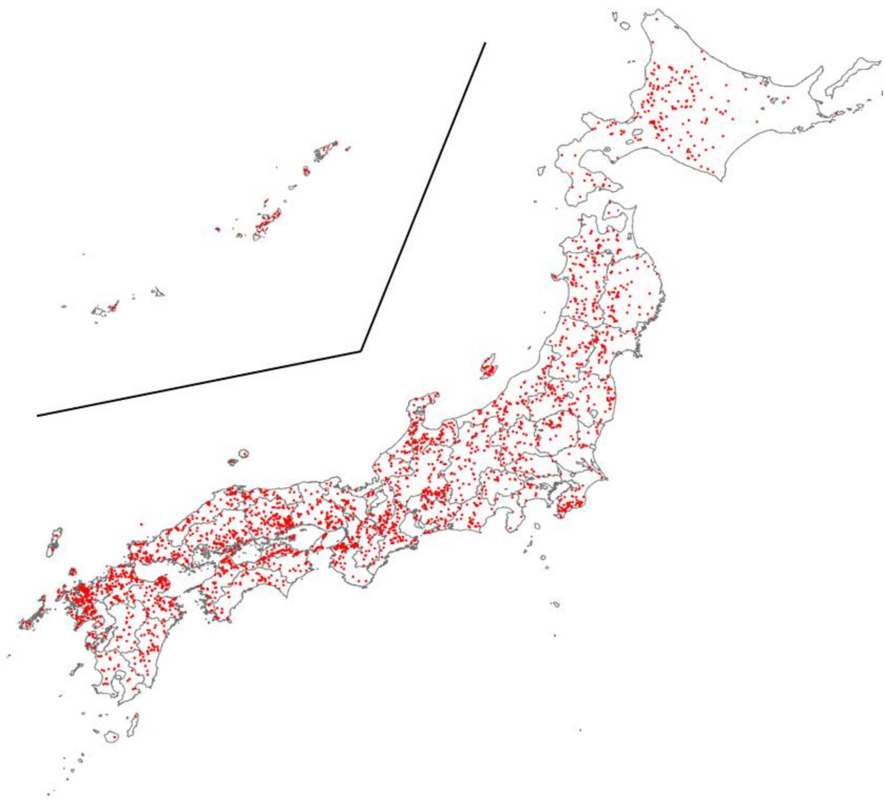

Figure 1 Location of reservoirs in Japan.

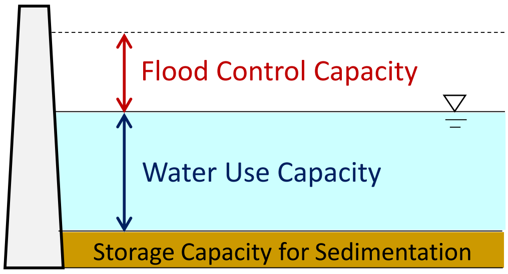

Figure 2 Example of storage allocation in a multi-purpose reservoir.

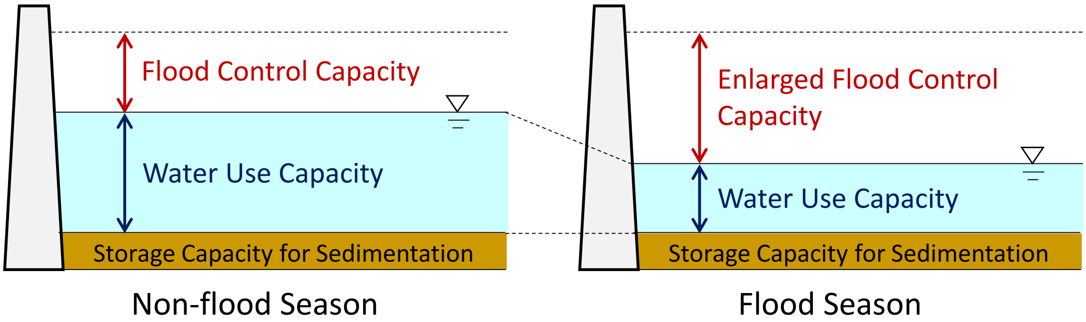

Figure 3 Different storage capacity allocation in non-flood and flood seasons.

Approximately 890 reservoirs are multi-purpose reservoirs [3] which are operated for more than one purpose. In most cases, storage allocation for each purpose (flood control, water supply or power generation) is clearly defined by operation rules considering needs for each operation purpose and cost allocation when the reservoir was constructed. Storage capacity for each operation purpose is therefore separately managed. **Figure 2** shows an example for typical allocation of storage capacity in a multi-purpose reservoir operated for flood control and water supply in Japan. Water can be stored only in the storage capacity for water supply (called water use capacity) in normal conditions (non-flood conditions), and storage capacity for flood control (called flood control capacity) must be vacant without storing water for securing its flood control function. This operation is needed to reserve enough empty storage volume for controlling sudden flash floods in steep rivers, which are often seen in Japan. On the other hand, flood control operation is conducted by storing water in the flood control capacity in case of flood conditions.

Because clear seasonality in precipitation is often seen in Japan as described in the previous section, allocation of storage capacity is changed in some multi-purpose reservoirs in the flood season so as to increase the flood control capacity to cope with more chance of large-scale floods occurrence (**Figure 3**). In this case, the water use capacity is reduced in the flood season. This reservoir drawdown, however, may increase drought risk during this period, because droughts often occur in the flood season in Japan. It is therefore very challenging to determine balanced storage allocation for this period.

Some multi-purpose reservoirs do not have much storage capacity enough to allocate exclusive storage capacity for each operation purpose (e.g., flood control and water supply) due to physical constraints of the construction site. In that case, a part of storage capacity is shared for multiple operation purposes. **Figure 4** shows reservoir storage allocation of a multi-purpose reservoir where flood control and water use capacities are partially overlapped. In such a reservoir, water can be stored up to the water use capacity in normal (non-flood) situation so as to have more capability for water supply, while reservoir storage level is lowered by conducting preliminary release in advance of flood occurrence with consideration of real-time hydrological forecasts so that it can have the vacant volume as much as the flood control capacity for effective flood management. This operation method can compensate disadvantages of a reservoir where storage capacity is not much enough to fulfill the needs from all of its operation purposes with exclusive (static) storage allocation.

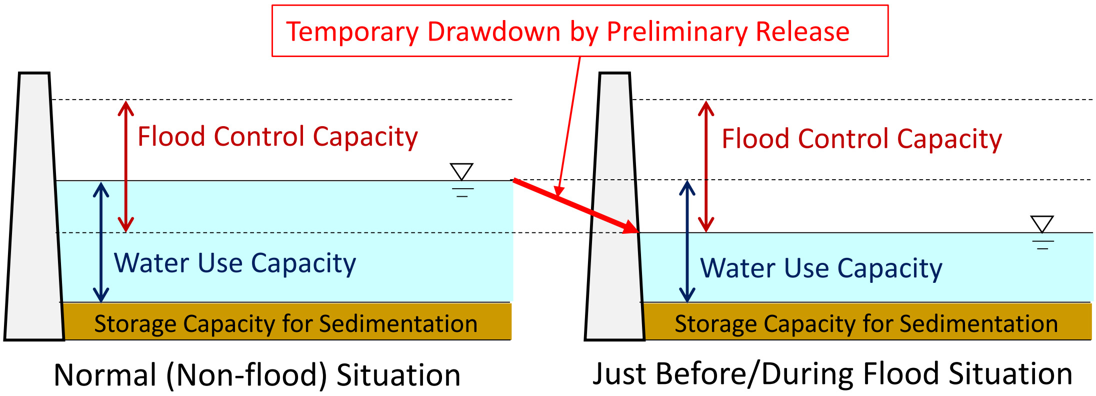

Figure 4 Storage allocation of a reservoir where preliminary release is applied.

2.2 Basic method & rule for dam reservoir operation

In general, reservoirs are operated based on their operation rules authorized by the river management authority (Ministry of Land, Infrastructure, Transport and Tourism (MLIT) or prefectures depending on the river system located). Flood control policy (FCP) of a reservoir is also defined by its operation rule. FCP of reservoirs which are operated for flood control are carefully determined so that it is consistent with the river improvement management plan (RIMP) in the river basin where the reservoir is located. For those reservoirs, a designed inflow pattern is firstly determined corresponding to the target designed flood level (usually 30- to 200-year return period) considered in RIMP, and water release policy from the reservoir is then designed considering the designed flood protection level in RIMP. Detailed examples for FCP of reservoirs are shown in the next section.

Reservoir operation for water supply is basically conducted so as to meet water demands in the downstream. Necessary and sufficient rate of water is released from the reservoir considering both water demands in the beneficiary areas and the amount of runoff water joining the river in the downstream of the reservoir. In order to take seasonality in water balance (between precipitation and water demands) into account, lower limit guidance of reservoir storage volume for water supply is designated for each period of time in operation rules of a reservoir. Reservoir storage volume for water supply, however, can get lower than this guidance in case of persistent rainfall scarcity. In such a case, real-time drought management is considered. Regulation of water release or water intake is usually considered as a method of real-time drought management to avoid further rapid decrease in reservoir storage volume. The extent of regulation (or water saving rate) is usually determined based on discussions at the drought conciliation council which consists of major stakeholders (e.g., authorities, reservoir managers, local governments and collective users) in the river basin.

On the other hand, power companies (or prefectures on behalf of industrial sector in some cases) usually have responsibility to conduct reservoir operation for power generation. If the reservoir is owned by such a sector and operated exclusively for hydropower generation, they can plan reservoir operation by themselves to the extent where reservoir operation does not harm the downstream. Because power demands often change greatly within a day, water release from hydropower reservoirs also has great daily fluctuation, which is not good for the downstream river environment. In order to diminish this daily fluctuation in river flow, compensation reservoirs are usually installed in the downstream of these reservoirs to stabilize the downstream river flow. There is also a set of hydropower reservoirs used for pumped-storage power generation, where two reservoirs are connected by water pipeline with the pump system which allows repetitive use of reservoir water for hydropower generation. On the other hand, hydropower generation in the multi-purpose reservoir is often conducted by using water to be released for water supply to the downstream for more efficient use of storage water.

In order to maintain a good water environment in the downstream river, most reservoirs are obligated to release a certain rate of water to the downstream. This operation is also effective to improve water quality in the downstream rivers as well as landscape. On the other hand, not only the amount but also the quality of water released from reservoirs is important for downstream river environment. Reservoirs trap turbid water during flood events, and high turbidity continues for a prolonged period compared to the natural rivers. This may cause a prolonged release of turbid water from the reservoir to the downstream, which is often harmful for fishery or ecology in the downstream. In order to solve this problem, selective withdrawal facilities, which can select the reservoir depth to take water for release, is installed in such reservoirs (**Figure 5**). This facility allows to take water from the reservoir elevation where turbidity is equivalent to that of inflowing water, which is more friendly for downstream river environment. This facility also enables to control temperature of released water because water temperature to be released can be changed to meet requirement from the downstream by changing water intake level in the reservoir where thermal stratification is typically seen.

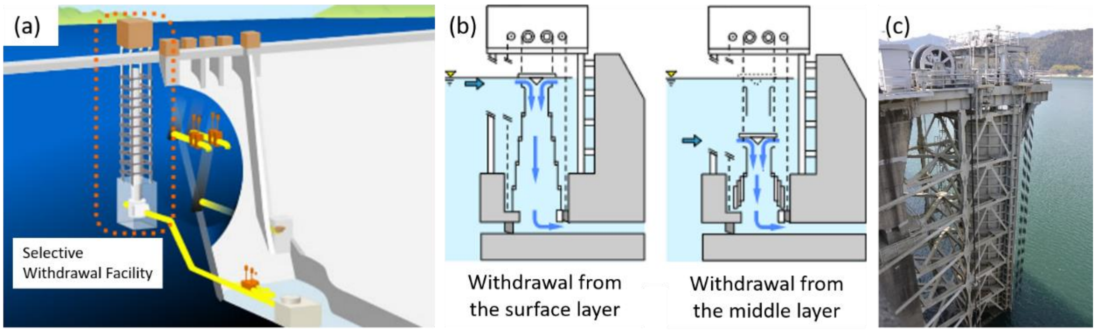

Figure 5 Selective withdrawal facility of the reservoir: (a) overview, (b) structure and function, and (c) facility installed in the Sameura Reservoir. Images in Figure 5 (a) and (b) are derived from Japan MLIT [4] with English translation added by the author.

3. Dam reservoir operation in the Yoshino River basin

3.1 Overview of the Yoshino River basin. It is desirable to refer Catalogue of Rivers

The Yoshino River is located in the Shikoku Island, one of the main islands of Japan (**Figure 6**). The Yoshino River basin is the largest river basin in Shikoku Island with drainage area of 3,750 km^2. The river basin lies on three out of four prefectures in Shikoku Island, namely, Tokushima (in the downstream), Ehime and Kochi Prefectures (in the upstream). Water of the

Yoshino River is also diverted to Kagawa Prefecture, which is located outside of the river basin. The river is therefore quite important for all of four prefectures in this island. Approximately 640,000 people live in the river basin, especially in the plain areas in the downstream.

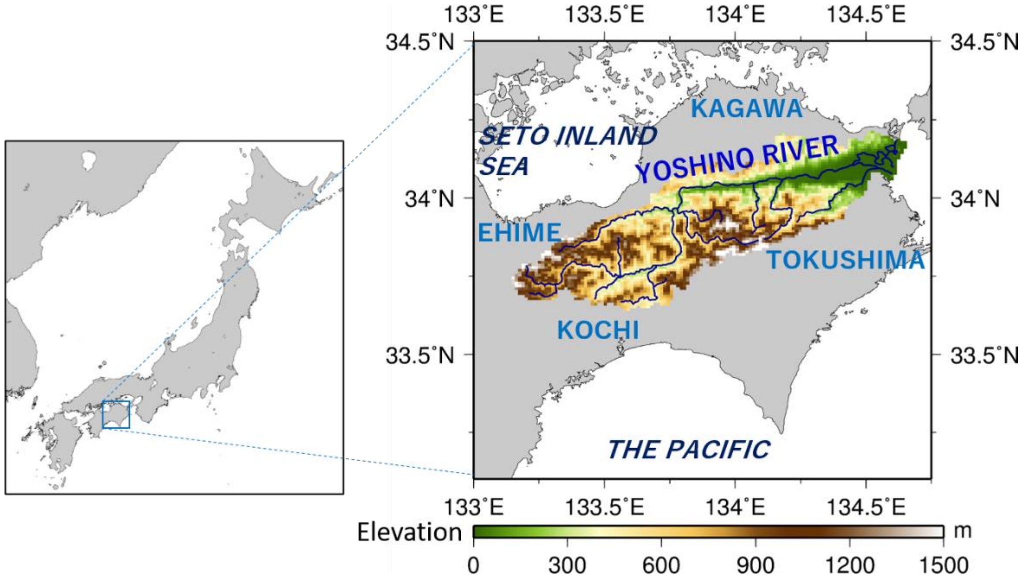

Figure 6 Location of the Yoshino River basin.

Annual mean temperature in the Yoshino River basin is 14-16 °C, although seasonal change in temperature is significant with hot summer and cold winter. Annual precipitation in the river basin ranges from 1,400 (in the downstream) to 3,000 mm (in the mountainous areas in the most upstream), while it is 800-1,200 mm in Kagawa Prefecture in the northern part of Shikoku Island where water is taken from the Yoshino River by diversion canals. **Figure 7** shows box plots of monthly precipitation values in Motoyama station, which is located in the upstream of the Yoshino River basin, for 43 years from 1977 to 2019. As shown in this figure, averaged monthly precipitations are high in summer (from June to September). However, they have great variation year by year, which implies that the river basin is prone to both floods and droughts in this season.

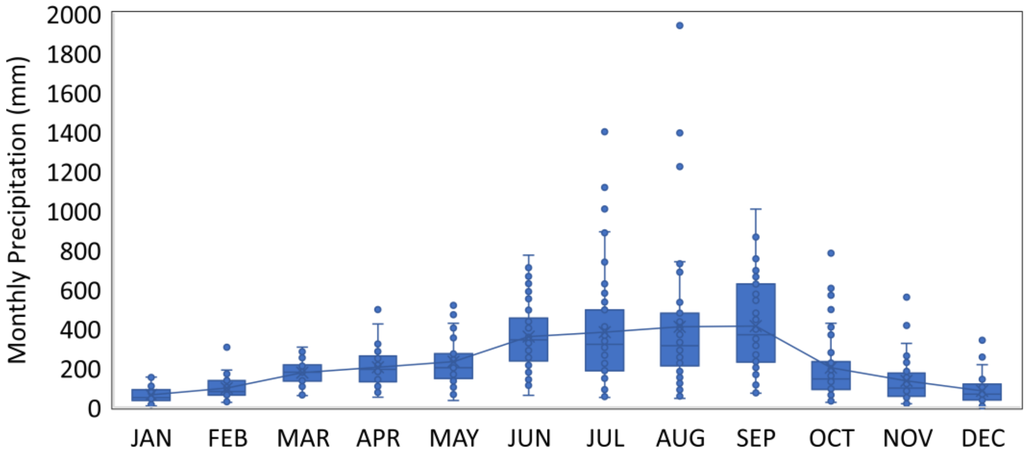

Figure 7 Location of the Yoshino River basin.

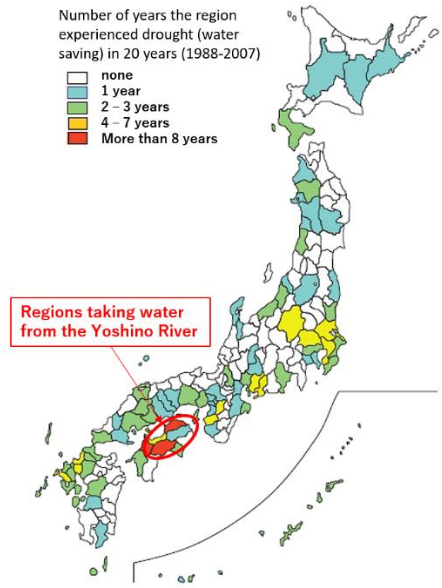

Figure 8 Number of years the region experienced droughts (water saving) in 20 years from 1988-2007 [5]. English translation was added by the author.

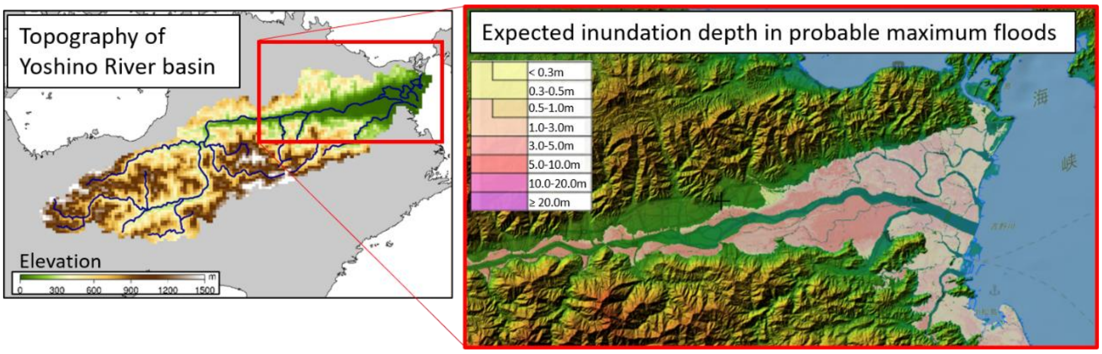

Figure 9 Topography (left) and expected inundation area and depth in probable maximum floods in the downstream [6] (right) of the Yoshino River basin. English translation was added by the author.

The Yoshino River basin has been actually suffered from frequent droughts. **Figure 8** shows the number of years the region experienced drought (water saving) in 20 years from 1988 to 2007 in Japan [5]. It can be seen in this figure that a part of the Yoshino River basin and its beneficiary areas experienced droughts more frequently than other river basins. This is mainly because of great variation in summer precipitation besides high water demand in the beneficiary areas with dry climate. Droughts are therefore a very important issue for this river basin.

The river basin is also prone to floods due to its topography and land use. Approximately 80% of areas are mountains in the river basin, and only 20% of lands are used for cultivation or residence. On the other hand, 75% of plain areas (used for cultivation or residence) has a potential to be inundated in large floods. **Figure 9** shows expected flood inundation areas and depth in case probable maximum rain occurs provided by Japan MLIT [6]. As a result, 77% of basin population is distributed in lowlands (15% of total basin areas) where inundation is expected. In fact, the river basin has been suffered from severe floods for many times in the past. Therefore, flood management is also crucially important for this river basin. Please also see Takeuchi et al. [7] for further details of characteristics of the Yoshino River.

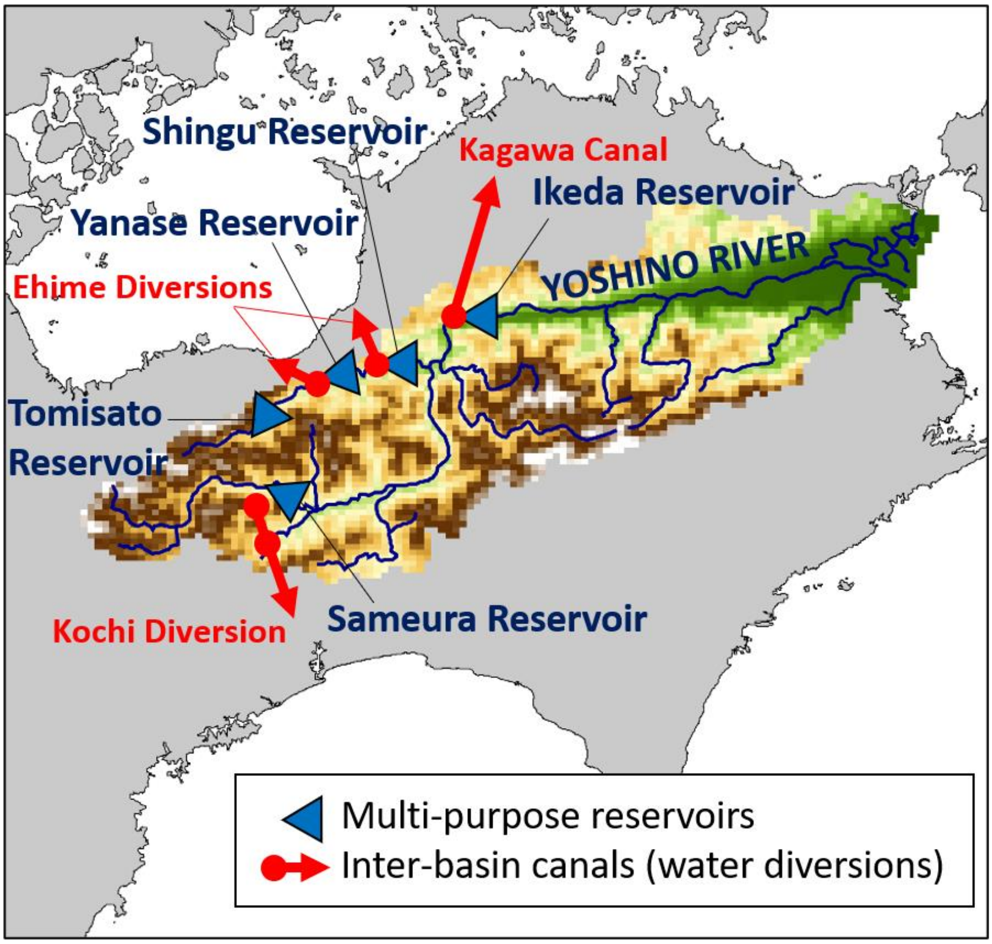

Figure 10 Multi-purpose reservoirs and inter-basin canals of the Yoshino River basin.

3.2 Overview of dam reservoir operation in the Yoshino River basin

In the Yoshino River basin, five major multi-purpose reservoirs, namely, Sameura, Tomisato, Yanase, Shingu and Ikeda Reservoirs, are operated for flood control, water supply, power generation and environmental flow besides hydropower dam reservoirs. Among these five multi-purpose reservoirs, Sameura Reservoir is located in the upstream of the main Yoshino River, while Tomisato, Yanase and Shingu Reservoirs are located in the Dozan River, one of the major tributaries of the Yoshino River (**Figure 10**). On the other hand, Ikeda Reservoir is located in the downstream of the Yoshino River, after the Dozan River joins the main stream. Four reservoirs, namely, Sameura, Tomisato, Shingu and Ikeda Reservoirs, are managed by Japan Water Agency (JWA), while Yanase Reservoir is operated by Japan MLIT. In addition to supplying water to agricultural, industrial and domestic sectors in the Yoshino River basin, the Yoshino River provides its water to surrounding areas through diversion channels as inter-basin water diversion.

Major inter-basin water diversions include Kochi Diversion (from the upstream of the Sameura Reservoir to the Pacific coast of Kochi Prefecture), Ehime Diversions (from Yanase and Shingu Reservoirs to industrial zones in Ehime Prefecture) and Kagawa Canal (from Ikeda Reservoir to Kagawa Prefecture which is a water scarce area) to improve water balance in those areas. Water of the Yoshino River is also diverted from hydropower dams to surrounding areas to generate power utilizing the difference in elevation.

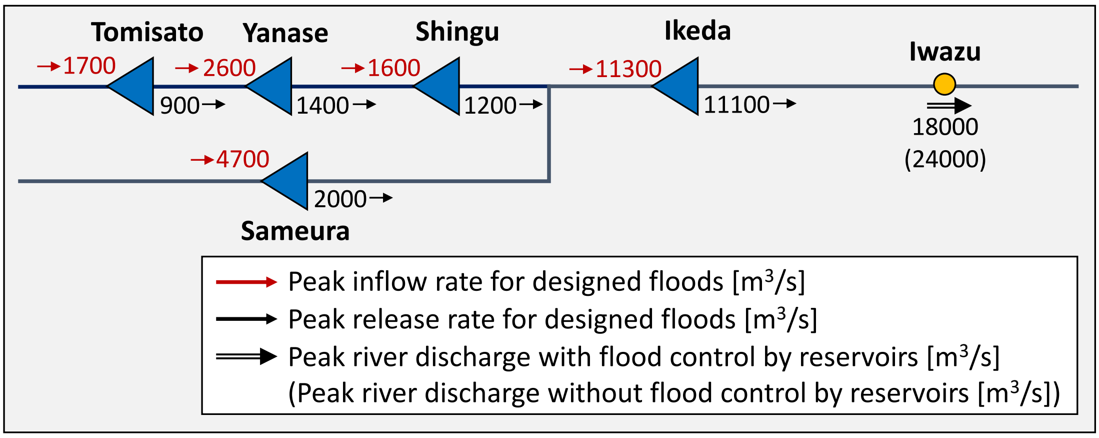

Figure 11 Schematic view of the flood control plan by reservoirs in the Yoshino River basin.

Flood operation rules of each multi-purpose reservoir in the Yoshino River basin is planned in accordance with the flood management strategy defined in the river improvement master plan (RIMP). Firstly, the target flood scale is determined by RIMP. For the Yoshino River basin, it is floods of 150-year return period currently. The target flood protection level at a reference point is then determined by RIMP considering vulnerability and exposure (capital, population) of the flood plains in the river basin. For the Yoshino River basin, it is planned to mitigate peak flood river discharge at Iwazu (in the downstream) by 6,000 m^3/s from 24,000 m^3/s to 18,000 m^3/s by flood control operation of upstream reservoirs. Target flow regulation level of each reservoir is determined so as to accomplish the target flood protection level in the reference point (Iwazu) in total with consideration of their storage capacities that can be allocated for flood control (**Figure 11**). Flood control rules are then defined for each reservoir, and they are operated independently in real-time during flood events based on their operation rules (**Figure 12**). This stand-alone approach allows reservoir managers to make a decision for reservoir operation in a simple and transparent manner in real-time during floods (in a short time) while reservoir systems in the river basin can be operated coordinately along with the flood management plan defined in advance.

On the other hand, reservoir operation for water supply is conducted based on water supply plan in the Yoshino River basin. Water resources development projects have been implemented in major river systems including the Yoshino River basin in Japan. In the Yoshino River basin, water resources development aimed at stable water supply in the target droughts of 10-year return period, and reservoirs (multi-purpose reservoirs) have been constructed to accomplish the goal. Water release from those five multi-purpose reservoirs is determined so that the target quantity of river water can be available in each target point for water intake or diversion in order to meet water demands at each target point (**Figure 13**).

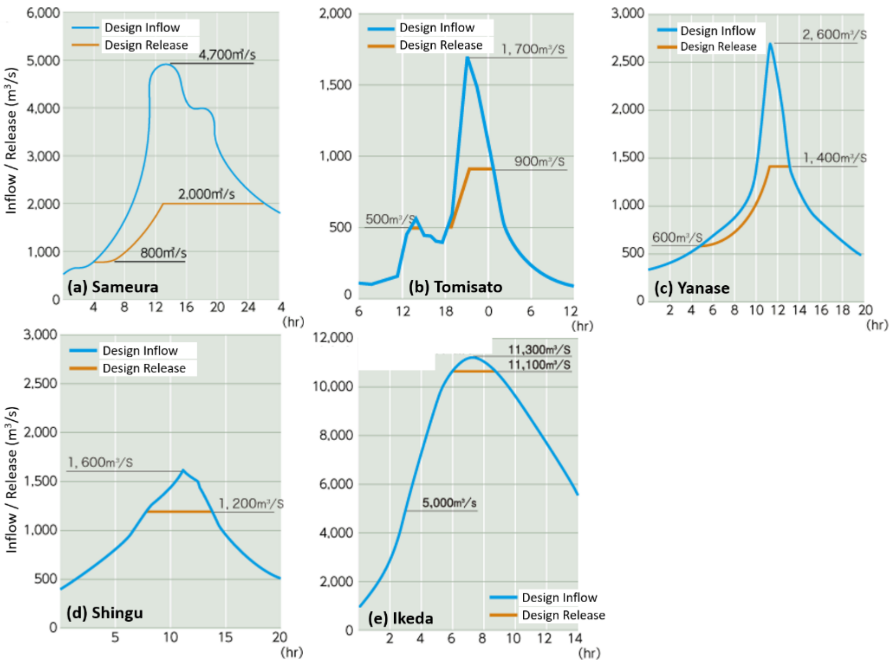

Figure 12 Control plans for the designed floods for five reservoirs in the Yoshino River basin: (a) Sameura, (b) Tomisato, (c) Yanase, (d) Shingu and (e) Ikeda Reservoirs [8]. English translation is added by the author.

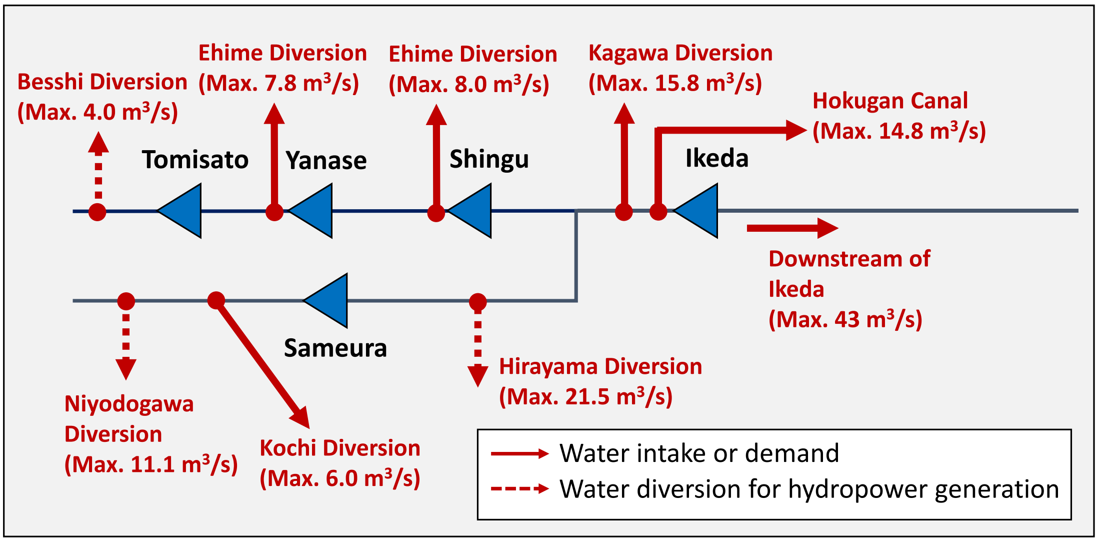

Figure 13 Water intake and demands in the Yoshino River basin.

In order to ensure stable water supply considering seasonal hydrological variability, lower limit guidance of reservoir storage volume for water supply is provided by operation rules of each reservoir. Reservoirs must be operated not to lower their storage volumes smaller than their lower limit guidance curves as much as possible. **Figure 14** shows storage allocation and lower limit guidance curve of the Sameura Reservoir. Due to high water demand for irrigation from May to October in this region, the lower limit guidance is high in this period. The lower limit guidance is set to be identical to water use capacity in some of this period. On the other hand, this period is also recognized as the flood season in this region, and storage allocation for flood control (flood control capacity) is increased in summer from June to October while the power generation capacity is decreased instead. Because reservoir storage needs to be maintained within a narrow range between high lower limit guidance and low upper limit rule curve (sum of water use and power generation capacities) due to seasonal hydrological characteristics, reservoir operation is challenging especially in summer in this river basin in order to balance needs from flood control and water utilization, and this is often the case in reservoir management in other river basins in Japan.

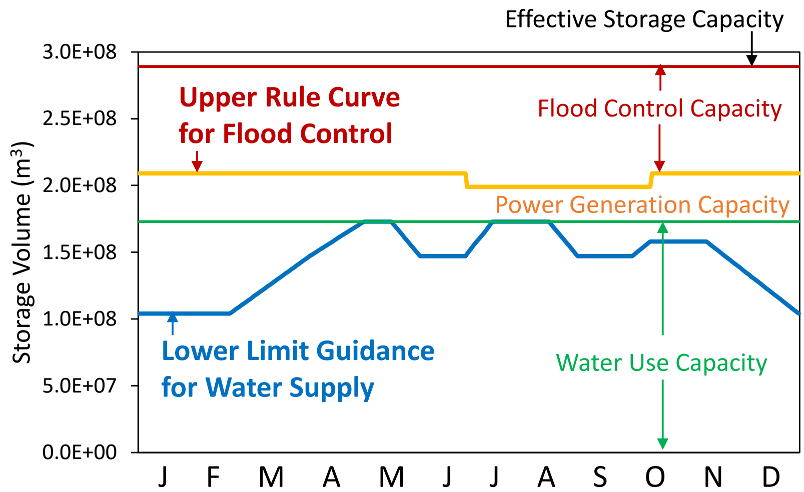

Figure 14 Lower limit guidance and upper rule curve for the Sameura Reservoir.

Despite of water resources development including construction of those five multi-purpose reservoirs, severe droughts have still occurred once 2-3 years in average in the Yoshino River basin. Water saving is conducted in such a case where reservoir water storage is decreased much less than lower limit guidance. The extent of water saving is determined by the drought conciliation council for irrigation, industrial and drinking water supplies. Members of the drought conciliation council in the Yoshino River basin include MLIT (as the river authority), Ministry of Agriculture, Forestry and Fishery (MAFF), Ministry of Economy, Trade and Industry, JWA, riparian prefectures (Kochi, Ehime and Tokushima Prefectures in addition to Kagawa Prefecture where diverted water is used), Electric Power Development Company (also known as J-Power) and Shikoku Electric Power Company.

3.3 Science and technology to support the dam reservoir operation

In order to operated reservoirs to meet requirements defined by their operation rules, latest hydrological condition of the river basin needs to be considered. Observation stations of rainfall and river water level (discharge) are therefore installed to monitor basin hydrological conditions, and reservoirs are carefully operated considering observed rainfall and river water level. Radar rainfall observation data provided by Japan MLIT or Japan Meteorological Agency (JMA) are also considered to understand spatial rainfall distribution in some reservoirs. Hydrological models are usually used to estimate reservoir inflow or river discharges especially in flood conditions, while simulation models for reservoir operation are employed to estimate reservoir conditions with given streamflow conditions in the near future.

In order to support reservoir operation which is a complex decision-making process which needs to consider reservoir states and hydrological conditions in various locations in the river basin as well as water demands and other constraints, reservoir operation support systems [9] and hydrological information systems are installed in reservoir control offices. These techniques are inevitable for efficient operation of reservoir systems. On the other hand, observation data of rainfall, river water level or reservoir states is also important for stakeholders in the river basin, such as water users, residents or riparian municipalities. River authorities or reservoir managers therefore provide data on reservoir states and basin hydrological conditions to the public through their web sites [10, 11] for transparent reservoir and water resources management.

In addition to hydrological observation data, real-time hydrological predictions are also needed for efficient reservoir operation especially for flood control. Real-time prediction of reservoir inflow or river discharge is often conducted from observed rainfall data to estimate future states of reservoirs and river flows. However, most reservoirs in Japan are located in upstream mountainous areas where river and slope are steep. River flow therefore rises very quickly—often only several hours after rainfall—due to fast runoff from the steep slopes. Consideration of real-time rainfall predictions is therefore important for flood control operation by reservoirs in Japan. Operational rainfall forecasts provided by JMA for the coming several hours to several days are often considered in reservoir operation for flood control (including prior release operation described in the following section) while rainfall forecast tailored to the reservoir catchment by weather companies is also considered in some reservoirs.

4. New approach for operation of reservoirs systems under climate change

4.1 Adaptive reservoir operation considering real-time hydrological predictions

Large-scale flood events with rainfall even more than the designed level of RIMP have occurred almost every year in Japan in last decade. Some studies have pointed out that historical global warming contributed to increase the amount of rainfall in some of those flood events [12,13]. In such flood events beyond the designed level for flood control operation of reservoirs, flood control capability of reservoirs may be lost in the middle of the flood event because flood control capacity is not enough and totally used up to store inflowing flood water before the flood event ends [14].

As a countermeasure against frequent occurrence of intensified floods under changing climate, an adaptive reservoir operation method has been introduced in many reservoirs in Japan based on the guideline provided by Japan MLIT after severe floods in 2018 and 2019 where severe flood damage was seen due to shortage of flood control capacity of some reservoirs [15]. In this operation, water stored in the reservoir is released just before flood water arrives to the reservoir so as to secure enlarged empty storage for flood control considering real-time hydrological predictions (**Figure 15**). This operation is often called as “prior release”, while some studies represent it by different terms such as “anticipatory release”, “pre-release” or “preliminary release”. The major difference between “prior release” and “preliminary release” described in Chapter 2 is that water is released from water use or power generation capacity for intentional drawdown to prepare additional storage capacity for flood control in prior release, while water is released from overlapped storage capacity for obligatory drawdown to secure designated flood control capacity before floods in preliminary release. This operation is also expected to bring out enhanced capability of reservoirs because the reservoir can keep its water level as high as possible for water utilization in no flood situation, at the same time as safely decreasing water level in advance of flood events for more effective flood management.

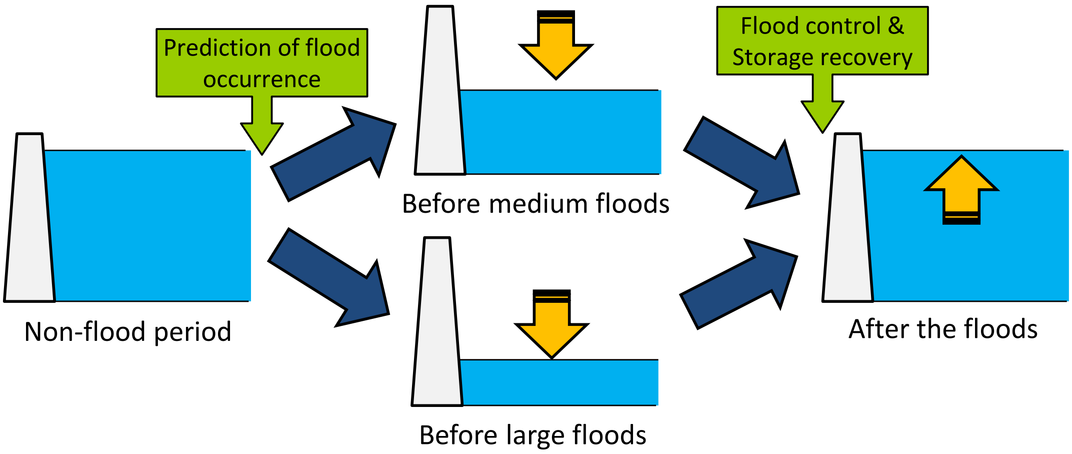

Figure 15 Reservoir prior release operation considering hydrological predictions.

In the guideline provided by Japan MLIT in 2020 [15], real-time rainfall forecasts for the coming 39 and 84 hours respectively provided by JMA's Meso-Scale Model (MSM) and Global Spectral Model (GSM) are considered for decision making whether prior release should be carried out or not. On the other hand, more vacant storage volume for flood control can be prepared in the reservoir as prior release is initiated earlier. From this point of view, studies have been conducted in recent years to introduce real-time hydrological predictions with longer forecast range. Ensemble hydrological predictions are often considered in such cases to secure robust decision making for prior release operation of reservoirs in order to deal with deep prediction uncertainty of long-range forecasts [16-18]. The amount of hydropower generation may also increase by conducting prior release through the outlets for power generation if prior release of hydropower reservoirs can be started from several days before a flood event considering long-range ensemble rainfall forecasts [19], which can be considered to mitigate carbon emission by increasing renewable energy generation.

4.2 Operation for sediment management for sustainable use of reservoirs

As described in Chapter 2, many reservoirs have already been constructed in Japan. There are not many suitable sites remained for constructing new reservoirs in river basins in Japan. Therefore, it is important to maintain the capability of existing reservoirs for water resources management in the future. It may also be needed to enlarge reservoir storage capacity available for water storage considering potential increase in flood and drought risks in the future due to climate change. One of the key issues for the sustainable management of exiting reservoirs is reservoir sedimentation. High sedimentation degrades the capability of reservoirs for water utilization or flood control. The sediment yield is, however, high in many river basins in Japan due to their topographical, geomorphological and hydrological conditions, especially in the hilly basins located on tectonic lines [20].

In order to avoid degradation of reservoir storage capacity by sedimentation, various sediment management techniques have been implemented in some of reservoirs in Japan. They include sediment removal, sediment sluicing, sediment flushing and sediment bypassing. One of the promising measures for sustainable sediment management is installation of sediment bypass tunnels (SBTs) for sediment bypassing, which can divert inflowing turbid water with high sediment concentration directly to the downstream of the dam reservoir without storing in the reservoir (**Figure 16**). This measure is expected not only as a sustainable sediment management method for reservoirs but also as an effective way to improve the river environment by supplying sediment to downstream river channels. On the other hand, reservoir operation becomes more complicated when considering water and sediment control with SBT. It is therefore the next challenge to identify how to optimize operation of reservoirs with SBT from the view point of both of water and sediment management (**Figure 17**). Real-time sediment inflow prediction is very useful for improving operation of the reservoir and SBT [22].

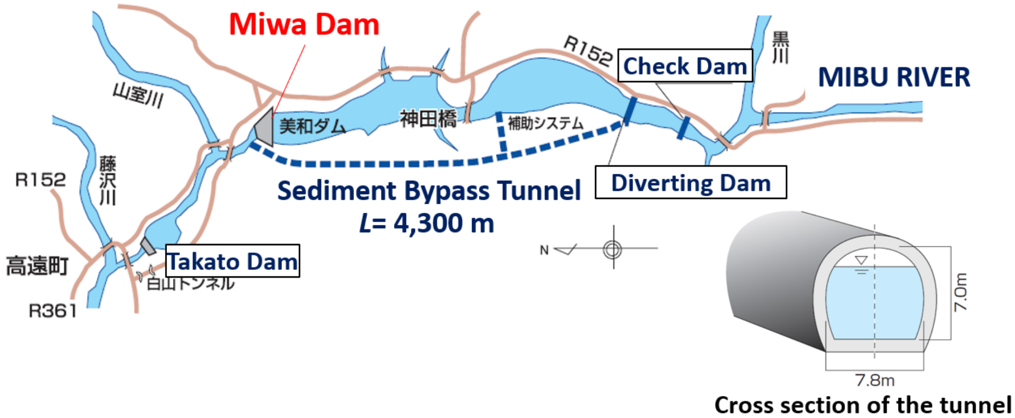

Figure 16 Sediment bypass tunnel installed in the Miwa Reservoir in the Mibu River for sustainable sediment management [21]. English translation is added by the author.

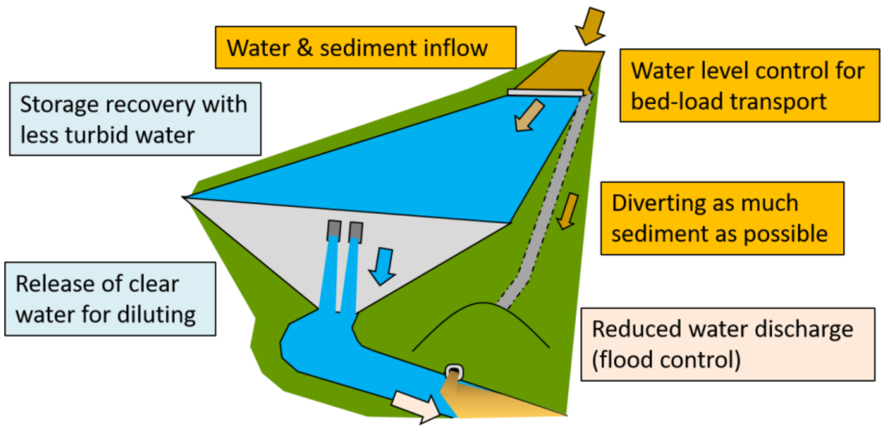

Figure 17 Integrated operation of reservoir and sediment bypass tunnel for effective water and sediment management.

4.3 Reservoir upgrading for more integrated reservoir operation under climate change

It is concerned that climate change can intensify not only floods but also droughts in river basins in Japan. Some studies pointed out that frequency and magnitude of droughts may increase in Japanese river basins in the future climate in the end of 21st century, and that current reservoir storage capacity is not sufficient to manage such extreme droughts [23]. In such a case, reservoir upgrading such as enlargement of storage capacity by dam raising can be a good adaptation option to hydrological changes due to changing climate (**Figure 18**). This is usually more cost effective than constructing a new reservoir in a different site of the river basin. On the other hand, integrated operation of existing reservoirs such as prior release is still important for enhancing their water management capability to mitigate impacts of extreme floods or droughts. However, such adaptive operation of reservoirs can be physically constrained by capacity or elevation of reservoir outlets. It is not possible to lower reservoir storage level quickly if the capacity of reservoir outlets is small, while reservoir storage level cannot be lowered under the bottom outlet. Reservoir upgrading is also effective to maximize the effects of adaptive reservoir operation by improving the capacity of reservoir outlets (**Figure 19**).

Figure 18 Example of dam raising (Shin-katsurazawa Dam in the Ishikari River basin [24]. English translation is added by the author.

Figure 19 Example for installation of new lower outlets to enhance reservoir drawdown capability (Tsuruda Dam).

5. Administrative and legal framework

Regulations in operation of reservoirs are generally stipulated by the River Law and the Specified Multi-purpose Dams Law. The River Law requests reservoir owners (reservoir managers) to define operation rules of the reservoir (Articles 14 and 47). If the reservoir is owned by an entity other than the river authority, operation rules of the reservoir must be approved and authorized by the river authority (Article 47 of the River Law). Reservoirs are owned (managed) by the Japan MLIT (river authority), JWA (in charge of water supply), prefectures (river authority, water supplier or hydropower operator), Japan MAFF (for irrigation water supply), municipalities (water supplier), power companies (for hydropower) and other private companies. The river authority is the Japan MLIT for important river sections (in 109 river basins, usually inter-prefectural rivers), while prefectures are the authority for other rivers sections. Operation of multi-purpose reservoirs (usually operated by MLIT, JWA or prefectures) is also ruled by the Specified Multi-purpose Dam Law.

Operation plans of reservoirs for flood control and water supply are defined in accordance with RIMP and River Improvement Plan (RIP) of the river basin, which are defined by the river authority based on Articles 16 and 16-2 of the River Law, respectively. One needs to be licensed water right by the river authority to take water from the river or reservoir (Article 23 of the River Law). These licensed water rights are periodically reviewed by the river authority to check the reasonability in light of water use purpose and water balance in the river basin. In case of drought conditions where water intake from the river (or reservoirs) for all the licensed water rights is not feasible, water use must be adjusted among water users (often negotiated through the drought conciliation council) (Article 53 of the River Law). However, traditional water uses which started before the River Law came into the force have priority over licensed water use which were newly started. In this sense, water right system in Japan is partially based on prior appropriation system.

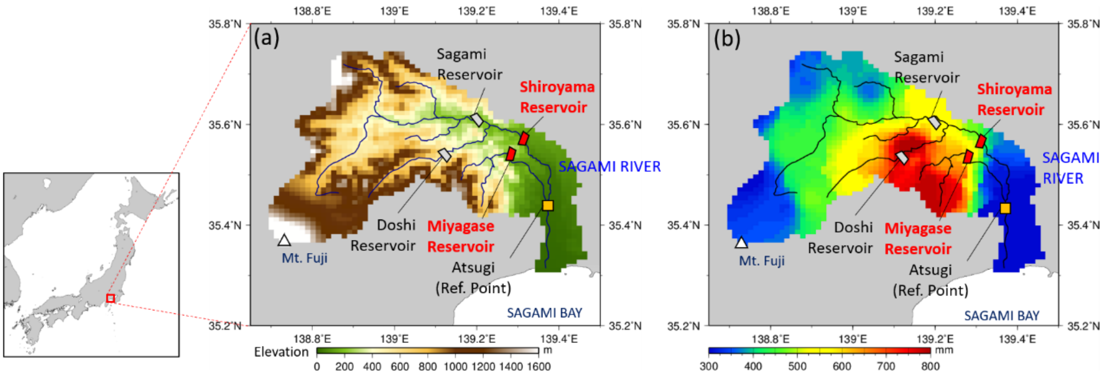

Figure 20 Sagami River basin and location of reservoirs: (a) with basin elevation, and (b) with spatial distribution of 24-hour rainfall in the flood event induced by Typhoon Hagibis in 2019.

6. Good practice, Lesson learned

6.1 Good practice I: Reservoir flood control in the Sagami River in 2019

One of the notably good practices of reservoir operation for flood management is flood control by reservoirs in the Sagami River basin (**Figure 20**) during floods induced by Typhoon Hagibis in October in 2019. Because the river basin is located in the pathway of Typhoon Hagibis, the river basin received a great amount of rainfall in this flood event. The basin mean 24-hour rainfall was almost equivalent to the designed level of RIMP which is 460 mm for 48-hour rainfall with 150-year return period (see **Figure 20** (b) for spatial distribution of 24-hour rainfall). During this large-scale flood event, two reservoirs operated for flood management in this river basin, namely, Miyagase and Shiroyama Reservoirs, greatly mitigated the flood discharges in the downstream river. It is estimated that river discharge at Atsugi station (reference point) in the downstream was decreased by 2,500 m^3/s by flood control of two reservoirs, reducing river discharge by approximately 35% compared to that without flood control by those reservoirs [14]. The effect of flood control of the Miyagase Reservoir was especially significant, reducing river discharge in the downstream by 1,650 m^3/s by regulating release rate to 100 m^3/s using 80% of its flood control capacity while maximum inflow rate was 1,750 m^3/s (**Figure 21**). Thanks to flood control operation of Miyagase and Shiroyama Reservoirs, no significant inundation was observed in the downstream areas of the Sagami River basin in this flood event. Other good practices were seen in other river basins such as the Tone River basin [25] in the same flood event induced by Typhoon Hagibis in 2019 [14].

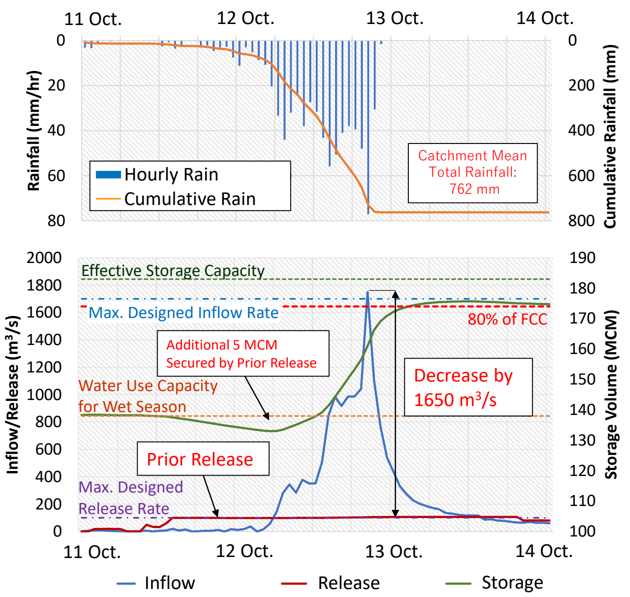

Figure 21 Flood control operation of the Miyagase Resevoir in the flood event induced by Typhoon Hagibis in 2019.

6.2 Good practice II: Flood control by cascade reservoirs in the Chikugo River in 2020

Flood control of upstream reservoirs in the Chikugo River basin [26] also contributed to mitigating flood inundation in Hita City in the downstream during the flood event in July, 2020. The Matsubara and Shimouke Reservoirs, a cascade reservoir system operated by Japan MLIT, successfully regulated water release from the reservoir system to the downstream although they received remarkable flood inflow due to prolonged rainfall caused by the active frontal system (**Figures 22 and 23**). This operation successfully minimized flood inundation in the downtown of Hita City, which is a flood-prone area as major tributaries join the main stream of the Chikugo River in that river section.

6.3 Good practice III: Flood control by reservoir systems in the Nabari River in 2009

Adaptive flood control of reservoir systems in the Nabari River, a tributary of the Yodo River basin [27], successfully prevented from flood inundation in Nabari City located in the downstream of those reservoirs during the flood event induced by Typhoon Melor in October, 2009. During the flood event, the river authority (Japan MLIT) and reservoir manager (JWA) carefully analyzed expected total rainfall, total inflow discharge and river water level in Nabari City based on real-time hydrological predictions, and came to the conclusion that severe flood inundation occurs in Nabari City if three upstream reservoirs (Shorenji, Hinachi and Murou Reservoirs (**Figure 24**)) are operated to control floods according to their flood control rules. Because the reservoirs were considered to have a room for further flood water storage considering rainfall prediction, they decided to change the flood control plan from their operation rules by regulating more flood water by those three reservoirs to avoid from flood inundation in Nabari City. During this advanced flood control by the reservoir system, water release rate from three reservoirs were carefully changed in an adaptive manner depending on vacant storage volume remained in each reservoir so as to optimize the performance of the whole reservoir system. As a result, flood inundation in Nabari City was successfully prevented by this operation while more than 1,000 houses was supposed to be inundated if the reservoirs were operated according to their operation rules [28].

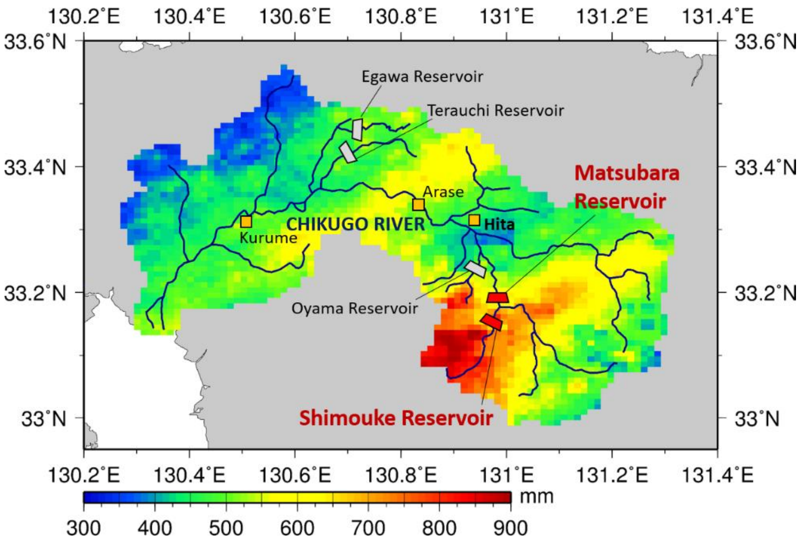

Figure 22 Chikugo River basin and location of reservoirs with spatial distribution of 48-hour rainfall in the flood event in July, 2020.

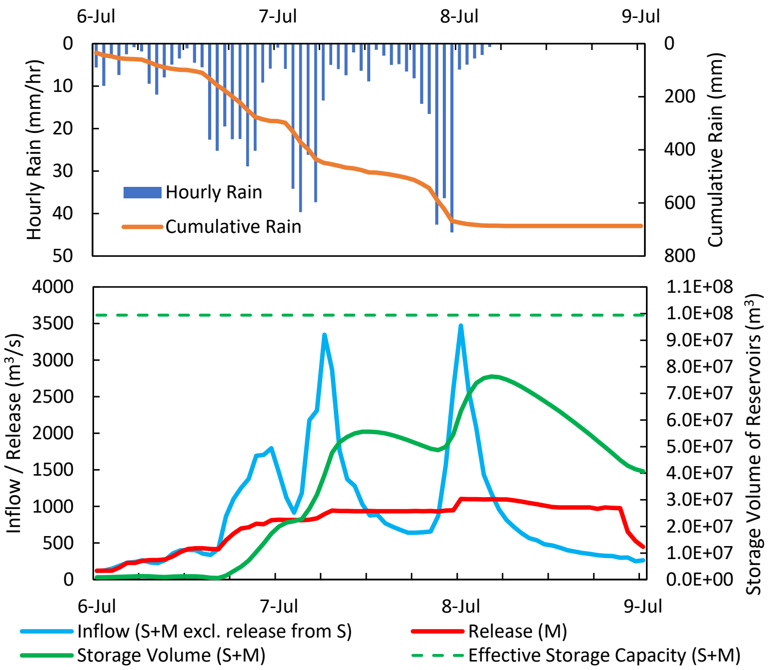

Figure 23 Flood control operation by the cascade reservoir system (Matsubara and Shimouke Reservoirs) in the flood event in July, 2020.

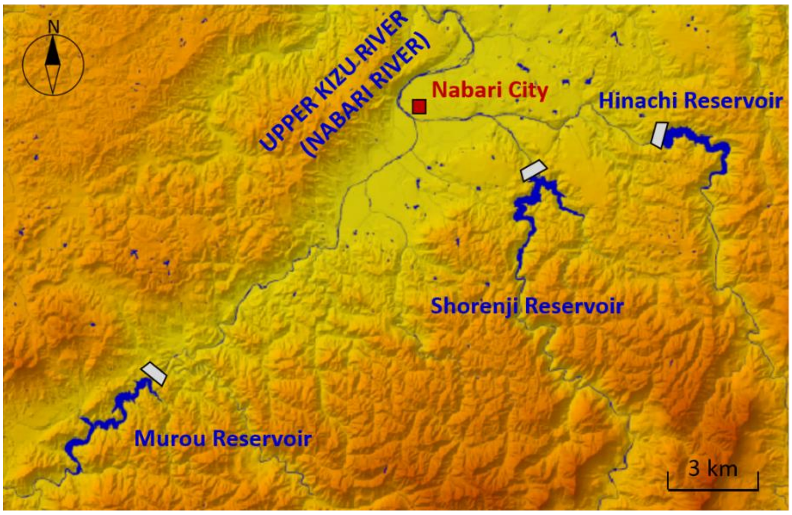

Figure 24 Location of reservoirs in the upper Nabari River, the Yodo River basin. Background map was derived from Geospatial Information Authority of Japan.

6.4 Good practice IV: Drought management in the Yoshino River basin in 2008

The Yoshino River basin was suffered from severe droughts due to scarce precipitation in summer, 2008. The storage volume of the Sameura Reservoir, the most important reservoir for water supply in the Yoshino River basin, sharply dropped due to lack in water inflow. The member of the drought conciliation committee of the river basin (see also Section 3.2) therefore decided to cooperatively conduct water saving among water users, and gradually raised the extent of water saving as storage volume of the Sameura Reservoir dropped to sustain reservoir water storage longer (**Figure 25**). By this water saving, they could delay the date where water storage in the water use capacity dried up by 10 days [29]. Because there were still water remained in the power generation capacity of the Sameura Reservoir, the reservoir released water from that capacity for water supply by consent of the power company while the water use capacity dried up for 20 days. Thanks to the cooperation among various stakeholders in the Yoshino River basin, all water users could manage to get through the extremely severe droughts without serious damage.

6.5 Good practice V: Drought and flood management in the Yoshino River in 2005

The Yoshino River basin was suffered from severe droughts also in 2005. Although water saving was also conducted in the river basin, water storage in the Sameura Reservoir for supplying water was dried up twice during this drought event. However, thanks to basin-wide water saving, the duration where the reservoir was dried up was minimized and significantly reduced by from 22 days to 3 days. Meanwhile, large-scale floods occurred due to Typhoon Nabi in the Yoshino River basin on 6 September. It was actually extreme floods, because the Sameura Reservoir received peak inflow rate of 5,400 m^3/s, which is beyond the designed peak inflow of the reservoir (4,700 m^3/s, see also Section 3.2). As reservoir was almost dried up when this extreme flood events occurred, the Sameura Reservoir could store most of inflowing flood water in the reservoir, mitigating flood impacts in the downstream to the utmost extent by regulating 5,200 m^3/s of water (almost twice as much as maximum flow regulation in its flood control plan), at the same time as fully recovering water storage for water supply within a day (**Figure 26**). This drought event followed by the extreme flood events showed a great capability of multi-purpose reservoirs for both drought and flood management.

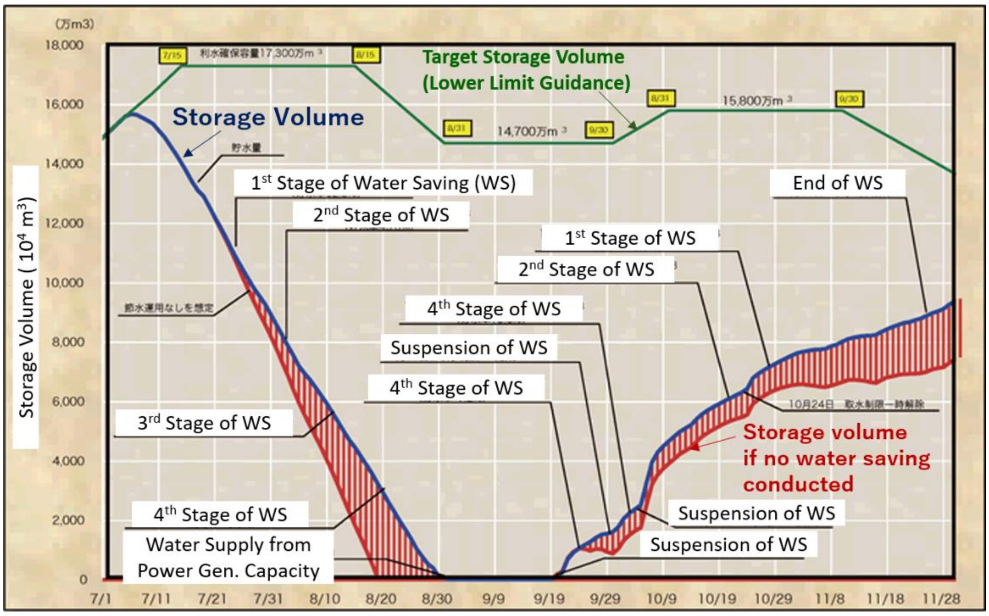

Figure 25 Trajectory of storage volume of the Sameura Reservoir and step-by-step water saving in droughts in 2008 [29]. English translation was added by the author.

Figure 26 Storage of the Sameura Reservoir: (a) under the drought condition (almost dried up) just before the floods, (b) just after the floods (on 7 September, 2005) [29].

Figure 27 Flushing release operation of the Takayama Dam (Yodo River basin).

6.6 Good practice VI: Flushing release from the reservoir for river environment

In the river basin where reservoirs are constructed upstream, flow regime of the downstream river is often too much stabilized. This often degrades river environment in the downstream, causing too much deposition of fine sediments or preventing from removing old algae attached to the river bed. In order to solve this environmental problem, flushing release operation has been introduced in reservoirs in Japan. In this operation, water release is intentionally increased to the extent of small floods to clean the river bed of the downstream river (**Figure 27**). It is confirmed that this operation is very effective to improve downstream river environment, promoting growth of new attached algae which is important for a good river environment [30]. Water volume needed for this operation is often secured in the part of flood control capacity by partially relaxing allocation of reservoir storage capacity [31] so as not to consume storage water for water supply in the low flow period.

6.7 Good practice VII: Coordinated sediment flushing of reservoirs in the Kurobe River

As reservoirs are created by constructing dams in the river channels, reservoirs essentially trap not only water but also sediment flowing from the upstream rivers. The storage capacity for sedimentation is therefore designed and prepared in the reservoir when a reservoir is newly constructed so that the effective storage capacity of the reservoir is not intruded by sedimentation. Although this capacity for sedimentation is usually designed to be much enough to store inflowing sediments for 100 years in Japan, reservoir sedimentation has grown rapidly in some reservoirs due to active sediment yield more than designed often because of geological and hydrological conditions.

Reservoir sedimentation problem is also serious in the Kurobe River (**Figure 28**) where sediment yield is very active in the upstream tributaries located in the steep mountains. The Unazuki Reservoir (operated by Japan MLIT) and Dashidaira Reservoir (owned and operated by Kansai Electric Power Company, KEPCO), which are two downstream cascade reservoirs located in the main river channel, are therefore equipped with sediment evacuation gates for sustainable reservoir sediment management. The two reservoirs have conducted cooperative sediment flushing and sluicing since 2001 by drawing down their water storage level in a coordinated manner so that sediment discharged from the upstream reservoir (Dashidaira Reservoir) is not trapped by the downstream reservoir (Unazuki Reservoir) to maximize the efficiency of sediment discharge from the reservoirs in total [32]. This cooperative sediment flushing or sluicing operation by the two reservoirs is conducted during flood events in the period from June to August every year. This period was carefully determined so as to mitigate adverse impacts of sediment discharge on downstream river environments and fishery [33]. Releasing sediments during floods is also expected to minimize impacts on downstream river environments by diluting sediment concentration of highly turbid water from the reservoirs by high natural stream flow of flood water. It is worth noting that sediment evacuation from a reservoir must be conducted as often as possible because sediments deposited in the reservoir are often altered by organic matters to dysoxic sludges over time which can cause immense impacts on downstream river environment once it is released from the reservoir. This is why the cooperative sediment flushing and sluicing are basically conducted in the Kurobe River ever year.

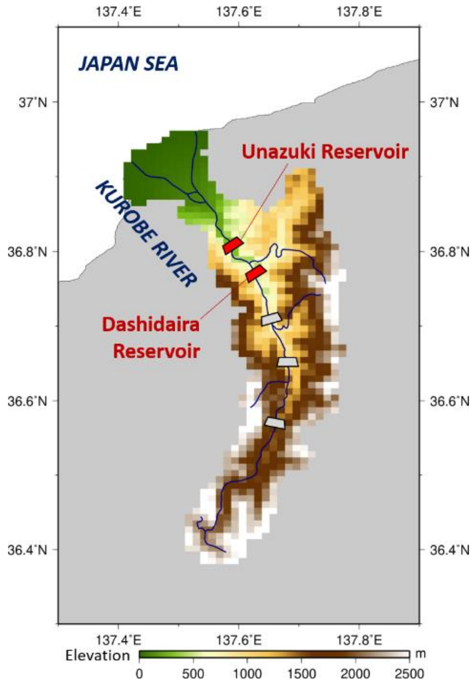

Figure 28 Location of Unazuki and Dashidaira Reservoirs in the Kurobe River basin.

6.8 Good practice VIII: Flexible operation after the Great East Japan Earthquake 2011

The flood protection level in the coast areas of the Natori River basin [34] was lowered after the Great East Japan Earthquake occurred in March, 2011 because of land subsidence (by 0.5-1.0 meters) after the earthquake as well as levees damaged by the earthquake and tsunami. In order to secure the original flood protection level in those areas, flood control plan of the Kamafusa Reservoir located in the upper tributary of the Natori River was changed so as to decrease flood river discharge in the downstream by regulating more flood water in the flood control capacity enlarged by prior release operation considering real-time hydrological prediction [35]. This is a good example for potential effectiveness of advanced operation of multi-purpose reservoirs for more resilient management of complex disasters.

6.9 Lesson learned: Reservoir operation against extreme floods in the Hiji River in 2018

In July in 2018, extreme floods occurred in many river basins in the western Japan due to heavy rainfall induced by the active seasonal frontal system. The Hiji River basin in Ehime Prefecture also received torrential rainfall beyond the designed level for flood protection, causing extreme floods with a sharp rise in hydrograph. Two reservoirs located in the upstream of the Hiji River, namely, Nomura and Kanogawa Reservoirs, were forced to conduct emergency spillway gate release operation (ESGRO) where the reservoir releases as much water as inflow in the middle of floods, because both reservoirs reached full storage by regulating floods. Because the most torrential rainfall was observed in the last several hours of the flood event, reservoirs received sharp rise in flood inflow at the end of floods, where storage capacity was no longer available for flood control. This forced the reservoirs to sharply increase water release rate, causing sudden increase in the downstream river water level and inundation depth. As a result, five people were killed in the downstream of the Nomura Reservoir, and four in the downstream of the Kanogawa Reservoir.

Many lessons have been learned from this flood event. The flood control operation rules of the Nomura and Kanogawa Reservoirs had been actually changed from the original plan when those reservoirs were constructed so as to regulate more flood water based on requests from municipalities located in flood-prone areas in the downstream to prevent frequent inundation caused by smaller-scale floods. This forced those reservoirs to store too much flood water compared to their flood control capability in large floods, which led to ESGRO before the peak of floods. This highlighted that flood control plan regulating water more than originally designed increases a risk of failing in flood control against large floods although it is effective to mitigate frequent inundation by smaller-scale floods in the downstream [36]. After the flood event, flood control plans of the reservoirs have been changed to regulate less water so that reservoir storage does not become full easily. Additional lower outlets have also been installed in the Kanogawa Reservoir, which allows the reservoir to release more water in the early stage of floods so that the reservoir can maintain more vacant storage volume for flood control through a flood event. Improvement of river channels in the downstream is also important in order not to rely on flood control by upstream reservoirs too much.

It must also be avoided to start ESGRO of the reservoir before the flood peak, because flood control effect cannot be gained at all in such a case. Countermeasures described above are also effective to decrease the risk to reach ESGRO before the flood peak.

Another lesson learned is communication with residents living along the downstream river of the reservoir. Those people need to well understand flood control policy of the reservoir located in the upstream, because they may need to evacuate in case of extreme floods beyond the flood control capability of the reservoir. Many residents in just downstream of the two reservoirs, however, did not know that their residential areas may be inundated in case of such extremely large floods because flood hazard maps had not been prepared for those areas. Recognizing this problem based on this flood event, the river authorities (Japan MLIT and Ehime Prefecture) and municipalities (Ozu and Seiyo Cities) prepared and provided the flood hazard maps also for the areas just downstream the reservoirs for improved flood risk communication with residents considering occurrence of extreme floods beyond the reservoir flood control capability [37].

7. Conclusions

Operation of reservoir systems in Japan is carefully planned for balancing various and conflicting needs from different operation purposes including flood control, water supply, power generation and river environment. Those reservoirs are operated to derive their maximized capability by use of real-time hydrological predictions for more adaptive water resources management. As a result, reservoirs have mitigated impacts of extreme floods and droughts historically. However, more integrated operation of reservoir systems will be needed to cope with hydrological changes expected in the future due to climate change. Effective measures against this challenge can be considered to include:

- more adaptive and flexible reservoir operation considering advanced hydrological predictions to improve Water-Food-Energy-Environment Nexus;
- structural measures such as dam upgrading for enlarged capability of reservoirs for more robust flood and drought management under changing climate;
- integrated sediment management for sustainability of reservoirs and downstream river environment;
- and close risk communication between reservoir managers and stakeholders or residents to maximize the effects of reservoir operation for more sustainable and resilient society.

8. References

[1] Japan Ministry of Land, Infrastructure, Transport and Tourism. 2020: Current status of water resources in Japan (Report for Fiscal Year 2020), https://www.mlit.go.jp/mizukokudo/mizsei/mizukokudo_mizsei_tk2_000028.html (in Japanese). (Last checked on 22 July, 2021.)

[2] Adler R, Gu G, Sapiano M, Wang, JJ, Huffman, GJ. 2017. Global precipitation: Means, variations and trends during the satellite era (1979-2014), Surv. Geophys. 38: 679-699. DOI: 10.1007/s10712-017-9416-4.

[3] The Japan Dam Foundation. 2019: Dams in Japan, http://damnet.or.jp/Dambinran/binran/TopIndex_en.html. (Last checked on 22 July, 2021.)

[4] Japan Ministry of Land, Infrastructure, Transport and Tourism: Selective withdrawal facility of the Miyagase Reservoir, https://www.ktr.mlit.go.jp/sagami/sagami00024.html (in Japanese). (Last checked on 22 July, 2021.)

[5] Japan Ministry of Land, Infrastructure, Transport and Tourism: Regions which experienced droughts in recent 20 years, Information relevant to water resources, https://www.ktr.mlit.go.jp/river/shihon/river_shihon00000023.html (in Japanese). (Last checked on 22 July, 2021.)

[6] Japan Ministry of Land, Infrastructure, Transport and Tourism: Portal web-site for hazard maps, https://disaportal.gsi.go.jp/ (in Japanese). (Last checked on 22 July, 2021.)

[7] Takeuchi K, Jayawardena AW, Takahashi Y. (eds.) 1995: Yoshino-gawa, Catalogue of rivers for Southeast Asia and the Pacific, the UNESCO-IHP Regional Steering Committee for Southeast Asia and the Pacific, 1: 117-129.

[8] Japan Ministry of Land, Infrastructure, Transport and Tourism: Introduction of reservoirs in the Yoshino River basin, http://www.skr.mlit.go.jp/yoshino/dam/d_sameura.html (in Japanese). (Last checked on 22 July, 2021.)

[9] Japan Ministry of Land, Infrastructure, Transport and Tourism. 2016: Standard specification and guidelines for designing dam management and control systems (in Japanese).

[10] For instance, Japan Ministry of Land, Infrastructure, Transport and Tourism: Water Information System, http://www1.river.go.jp/ (in Japanese). (Last checked on 22 July, 2021.)

[11] For instance, Japan Ministry of Land, Infrastructure, Transport and Tourism, Disaster Information System for River, https://www.river.go.jp/e/. (Last checked on 22 July, 2021.)

[12] Kawase H, Imada Y, Sasaki H, Nakaegawa T, Murata A, Nosaka M, Takayabu I. 2019: Contribution of historical global warming to local-scale heavy precipitation in western Japan estimated by large ensemble high-resolution simulations, Journal of Geophysical Research: Atmospheres, 124: 6093-6103. DOI: 10.1029/2018JD030155.

[13] Kawase H, Yamaguchi M, Imada Y, Hayashi S, Murata A, Nakaegawa T, Miyasaka T, Takayabu I. 2021: Enhancement of extremely heavy precipitation induced by Typhoon Hagibis (2019) due to Historical Warming, SOLA, 17A: 7-13. DOI:10.2151/sola.17A-002.

[14] Nohara D and Sumi T. 2021: Reservoir operation against large-scale floods due to Typhoon

Hagibis and applicability of ensemble forecast to preliminary release, Journal of Japan Society of Civil Engineers (in press).
[15] Japan Ministry of Land, Infrastructure, Transport and Tourism. 2020: Guidelines for reservoir prior release (in Japanese).
[16] Nohara D, Nishioka Y, Hori T, Sato, Y. 2015: Real-time reservoir operation for flood management considering ensemble streamflow prediction and its uncertainty. Advances in Hydroinformatics: 333-347. DOI: 10.1007/978-981-287-615-7_23.
[17] Oishi S. 2017: Optimization of integrated operation of dams using ensemble prediction. Sustainable Water Resources Planning and Management under Climate Change: 133-154. DOI: 10.1007/978-981-10-2051-3_6.
[18] Inomata H, Kawasaki M, Kudo S. 2018: Quantification of the risks on dam preliminary release based on ensemble rainfall forecasts and determination of operation, Journal of Disaster Research, 13(4): 637-649. DOI: 10.20965/jdr.2018.p0637.
[19] Nohara D, Kitani K, Michihiro Y, Sumi T. 2020: Applicability of ECMWF Medium-range Ensemble Rainfall Forecast to prior release operation of a hydropower dam. Journal of Japan Society of Civil Engineers Ser. B1 (Hydraulic Engineering), 76(2): I_829-I_834 (in Japanese).
[20] Sumi T. 2006: Reservoir sediment management measures and necessary instrumentation technologies to support them. Proc. 6th Japan-Taiwan Joint Seminar on Natural Hazard Mitigation.
[21] Japan Ministry of Land, Infrastructure, Transport and Tourism. 2003: Sustainable sediment management measures in the Miwa Reservoir (in Japanese).
[22] Nohara D, Sumi T, Kantoush, SA. 2013: Real-time sediment inflow prediction for sediment bypass operation at Miwa Dam in Japan, Advances in River Sediment Research, Proc. 12th International Symposium on River Sedimentation: 1211-1217.
[23] Nohara D, Sato Y, Sumi T. 2020: Effectiveness of adaptation options for multi-purpose reservoir operation to climate change: a case study in Japanese river basins. Climate Change-Sensitive Water Resources Management: 65-89. DOI:10.1201/9780429289873-6.
[24] Japan Ministry of Land, Infrastructure, Transport and Tourism.: Cost saving approach in the Shin-katsurazawa Reservoir Project, https://www.hkd.mlit.go.jp/sp/ikushunbetu_damu/kluhh4000000c0j3.html (in Japanese). (Last checked on 22 July, 2021).
[25] Ibbitt R, Takara K, Desa MNBM, Pawitan H. (eds.) 2002: Tone-gawa, Catalogue of rivers for Southeast Asia and the Pacific. the UNESCO-IHP Regional Steering Committee for Southeast Asia and the Pacific, 4: 95-109.
[26] Jayawardena AW, Takeuchi K, Machbub B. (eds) 1997: Chikugo-gawa, Catalogue of rivers for Southeast Asia and the Pacific. the UNESCO-IHP Regional Steering Committee for Southeast Asia and the Pacific. 2: 102-114.
[27] Ibbitt R, Takara K, Desa MNBM, Pawitan H. (eds.) 2002: Yodo-gawa, Catalogue of rivers for Southeast Asia and the Pacific. the UNESCO-IHP Regional Steering Committee for Southeast Asia and the Pacific, 4: 110-124.
[28] Kamiya, H. 2011: Integrated flood control operation of three reservoirs in the upper Nabari River basin during floods induced by Typhoon Melor in 2009 (in Japanese).
[29] Japan Ministry of Land, Infrastructure, Transport and Tourism.: Major water-related disasters in the past (in Japanese), http://www.skr.mlit.go.jp/yoshino/dam/saigai_kako.html. (Last checked on 22 July, 2021.)
[30] Japan Ministry of Land, Infrastructure, Transport and Tourism. 2018: Reservioir flushing release for improvement of river environment in the Dozan River basin, http://www.skr.mlit.go.jp/yoshino/kouhoushi/pdf/kawa_katsu03-06.pdf (in Japanese). (Last checked on 22 July, 2021.)
[31] Yanase Y, Okakawa E, Ishikawa H. 2021: Towards improvement of river environment for the Dozan River. Proc. Annual Meeting on Technical and Operational Research 2021,

Shikoku Regional Development Bureau, Japan Ministry of Land, Infrastructure, Transport and Tourism: II-13 (in Japanese).

[32] Sumi T, Nakamura S, Hayashi, K. 2009: The effect of sediment flushing and environmental mitigation measures in the Kurobe River. Proc. 23rd International Commission of Large Dams (ICOLD) Congress: Q89-R6.

[33] Japan Ministry of Land, Infrastructure, Transport and Tourism, Kansai Electric Power Company. 2017: Guidelines for cooperative sediment flushing by Dashidaira and Unazuki Reservoirs in the Kurobe River (draft). 81pp. (in Japanese).

[34] Tachikawa Y, James R, Abdullar, K, Desa, MNBM. 2004: Natori-gawa, Catalogue of rivers for Southeast Asia and the Pacific. The UNESCO-IHP Regional Steering Committee for Southeast Asia and the Pacific. 5: 72-83.

[35] Galvao CO, Kim YO, Kolokytha E, Mondal A, Mujumdar P, Nohara D, Oishi S, Ranzi R, Teegavarapu R. 2017: The contribution of IAHR's communities of water management and climate change towards the SDGs, Hydrolink, 3/2017: 77-79.

[36] Nohara D, Takemon Y, Sumi T. 2020: Real-time flood management and preparedness: Lessons from floods across the western Japan in 2018, Advances in Hydroinformatics - Models for Extreme Situations and Crisis Management: 287-304.

[37] Japan Ministry of Land, Infrastructure, Transport and Tourism. 2018: Report of the Review Committee on risk communication on operation of Nomura and Kanogawa Reservoirs: 6-7 (in Japanese).

Dam Reservoir Operation in the Republic of Korea

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Abstract

The chapter shed light on technologies, procedures, and systems in the dam reservoir operations of the Republic of Korea which have played a significant role in managing floods and droughts. Korea's socioeconomic development and environmental sustainability have been possible thanks to the efficient operation of approximately 18,000 dams, which has contributed to water supply for domestic, industrial, and agricultural purposes, flood and drought management, ecosystem preservation, and spaces for leisure activities. Advanced ICT technologies have been introduced and developed for dam operation in line with relevant procedures and guidelines, and administrative and legal frameworks have supported key water infrastructures, i.e., multipurpose dams. The combination of structural and non-structural measures in dam reservoir operations has culminated in reducing potential damage triggered by severe typhoons, as seen from the case of the Namgang Dam in 2012. The country should strive to introduce an integrated way to cope with floods and droughts in the era of climate change based on its strength in dam technologies and systems.

Key Words The Republic of Korea, Flood, Drought, Socio-Economic Development, Environmental Sustainability, Multipurpose Dams, Namgang Dam, ICT technologies, Climate Change

Tables of Contents

1. Introduction

This chapter discusses technologies, procedures, and systems in the dam reservoir operation for tackling floods and droughts in the Republic of Korea. The country is located in East Asia, which is mainly affected by the summer monsoon climate. Heavy rainfall is common in the summer months from June to August, and this climatological and hydrological feature accompanies several typhoons per annum, which has frequently wreaked havoc on the country, causing the loss of lives and tremendous scales of economic damage. Droughts occasionally occur in the country but not as often as floods. Climate change-induced uncertainties and new normal may gradually change this weather pattern in the foreseeable future. More attention should be placed on the frequent outbreak of localized heavy rainfall in small areas, which culminates in flash floods in urban areas of the country.

The Republic of Korea has endeavored to introduce cutting-edge technologies and systems to improve the capacity to tackle floods and droughts closely associated with dam reservoir operations. It is common to observe various water resources management forest and operation gadgets and equipment within and outside dams in the country, i.e., meteorological radars, stage gauges, water quality monitoring equipment, rain gauges, warning stations, and CCTVs.

More than 20 multipurpose dams have made substantial contributions to the country's economic development, social well-being, and environmental sustainability by providing stable water supply for diverse purposes, flood and drought management, and creating spaces for leisure activities. Approximately 18,000 dams in the country have served as a solid foundation for Korea's sustainable development for a few decades.

In addition to such structural measures, administrative frameworks in dam management have neatly developed since the 1960s, and the recent water sector reform has witnessed the reshuffling of water-related ministries, which paves the way for the empowerment of the Ministry of Environment. The MoE is the competent ministry mainly in charge of water resources management, including dam operation for floods and droughts, and the enactment of the Water Management Basic Act in 2008 will facilitate river basin management. A set of national laws related to water-related disasters facilitates the efficient management of various dams in the country.

The case study of the Namgang Dam with reference to severe flooding in 2012 highlights the competency of Korea's preparedness against typhoon-caused floods. Various systems of dam operation, such as RHDAPS, PFS, FAS, and GIOS, functioned efficiently for reducing potential damage caused by the typhoons.

The first part of the chapter explores flood and drought management by describing the characteristics of flood and drought patterns in the country over the few decades. Technologies of water resources management forecast and operation are introduced, and discussions are made on various types of dams, including multipurpose dams, and river maintenance. The second part focuses on the reservoir operation in flood events and water supply and drought response. Special attention is paid to the administrative and legal frameworks related to dam reservoir operation in the country, discussing dam and natural disaster-related ministries as well as a myriad of relevant laws. The last part of the chapter goes to the good practice, having a close look at the operation of the Namgang Dam in the flood events in 2012 that will shed light on the effectiveness of dam operation technologies, and systems.

2. Flood and drought management

2.1 Flood disasters

Large-scale flood damage in the Republic of Korea, measured in terms of human casualties (dead and missing), has decreased since 1959 while property damage has also reduced since 2002. These trends are a result of water resources management policies that have enhanced the flood control ability and the stream discharge capacity through multipurpose dams and stream maintenance projects for flood prevention. This implies the significance of establishing water resources management infrastructure, including dams and stream facilities for flood mitigation. **Table 1** indicates some of the most fatal typhoons in the country from 1925 to 2006, ranked by the loss of lives and property damage.

Table 1. Summary of Damage from Top 10 Typhoons in the Republic of Korea from 1925 to 2006, ranked by the Loss of Lives and by Property Damage

Rank	Ranking according to loss of lives			Ranking according to property damage		
	Typhoon	Period	Death Toll (Persons)	Typhoon	Period	Property damage* (US$ 1,000 million)
1	3693	28 August 1936	1,232	Rusa	31 August-1 September 2002	5.59
2	2353	11-14 August 1923	1,157	Maemi	12-13 September 2003	4.59
3	Sara	15-18 September 1959	846	Olga	23 July-4 August 1999	1.08
4	Bete	18-20 August 1972	550	Selma	15-16 July 1987	0.60
5	2560	15-17 July 1925	516	Jenis	19-30 August 1995	0.55
6	1427	7-13 September 1914	432	Ewiniar	9-10 July 2006	0.38
7	3383	3-5 August 1933	415	Gladis	22-26 August 1991	0.32
8	Selma	15-16 July 1987	345	Yani	26 September-1 October 1998	0.28
9	3486	20-24 July 1934	265	Prapiroon	23 August-1 September 2000	0.25
10	Rusa	31 August-1 September 2002	246	Jun	31 August-4 September 1984	0.25

Remarks: * Property damage converted to the monetary value of 2006
Source: Kang et al. (2013).

However, water-related disasters frequently take place due to climate change, which poses a grave threat to water resources management in the country. Flood damage is especially greater in regions where heavy torrential rainfall is concentrated in a small area. The scale of flood damage in the 2000s was 5.3 times greater than in the 1980s. Similar to the phenomenon of flood events, droughts come into being more frequently than before. In the 1970s, a drought took place once every five to seven years. In the 2010s, droughts are more frequent, occurring every two to three years.

Climate change has entailed hydrological and climatological patterns and often culminates in excessive flooding. These changing patterns increase precipitation, decrease days of precipitation, and facilitate an upsurge of localized heavy rain in the short term. The frequency of localized heavy rain for 30 mm per hour or more increased by 37% from 60 times in the 1980s to 82 times from 2000 to 2018. For example, the total localized heavy rainfall in Dongducheon City, Gyeonggi Province, reached 449.5 mm per day. In Moonsan City, Gyeonggi Province, 322.5 mm per day on July 27th, 2011, and Gwanak-Gu, Seoul witnessed 113 mm on the same day. In 2011, large-scale landslide accidents were triggered by localized heavy rainfall in Woomyeon Mountain, Seoul, and Chuncheon City, Gangwon Province. These flood disasters mainly stem from a change in rainfall characteristics. Compared with the last three decades (1976-2015), a chance of future 100-year frequency maximum precipitation by region can increase more than twice (Kim et al., 2018; Lee, 2021).

2.2. Technologies of Water Resources Management Forecast and Operation

The Korean government has applied the Integrated Water Resources Management (IWRM) practices through the whole process of the hydrological cycle, which would enable the efficient use and management of water resources, including rainfall and water flowing from basins and rivers. **Figure 1** demonstrates hydraulic infrastructure maintenance and safety management technologies and how such technologies are utilized for dam operation and maintenance. These technologies support the integrated safety management system for hydraulic structures, dam risk analysis, and assessment, enhancing the flood control capacity and aging dams' capacity.

A variety of technical equipment and facilities are installed for preventing floods and droughts. These include stage gauges, rain gauges, warning stations, CCTV, and meteorological radar, which collect and send real-time data and information to the K-water Water Resources Operation Centre. The center serves as an important knowledge and decision support hub that enables water managers at the center and the local level to decide dam reservoir operation, particularly faced with floods or droughts (**Figure 1**).

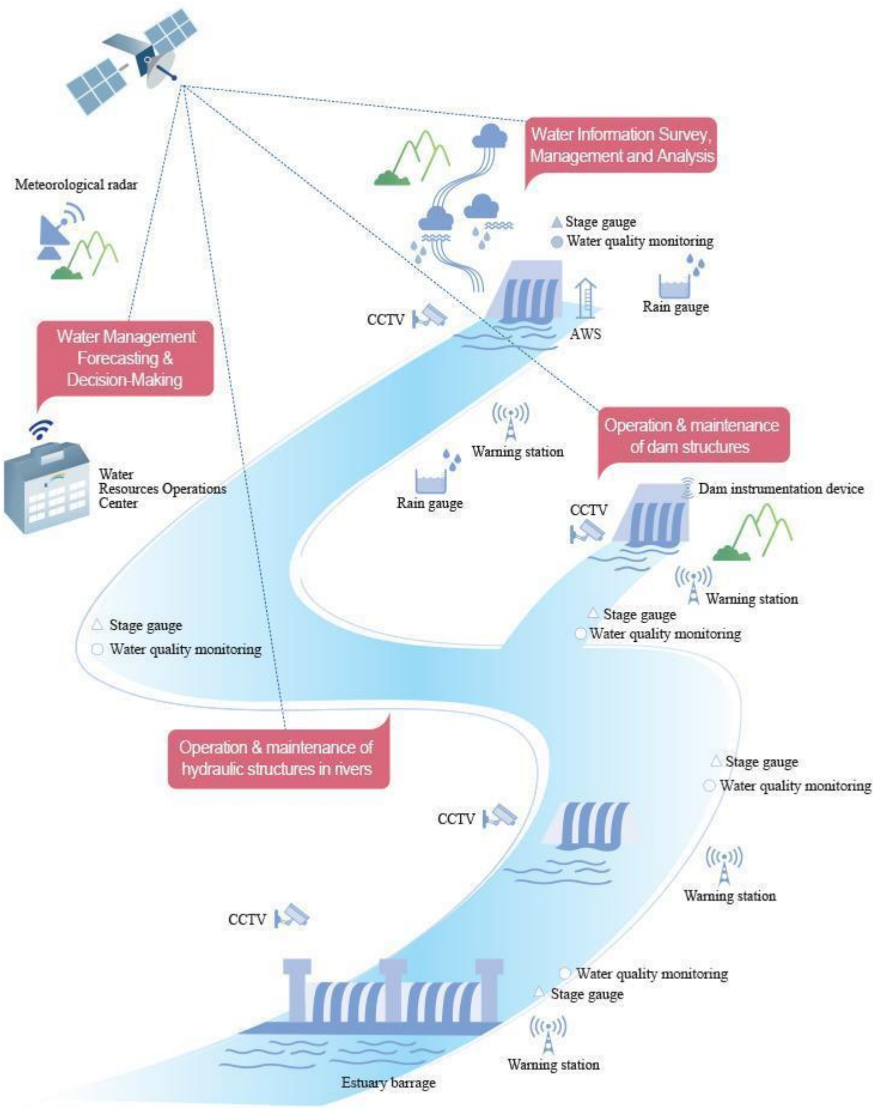

Figure 1 Dam structures operation and maintenance concept diagram
Source: K-water (2015).

2.3. Dam Construction and River Maintenance

An imperative structural countermeasure against floods and droughts is associated with the enlargement of detention storage via the construction of dams or reservoirs. Two interventions are crucial with respect to flood damage prevention: (1) to detain flood discharge as much as possible for decreasing the peak discharge; and (2) to divert substantial amounts of flood discharge in rivers and streams to the sea. Dams are constructed for improving flood detention while river maintenance is essential for enhancing flood protection.

Dams are instrumental in providing sufficient amounts of water for various purposes, household, industrial and agricultural uses in addition to environmental water use. The Multi-Regional Water Supply System in the country has played a pivotal role in providing clean water and proper sanitation services for major urban centers, including the Seoul Metropolitan Area, which encompasses the capital city, Seoul and supports more than 20 million population. Korea's unprecedented socioeconomic development has been attributed to numerous multipurpose, domestic or industrial water supply, hydropower, and agricultural water supply dams, which is as large as almost 18,000 dams as seen from **Table 2**.

Table 2 Specifications of Dams in the Republic of Korea

Items	Total	Multipurpose dams	Water supply dams	Hydropower dams	Agricultural water supply dams
No. of dams	17,490	20	54	15	17,401
Capacity (million m3)	13,708.2	9,170.0	536.3	992.8	3,009.1
Storage fraction (%)	100%	66.9%	3.9%	7.2%	22.0%

Source: K-water (2019).

2.3.1. Construction of Dams

As of late 2016, there were a total of 17,491 dams and reservoirs in the country, including dams under construction. Among them, 21 multipurpose dams accounted for 66.8% of the gross effective storage, which is equivalent to approximately twice the storage capacity of other dams. The five dams were specially designed and operated for flood control, i.e., the Peace Dam, the Gunnam Flood Regulating Reservoir, the Damyang Flood Regulating Reservoir, the Hwasoon Flood Regulating Reservoir, and the Hantan River Flood Regulating Dam. The general pattern of rainfall in the country is concentrated in three summer months and often entails floods. Large amounts of river water discharge to the sea in those months thanks to steep slopes. Such unique conditions are why the Korean government has been committed to constructing multipurpose dams for flood prevention, water supply, and power generation (see **Table 3**).

Table 3 Multipurpose dam details located on major rivers in the Republic of Korea

Water System	Dam	Area of Basin (km^2)	Height (m)	Length (m)	Total Storage (Million m^3)	Effective Storage (Million m^3)	Power Generation Capacity (Thousand kW)	Flood Control (Million m^3)	Water Supply (Million m^3/year)
Han River	Soyang River Dam	2,703	123	530	2,900	1,900	200	500	1,213
	Chungju Dam	6,648	97.5	447	2,750	1,789	412	616	3,380

	Hoengseong Dam	209	48.5	205	86.9	73.4	1.3	9.5	119.5
Nakdong River	Andong Dam	1,584	83	612	1,248	1,000	91.5	110	926
	Imha Dam	1,361	73	515	595	424	51.1	80	591.6
	Hapcheon Dam	925	96	472	790	560	101.2	80	599
	Namgang Dam	2,285	34	1,126	309.2	299.7	14	270	573.3
	Miryang Dam	95.4	89	535	73.6	69.8	1.3	6	73
	Seongdeok Dam	41.3	58.5	274	27.9	24.8	0.2	4.2	20.6
	Gunwi Dam	87.5	45	390	48.7	40.1	0.5	3.1	38.3
	Gimcheon buhang Dam	82	64	472	54.3	42.6	0.6	12.3	36.3
	Gimcheon buhang Dam	32.6	58.5	250	22.1	17.9	0.2	3.5	14.9
Geum River	Daecheong Dam	4,134	72	495	1,490	790	90.8	250	1649
	Yongdam Dam	930	70	498	815	672	26.2	137	650.4
Seomjin River	Seomjin River Dam	763	64	344	466	370	34.8	32	350
	Juam Dam	1,010	58	330	457	352	1.4	60	271.7
	Juam Regulating Reservoir	134.6	99.9	562.6	250	210	22.5	20	218.7
Jikso Stream	Buan Dam	59	50	282	50.3	35.6	0.2	9.3	35.1
Ungjin Stream	Boryeong Dam	163.6	50	291	116.9	108.7	0.7	10	106.6

Tamjin River	Jangheung Dam	193	53	403	191	171	0.8	8	127.8

Source: K-water (2016).

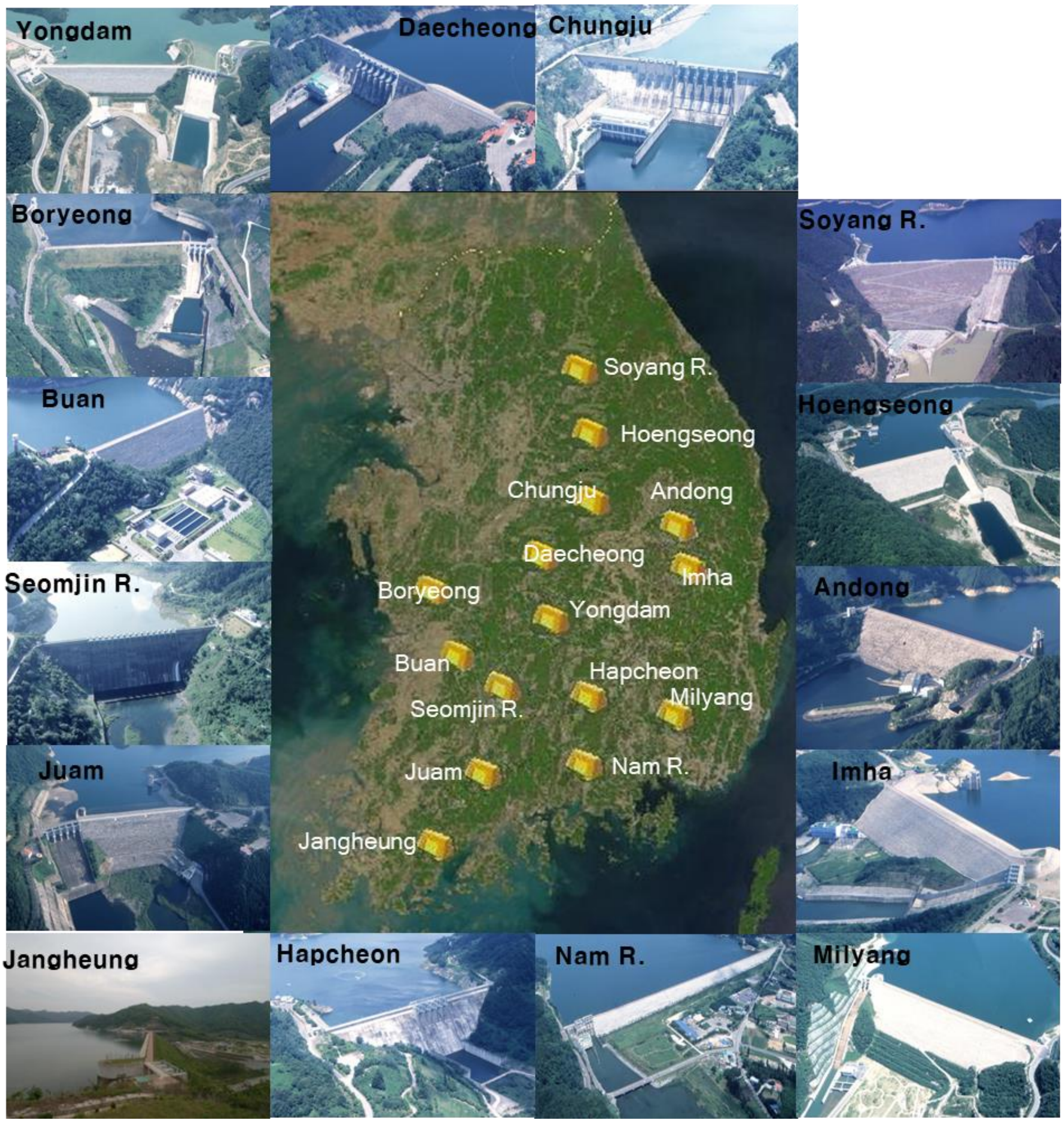

Figure 2 Dams of the Republic of Korea

The gross storage capacity of all multipurpose dams in the country amounted to approximately 12.7 billion m3 as of 2016. The dams are equipped with a power generation capacity of approximately 1.05 million kW with a flood control capacity of 2.2 billion m3 and the water supply capacity of 11 m3 per annum. The Soyang River Dam boasts the largest storage capacity (2.9 billion m3) with its annual water supply capacity of 1.2 billion m3, which is less than the

Chungju Dam (3.4 billion m3). The Chungju Dam is recognized as the dam with the largest hydropower generation capacity in the country, 0.41 million kW.

Multipurpose dams prevent flood events and provide domestic, industrial, agricultural, and river maintenance water in normal and dry or drought periods. The dams contribute to the production of clean energy through hydropower generation. In addition, reservoirs and riverine areas around the dams serve as a venue for diverse leisure and recreational activities that help boost local economies. Despite the benefits and magnitude of multipurpose dams, social conflicts about dam construction have recently come into being. These include controversies about environmental protection, backlash against the submergence of existing residential areas, and property rights concerns (see Table 4).

Accommodating those concerns regarding dam construction, the Korean government decided to introduce the "Improvement Plan of Dam Project Procedures (June 2013)." The plan involves consensus building among relevant stakeholders, including experts, NGOs, and residents of areas in which dam projects are planned. The approval of the Dam Pre-review Council is a prerequisite for new dam construction, and the plan assures public consultation procedures for affected local communities. In addition, the government has striven to adopt diverse systems for reflecting various concerns of local communities who would be affected by the dam construction, including the 'Dam Construction Application System'. The new system allows the communities to convey their views and opinions more easily so that theirs should be reflected within the plan at the early designing period of the dam project.

Table 4 Function of a multipurpose dam

Function	Content
Efficient Flood Damage Reduction	• Flood outflows take approximately 41% of the total amount of water resources in the Republic of Korea. Dams keep the water to decrease flood damage and utilize the saved water if necessary. • Frequent large-scale localized heavy rainfalls underscore the necessity of multipurpose dam construction. Multipurpose dams are useful in sharing flood discharge in river basins with riverbanks.
Creation of Sound River Environment	• Dams provide river maintenance water throughout the year to prevent dry stream phenomenon, improve water quality, and enhance the assimilative capacity of rivers for diluting pollution, which helps prevent water pollution accidents and inhabitation of fish resources. • Before the multipurpose dam was introduced to the country, rivers showed large gaps between maximum and minimum flows. River flows were stabilized as river maintenance water was provided after dam construction. • Based on the soaring demands of people for sound water environments, the role of the dam to provide waterfront amenities is emphasized.
Contribution to Local Economy	• Functional aspects of water resources were previously emphasized in dam construction. Current models consider effects on the ecological environment and society, including

	tourism, leisure, local community development, fish preservation, river environment management, and developing diverse aspects of the dam. Dam projects are expected to contribute to regional development and bring benefits for local communities.

Source: Modified based on K-water (2017).

2.3.2. Multi-functional Weir (Low-head dam)

The Korean government implemented the Four River Restoration Project between 2009 and 2013. The project has several purposes for preparing the country to cope with climate change-driven challenges, such as water shortage, floods and droughts, and ecosystem disruption, and to set a blueprint for bolstering local economies out of economic downturns caused by the 2008 financial crisis. The detailed aims are to secure additional water resources through weir construction, conduct dredging for river maintenance, construct small- and mid-scale dams, and level up embankments for the enlargement of agricultural reservoirs. Furthermore, the project created ecological parks, bicycle roads, and camping sites for leisure and recreational activities and aimed to contribute to a better quality of life. Table 5 shows the list of multi-functional weirs constructed by the project.

Table 5 List of multi-functional weirs (Low-head dams)

Basin	Weir	Area of Basin (km^2)	Height (m)	Length (m)	Type of gate (Number of gates)
Han River	Gangcheon Weir	10,972	8	440	Rising sector type (7EA)
	Yeoju Weir	11,115	8	513	Shell type (12EA) Turning type (1EA)
	Ipo Weir	11,803	6	521	Shell type (6EA)
Geum River	Sejong Weir	6,942	2.8 4.0	348	Turning type (3EA)
	Gongju Weir	7,408	7	280	Truss type (3EA) Turning type (3EA)
	Baekje Weir	7,976	5.3	311	Shell type (3EA)
Yeongsan River	Seungchon Weir	1,327	7.5	512	Truss type (4EA)
	Juksan Weir	2,359	3.5	184	Shell type (4EA)
Nakdong River	Sangju Weir	7,407	11	335	Shell type (2EA)

	Nakdan Weir	9,221	11.5	286	Truss type (1EA)
	Gumi Weir	9,557	11	374	Shell type (3EA)
	Chilgok Weir	11,040	11.8	400	Shell type (2EA) Turning type (2EA)
	Gangjeong Goryeong Wire	11,667	11.5	954	Rising sector type (2EA)
	Dalseong Weir	14,248	9.5	580	Rising sector type (3EA)
	Hapcheon Changryeong Weir	15,074	11.5	328	Truss type (3EA) Turning type (2EA)
	Changryeong Haman Weir	20,697	10.7	549	Rising sector type (3EA)

Phase 1) Infrastructure for water management and flood control technology
To acquire stable data such as hydrological data generation, processing, and transmission. It is necessary to replace old sensors such as water and rain gauges with the latest products and power sources, lightning protection facilities, data acquisition, storage, and transmission functions such as the Smart-TM Configuration.

Phase 2) Construction of real-time hydrological information and image system
The next step is to establish an integrated database of dam hydrological data, the production of data through a system that includes data verification and correction, the real-time hydrological information (RHDAPS) based on the user-customized Graphic User Interface (GUI), and the real-time video system to support decision making.

Phase 3) Building a decision-making system
Water management technologies such as flood analysis, water supply, drought information, and safety management will be necessary considering the country's water use and water control. A flood analysis model and an early flood warning system through an integrated Database analysis shall be established, and monitoring and warning criteria are settled through the visualization of expected water level and flood range in conjunction with GIS.

Phase 4) Integrated Water Management Center with ICT
The Integrated Water Management Center integrates collected data and quickly responds through real-time hydrological information such as hydrological data and CCTV images and decision-making systems. More details are as follows.

- ✔ Independent configuration: this method is adopted when the independent operation is advantageous or when there is a lack of communication infrastructure.

- ✔ Partially integrated configuration: if several power plants are operated in an area, partial integration in the area or center will be implemented.
- ✔ Integrated configuration: Considering the integrated operation of remotely located power plants in the center, the national communication infrastructure should be well-connected and the operator's skill level should be high.

3. Reservoir Operation during Flood and Drought

The Republic of Korea is influenced by the monsoon climate, where more than 80% of annual precipitation occurs from late June to early August. Stable water supply in the dry season from October to June in the following year is critical for the country. Significant decisions for multipurpose dam management depend on the water surface level of dam reservoirs in which the monthly target water surface level is usually set for water supply. For example, the dam increases the water supply if the current water surface level is higher than the target water surface level. The target water surface level in each month is established and adjusted depending on the dam operation's actual inflow and outflow amount. In terms of flood control, the storage for flood control is specifically assigned, which is called "Flood Control Storage". The reservoir storage, which is assigned for water supply, is called "Effective Storage". "Emergency Storage" is for the emergency water supply during drought periods (**Figure 3**).

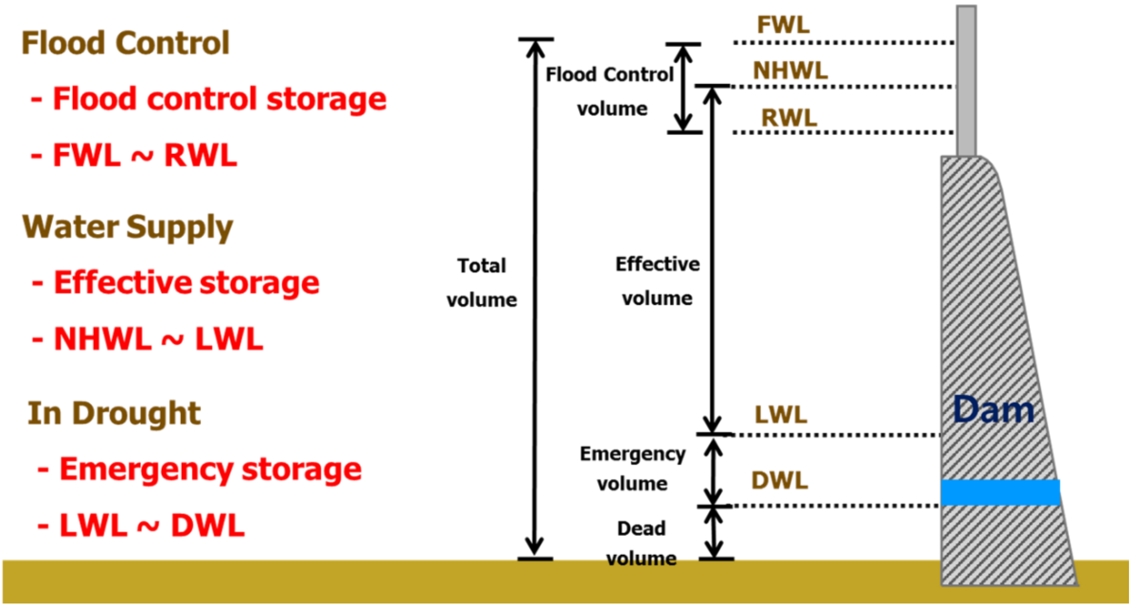

Figure 3 Dam Storage and Water Level for Reservoir Operation during Flood and Drought

A specific regulation is applicable during the drought season, which reduces water supply depending on precipitation forecast and actual dam inflows. There are "Upper Guidelines" and "Lower Guidelines" and the storage amount between these two guidelines is assigned for a specific purpose. These guidelines can be modified during the flood season (June 21st ~ September 20th) and are different for each dam (**Figure 4**).

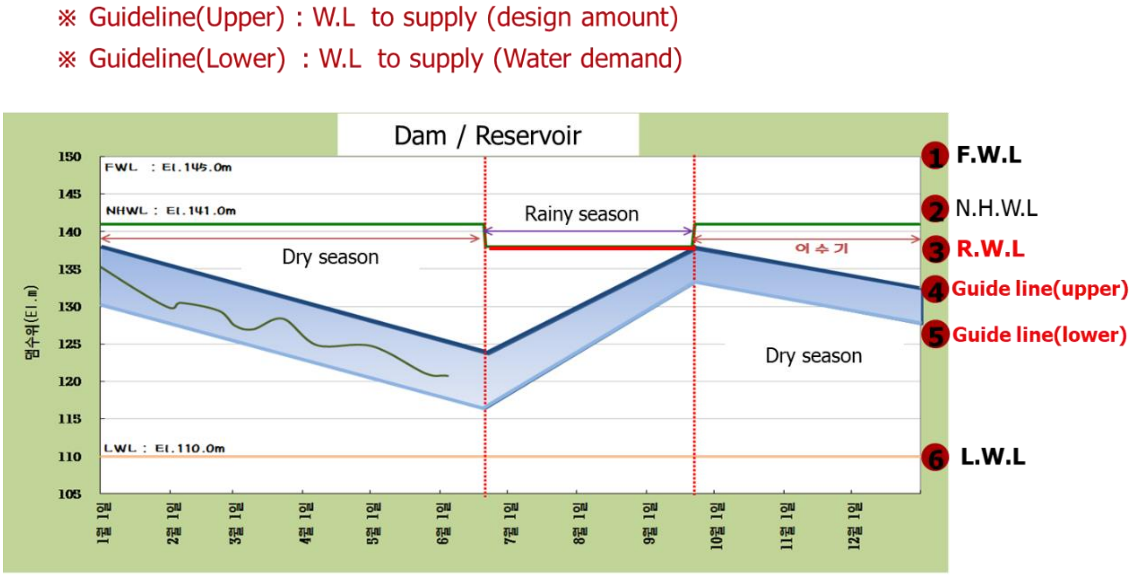

Figure 4 Reservoir Operation Rule for Flood and Dry Period of the Republic of Korea

3.1. Dam Operation for Flood Control

The dam operation for flood control can be divided into a single operation and a multi-reservoir operation. Flood regulation in the dam operation works based on Auto ROM (Automatic Reservoir Operation Method), SRC ROM (Spillway Rule Curve Reservoir Operation Method), Rigid ROM (Rigid Reservoir Operation Method), and Technical ROM (Technical Reservoir Operation Method), which can be combined with actual flood control. K-water, the government-owned enterprise, operates multipurpose dams in the country and has developed its own operation kit (K-HIT, K-water Hydro Intelligent Toolkit) for the efficient combination of forecast and operation. The K-HIT comprises a hydrologic module (RHDAPS, Hydrological Data Acquisition, and Processing System), a short-term and long-term precipitation forecasting model (PFS, Precipitation Forecast System), and a dam operation module (FAS, Flood Analysis System) (**Figure 5**).

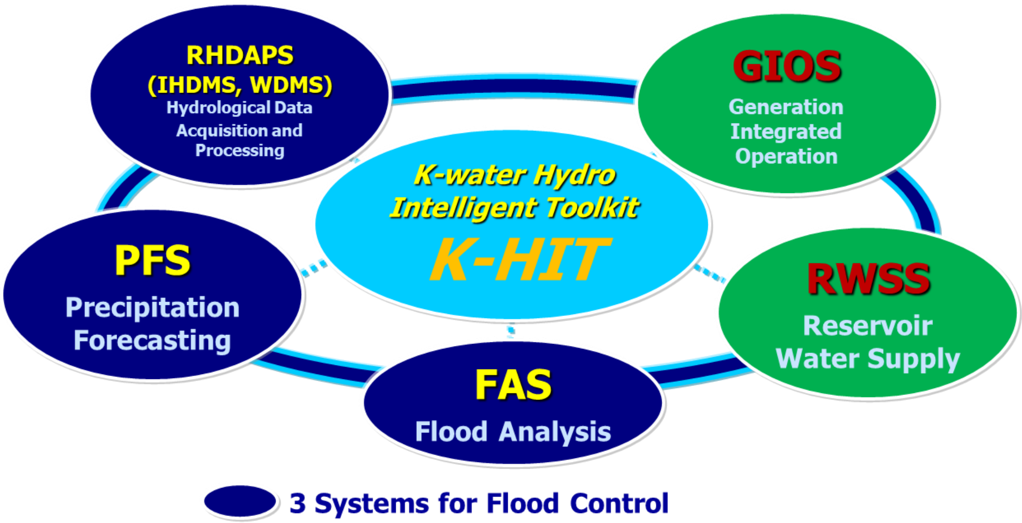

Figure 5 K-water's Flood Control Models using Multipurpose Dams

As mentioned earlier, there are "Upper Guidelines" and "Lower Guideline", and the storage amount between these two guidelines is assigned for a specific purpose. These guidelines can be modified during the flood season (June 21st ~ September 20th). The upper guideline during the flood season complies with the flood water level (FWL) (**Table 6**).

Table 6 Guideline for Reservoir Operation during Flood Season

Guideline	Detail
Lower Guideline	A threshold that can supply water without inflows for 30 days
Upper Guideline	A threshold that can store flood without additional outflows

3.2. Dam Operation for Water Supply and Drought Response

The dam operation is composed of a long-term inflow forecast and a water budget model, Reservoir Water Supply System (RWSS). The RWSS aims to maximize the utilization of water resource facilities such as dams, weirs, and agricultural reservoirs. By linking rivers with these facilities, the system facilitates the integrated management of water resources. Based on the amount of water inflow and water consumption for each river system, the system can help operate a series of dams and play a supporting role in deciding the necessary amount of water discharge. In addition, the system is useful in determining the amount of the discharged water as an input for a water balance analysis and water quality (see **Figure 6**).

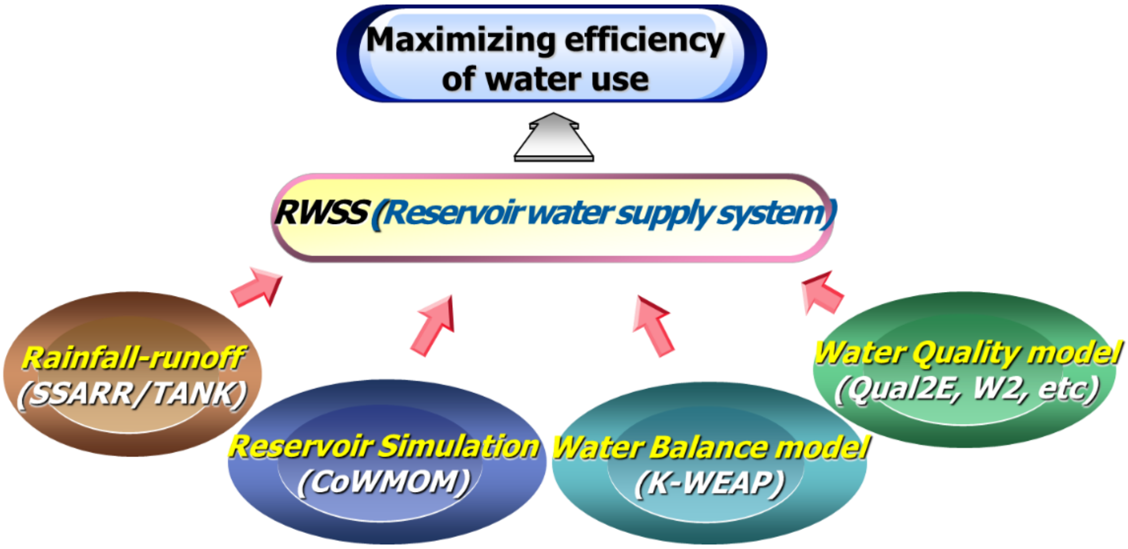

Figure 6 K-water's Reservoir Operation System and Process for Optimized Water Supply

The RWSS (Reservoir Water Supply System) consists of long-term rainfall-runoff models, a reservoir simulation model, a water balance (budget) model, and a water quality model as seen from **Figure 7**.

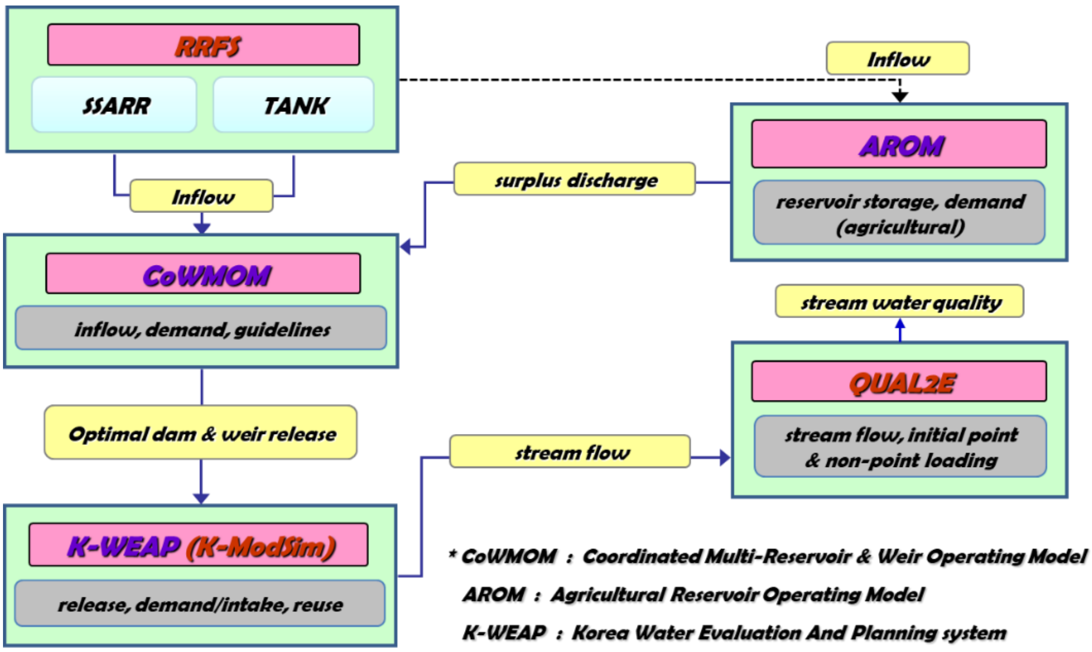

Figure 7 Subcomponent of RWSS and Water Supply Simulation Process

Water supply during the drought period is regulated by a four-alert-stage systematic response: 1) Warning; 2) Caution; 3) Severe; and 4) Very Severe. All the related authorities and agencies follow an action plan to manage the drought when these stages are issued. The action plan starts off from the 1st stage that regulates the stream maintenance water. The 2nd stage regulates the entire amount of the stream maintenance water. The 3rd stage regulates the entire amount of the stream maintenance water and a fraction of the agricultural water supply. The 4th stage regulates 20% of the municipal water supply additionally (**Figure 8**).

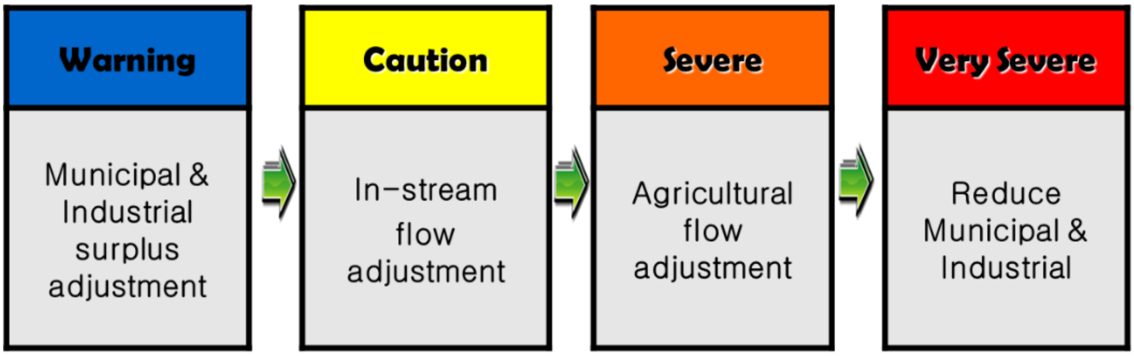

Figure 8 Water Supply Adjustment and Process during Drought Period

The country was confronted with a severe drought in 2012, and the multipurpose dams provided water three times more than the inflow amount. The example demonstrates the efficiency of dam operations during the drought event (**Table 7**).

Table 7 Water Supply and Reservoir Inflow during the 2012 Drought Year

Index	Inflow (A) (Million m3/day)	Supply (B) (Million m3/day)	Ratio (B/A)
Total	11.9	40.5	3.4
Han River	4.9	15.7	3.2
Nakdong River	2.9	11.0	3.8
Geum River	2.5	7.7	3.0
Sumjin River	1.4	5.3	3.8

4. Administrative and legal framework

4.1 Administrative framework

The ministry in charge of dam operation in the country is the Ministry of Environment (MOE). The country has undergone a significant reshuffling of water-related ministries and agencies from 2018 to the present. A major policy change is the empowerment of the environment watchdog, the MOE, whereas the Ministry of Land, Infrastructure, and Transport (MOLIT) lost its influence in water resources management. The MOE takes most of the water resources management responsibilities from the MOLIT, including dam operation for flood and drought management.

In addition, in May 2018, there was a noteworthy policy shift in Korea's water resources management – the enactment of the Water Management Basic Act. The act explicitly promotes Integrated Water Resources Management (IWRM) by establishing new water organizations favoring river basin management, including the National Water Management Committee at the center and the River Basin Committees in the Four Major River Basins. Such river basin organizations are expected to enhance flood and drought management capacity, reflecting needs and demands from diverse stakeholders at the river basin level, which have often been neglected and marginalized due to the centralized flood and drought management system.

K-water is the main agency in operating large dams in the country under the auspices of the MOE. Since the company operates 49 dams and weirs (33 dams and 16 run-of-river weirs), 25 hydropower plants, 186 warning stations, and 446 gauging stations, other flood and drought control institutions closely work with the company for access to up-to-date information and analyses, i.e., Flood Control Office (flood control) and Environment Management Office (water quality management, conservation of nature).

4.2 Legal framework

The legal framework of the country about floods and drought encompasses several laws and regulations. A total of five laws are related. The first two laws are in the hands of the Ministry of Environment whereas the third, the fourth, and the fifth laws are taken care of by the Ministry of Interior and Safety. First, the River Act is discussed. The act stipulates a series of articles to manage rivers properly and promote the public welfare by designing, managing, utilizing, and conserving rivers to increase benefits from river use, the nature-friendly maintenance and preservation of rivers, and the prevention of damage caused by river flows.

Second, the Dam Construction and Support Adjacent Areas Act is worth paying attention to. The act declares the rational development and use of water resources and promotes the development of the national economy through the construction and management of dams, the revolving investment in costs for the construction of dams, environmental measures in relation to dams. In addition, the act explicitly states the need to support residents living adjacent to dams.

Third, the Small Stream Maintenance Act is becoming more important than before thanks to the increasingly intensifying adverse impacts of climate change. The act includes articles to prevent disasters and contribute to the improvement of living environments and stipulates the need for the maintenance, utilization, management, and conservation of small rivers.

Fourth, the Natural Disaster Countermeasure Act points out natural disaster prevention, recovery, and other countermeasures to protect the national land, people's lives and properties, and key infrastructures from typhoons, floods, and other natural disasters.

Fifth, the Disaster and Safety Management Basic Act is the key foundation to establish the disaster and safety control system at the national level and to promote prevention, preparation, countermeasure, and recovery against natural disasters (Lee, 2019; Lee, 2021).

5. Good Practice: Flood Control by Namgang Dam

This section discusses the case of the Namgang Dam operation during the 2012 flood period. The 2012 rainy season began with a low level of rainfall (a scenario which is referred to as the 'dry rainy season) in the early phase. Although the full-scale rainy season came after June 29th, the season ended earlier than usual with a seasonal rain front that advanced to Northeast China thanks to Typhoon Khanun.

After the seasonal rain, troughs passed through continuously, and three typhoons struck the Korean Peninsula, which led to massive volumes of rainfall than in the average year. The three consecutive typhoons (Typhoon No.15 Bolaven, Typhoon No.14 Tembin, and Typhoon No.16 Sanba) after the middle of August 2012 badly hit the country, primarily due to the expanded North Pacific anticyclone. Such flood events were the first phenomenon of its type since the country's meteorological observation commenced and required more comprehensive disaster responses.

Bolaven and Tembin battered the country in 2012, and the phenomenon was the first time when two typhoons struck the Korean Peninsula within 43 hours. Bolaven made landfall in the peninsula first as Tembin moved slowly in the unusual course of an 'α shape' due to the Fujiwhara Effect. Bolaven was the strongest typhoon among those that advanced to the Yellow Sea since 2000.

Then, Sanba landed from the South Sea at around 12:00 on September 17th. From the morning of September 17th, the typhoon brought in localized heavy rain on the inland areas of Gyeongnam where the Namgang Dam is located. Heavy rain amounting to 267 mm between September 15th and 17th fell into the Namgang Dam Basin, and the maximum rainfall for 24 hours was estimated at 230 mm (Figure 9).

K-water was on high alert and prepared itself for Sanba's landfall. The company immediately started to collaborate with flood control-related agencies and institutions at the national level following flood prevention procedures as seen from Figure 10. K-water conducted a runoff analysis and simulated reservoir operations by applying FAS based on forecast data calculated by PFS. From September 13th (two days before the typhoon was expected to impact upon the areas), K-water opened the gates of the dam for lowering the water level at a rate of 300 m3 per second, which is within a discharge range that would not give any damage to downstream areas. K-water secured an additional flood adjustment capacity of 142 million m3.

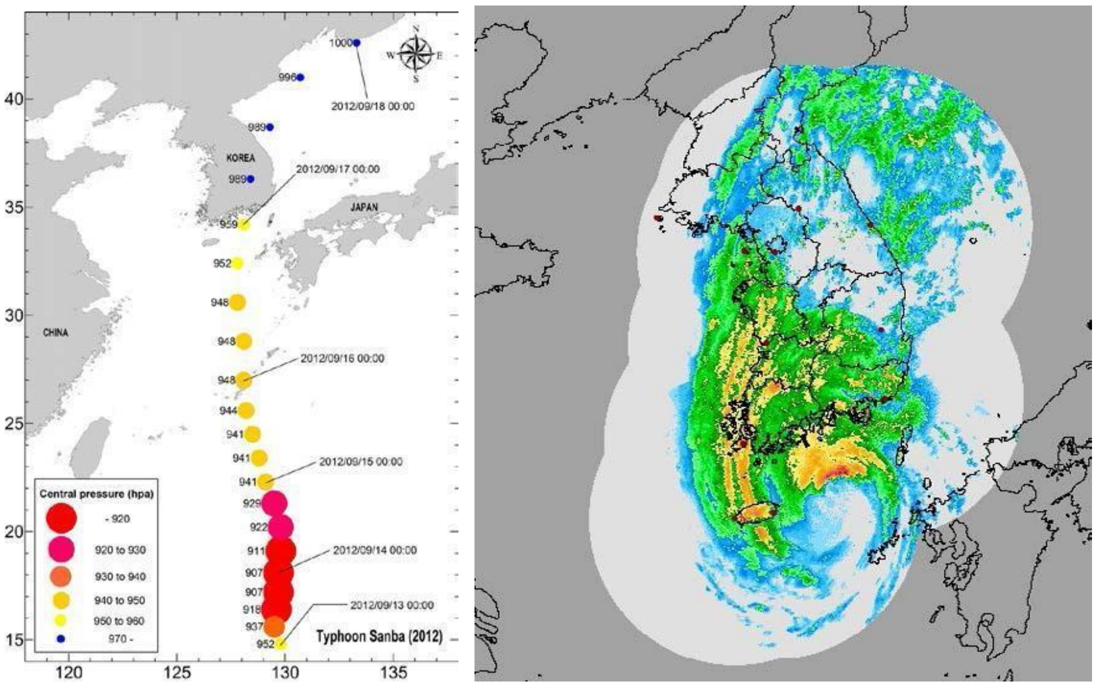

Figure 9 Path of Typhoon Sanba and rainfall radar image in 2012

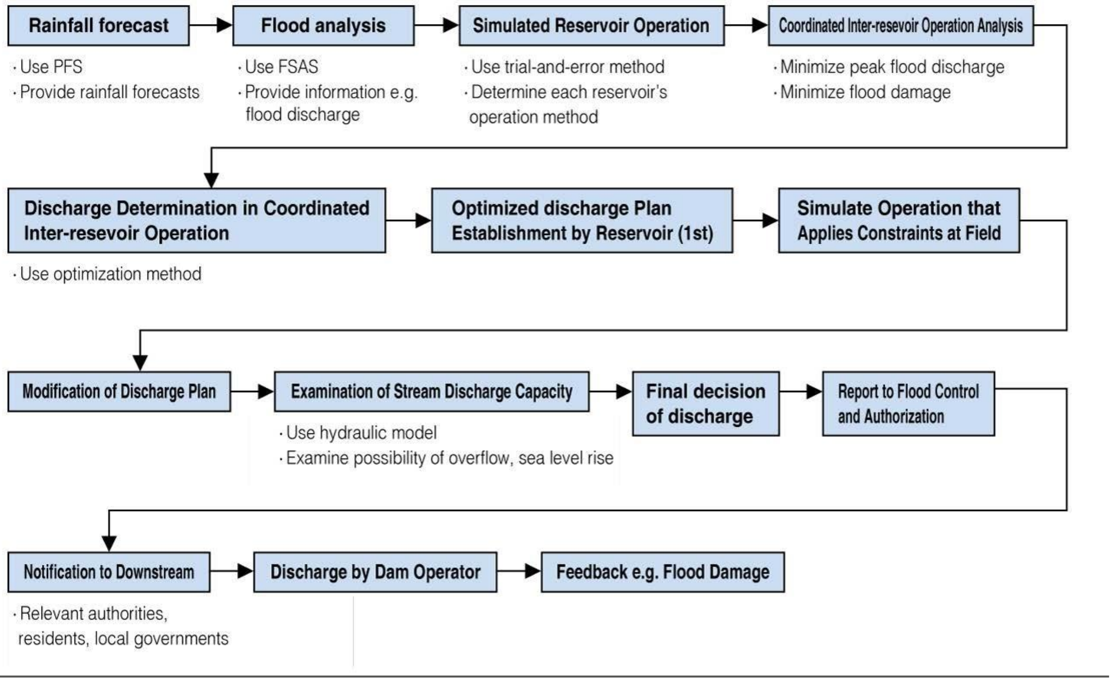

Figure 10 Flood prevention procedures in the Republic of Korea

As the typhoon gave the heaviest impacts on the country, 14,100 m3/s of water surged into the Namgang Dam Basin, exceeding the dam's designed flood discharge capacity, 10,400 m3/s. The typhoon's inflow amount to the dam, 14,100 m3/s was very close to 14,818 m3/s, which was the largest inflow from Typhoon Rusa in 2002.

The dam secured the flood adjustment capacity in advance, discharging water downstream at a rate of 2,510 m3/s (maximum), which is far lower than the designed discharge rate, 4,050 m3/s. The efficient response to the flood was made through a conjunctive utilization of diverse water resources management systems. The systems consist of flood adjustment capacity securement by pre-releasing discharge, hydrologic data (e.g., rainfall, water level, water flow) monitoring by using RHDAPS, rainfall forecast using PFS, and real-time flood analysis using FAS, and discharge adjustment. The Namgang Dam succeeded in minimizing flood damage by Sanba although the amount of water discharge downstream was estimated at 2,510 m3/s.

As described above, the utilization of various systems, including RHDAPS, PFS, FAS, and GIOS, enabled efficient dam operation, helping decision-making and adjustment of discharge through runoff analysis and downstream impact analysis. The maximum water level when Sanba struck was EL.44.3 m at 23:00, September 17th, by which the 1.7 m of freeboard was secured in comparison with the designed flood level (EL. 46.0 m). The Namgang Dam's flood adjustment rate for Sanba was 82.2%, and it was analyzed that the flood adjustment by the Namgang Dam lowered the water level at Jinju point in the dam's downstream area to 0.23 m, thereby reducing flood damage (Figure 11).

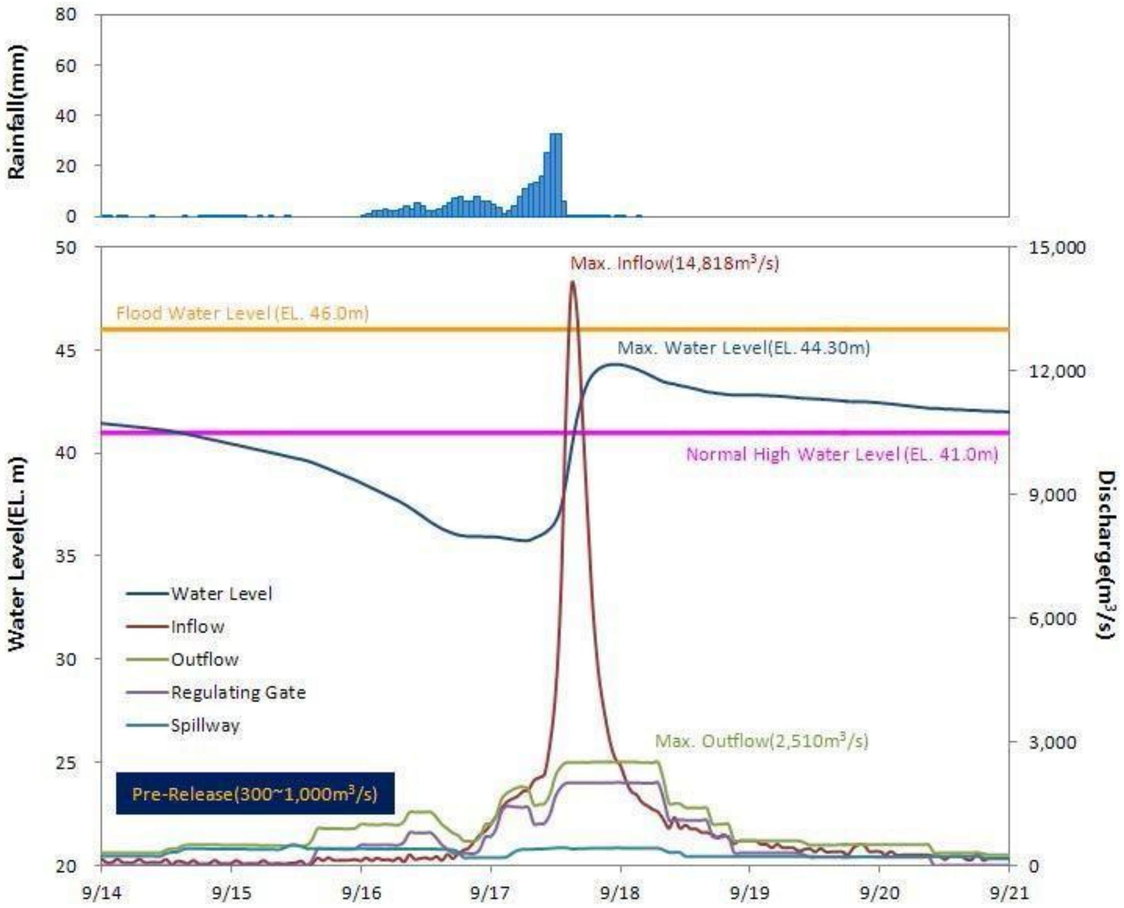

Figure 11 Example of flood control using the Flood Analysis System in the Namgang Dam in 2012

6. Conclusion

This chapter has explored technologies, procedures, and systems in dam reservoir operations for tackling floods and droughts in the Republic of Korea. Discussions on the patterns of floods and droughts over the past few decades have confirmed the successful achievements of Korea's dam reservoir operations despite its natural disadvantages that are triggered by the monsoon climate, which shows heavy rainfall in summer and long-spelled dry periods in the rest of the year, and climate change. More concerns are arising with regard to localized heavy rainfalls that frequently entail flash floods in urban areas as a new type of flood that should be focused on in the future.

Cutting-edge technologies, equipment, facilities, and systems in dam operations are never insufficient in the country. In contrast, ICT industries and non-structural and structural systems have been well equipped to cope with climatological and hydrological uncertainties closely linked to the outbreak of severe flooding and drought events.

Korea's unprecedented economic development, social well-being, and environmental sustainability has massively been contributed by efficient water resources management, especially related to superb systems of dam reservoir operations. The ongoing water sector reform, which has been embarked on since 2018, is expected to bring about more comprehensive benefits for Korean society based on river basin management. One of the core issues in the reform is if this new campaign for improving water resources management can improve water security for the whole society, which is closely associated with the efficient operation of dam reservoirs in each river basin.

Climate change entailed uncertainties and risks in water resources management. It leaves us formidable challenges to tackle heavy rainfall, frequent typhoons, flash floods, extreme heat waves, and long-spelled droughts and provides a window of opportunity to develop brand-new and innovative ideas.

The Korean government must make large investments in water infrastructures such as dams as well as non-structural measures, i.e., economic instruments and governance systems under the era of climate change. Based on a good level of technological advancement in dam reservoir operations, the country should emphasize the introduction of an integrated approach to operating a number of dams located in different regions and river basins.

7. References

Kang, M. G., H.S. Jeong, J H. Lee, and B. S. Kang. 2013. Assessing national flood management using a sustainable flood management framework. Water Policy 15, 418-434.

Kim, H. Y., C. Shin, Y. Park, and J. Moon. 2018. Water Resources Management in the Republic of Korea: Korea's Challenge to Flood & Drought with Multi-purpose Dam and Multi-regional Water Supply System. Inter-American Development Bank Technical Note, 1566, IDB, Ministry of Environment, and K-water.

K-water. 2015. Smart Water Management Technology

K-water. 2016. Task Guide for Dam Operation. Integrated Water Resources Management Department.

K-water. 2017. Water and Future 2017. Daejeon, Ministry of Environment and K-water.

K-water. 2018. Case studies: K-water's Integrated Water Resources Management System.

K-water. 2019. Water and Future. Daejeon, Ministry of Environment and K-water.

Lee, Namsoo. 2019. Water Policy and Institutions in the Republic of Korea. ADB Institute Working Paper Series No 985. August 2019.

Lee, Seungho. 2021. Chapter 4: Patterns of Risk Management Policies and Systems in South Korea: Special Reference to Water-Related Disaster Management. In Jing Yijija, Jung-Sun Han, and Keiichi Ogawa (eds.) Risk Management in East Asia: Systems and Frontier Issues. Singapore, Palgrave Macmillan.

Dam Reservoir Operation for Safe Communities at the Perak River Basin in Malaysia

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Abstract

Dams are typical water retaining structures built across a stream, river, or estuary to serve multiple purposes such as mitigating floods, securing water supplies and generating hydropower. Malaysia has 104 dams, including 16 dams that serve hydropower generation as a primary purpose or an additional function where a dam is built for multipurpose. Efficient and effective reservoir management is thus vital for dam operation. This paper discussed the initiatives taken by Tenaga Nasional Berhad through TNB Power Generations Sdn Bhd at Sungai Perak Hydroelectric Scheme in ensuring safe and optimum reservoir operation, taking into account the impact of climate change. The initiatives are supported by Strategic Dam Operator Competencies Program for capacity building in dam engineering and safety. Among the initiatives include Temengor Reservoir Inflow Forecasting, Review of Probable Maximum Precipitation and Probable Maximum Flood, Dam Break Studies, Dam Safety Emergency Response Plan, Integrated Community Based Disaster Management, Risk-Informed Decision Making and Automatic Dam Safety Management System. The implementation of Malaysia Dam Safety Management Guidelines in reservoir operation aims to support the Government of Malaysia, to ensure a holistic and sustainable dam safety management, primarily dam operational decision making.

Key Words: Reservoir Operation, Dam Safety, Malaysia, Sungai Perak Hydroelectric Scheme

1. Introduction

Malaysia has an average annual rainfall of approximately 2000-3000 mm/year. While rain varies with time and space, the precipitation is higher than the average rainfall in East Malaysia. Severe floods occur in low-lying areas during the wet season, and reduced water inflow into rivers during the dry season causes prolonged drought and depleted water resources in some areas. Dams are built-in positions to alleviate these water resources issues sustainably and effectively. Dams provide many endless benefits and solutions to water resources problems in Malaysia. But dam failures can be catastrophic, causing loss of life and property, psychological impact to victims, and structural and non-structural damages to the environment. When a dam fails, it may thus negate the benefits previously provided over many years. Therefore, dams have to be sustainable yet resilient against failures throughout their entire lifecycle.

The dam development for water resources management in Malaysia began as early as the end of the 19th century by the British Government, mainly for water supply and irrigation. The first large dam built in Malaysia was the Air Keroh Dam in Malacca (the 1890s). Dams in Malaysia are generally of the embankment type. The embankment type of dam, due to the geological conditions in the country that are suitable for the foundations of embankment dams and build embankment dam materials, this type of dam material is available in abundance. Once the dam is built, it requires constant maintenance and monitoring, regular safety inspections, and scheduled rehabilitation to ensure its capability to function well. Dams may pose a potential safety threat to populations living downstream of dams and people surrounding associated reservoirs. As dams age, they can deteriorate, which also may pose a potential safety threat. The risks of dam deterioration may be amplified by lack of maintenance, misoperation, development in surrounding areas, natural hazards (e.g., weather and seismic activity), and security threats. Structural failure of dams may threaten public safety, local and regional economies, and the environment and cause the loss of services. In line with the current global awareness of water security, the aspect of dam safety has drawn attention from the public, as it constitutes the element of a country's national security. The consequences of dam failure may involve substantial downstream injury, loss of lives, property damage, catastrophic and long-lasting environmental effects [1].

There are 104 dams in Malaysia with a total storage of approximately 84,000 MCM of water. Of these dams, 83 are in Peninsular Malaysia and 21 in Labuan, Sabah and Sarawak. MyDAMS has classified 81 large dams while the remaining 23 are small dams [2]. Among these dams, there are 16 hydropower dams in Malaysia, of which 12 dams are in Peninsular Malaysia under the responsibilities of TNB, and four are in Sarawak under the responsibilities of Sarawak Energy Berhad (SEB). The total storage for hydropower dams is 80,000 MCM. The largest hydropower dam is Bakun Dam in Sarawak, with a total storage of 43,800 MCM of water and a total surface area of 695km^2. ICOLD lists Bakun dam as 41 out of 60 highest dams in the world. Meanwhile, five dams for flood mitigation are under the responsibilities of JPS, 14 dams for irrigation and 63 dams, which are under the responsibilities of JBA for water supply. About 60 percent of these dams are of the earth fill type, and 40 percent of these dams are more than 50 years old [3].

Dam related disasters could be devastating for people, community structures, the environment, and the circular economy. The possible consequences of a dam failure may include social, economic and environmental catastrophes, among which the potential life-loss is the most crucial aspect. The impact of dam failure can cause a disastrous flood and result in high fatality rates of more than 10,000 lives and more than RM 1.25 Billion of property damages, especially when flooding overwhelms an unsuspecting group of people [4]. Thus, dam safety programs, especially the reservoir operation, are vital to minimise the impacts on the communities downstream of the dams. In addition, it is essential to ensure that the dam owner and related agencies are ready and equipped with the necessary knowledge and action plans in the event of dam failure.

In Malaysia, hydropower generation constitutes a fundamental reason for building dams, particularly in the states of Sarawak and Perak [5]. There are 16 hydropower dams in Malaysia, of which 12 are in Peninsular Malaysia under the responsibilities of Tenaga Nasional Berhad (TNB), and four are in Sarawak State under the responsibilities of Sarawak Energy Berhad (SEB). Hydropower refers to either mechanical power or electrical power generated from the kinetic energy freed by falling water. Dam operators need to maintain a balance between conflicting needs. Nowadays, dam reservoir operation is becoming more sophisticated as the demand for efficiencies in water and power continually increases, while maintaining and safety of dams remain of paramount importance [6]. Therefore, the reservoir operation rules and methods need to be updated to ensure the sustainable operation of water released from the dams.

The terminology of firm energy (also known as primary baseload) refers to the power produced by a hydropower plant with no risk. For a single hydroelectric power plant, it commonly corresponds to the minimum availability of storage. Meanwhile, the power available more than firm power is defined as surplus or secondary power, in which its rate is usually less than that of firm power and cannot be relied on. It is essential to know the minimal power that a hydropower plant can produce so that the continuity of the power generation process is guaranteed. When the water head is kept constant, the only uncertainty in estimating the firm energy is the available streamflow attributed to rainfall, evaporation, groundwater recharge, and baseflow.

This paper discusses four parts: the dams in Malaysia, the local best practices on dam safety, reservoir operation by hydropower scheme, and related activities that can minimise the impact of reservoir operation downstream. There is a need for more investment in testing, demonstration sites, and other mechanisms to share knowledge and encourage broader adoption of these practices to achieve the goals. By sharing experiences, these topics can help adapt to the dam designers and operators due to climate change, ageing infrastructures and population growth.

2. Dam Safety Management Practices in Malaysia

The Department of Irrigation and Drainage (DID), Malaysia has established the first national guidelines on dam safety management, titled Malaysia Dam Safety Management Guidelines (MyDAMS), in September 2017 [2]. The framework of dam safety management in MyDAMS was derived from various safety guidelines from Australia, Canada, New Zealand, United States and technical bulletins from the International Commission on Large Dams (ICOLD). MyDAMS outlines the safety aspects of the entire life cycle of dams' management, comprising the legal requirements, potential hazards of dams and safety principles, dam safety management system, investigation and design, construction and commissioning, operation and maintenance, surveillance and safety review, rehabilitation, emergency action plan, changes and decommissioning.

As stipulated in MyDAMS, all dam owners are required to establish their dam safety program. Safety Principle No. 7 of MyDAMS: A dam safety management system commensurate with the consequences of dam failure and incorporating policies, procedures and responsibilities should be in place for all dams. An essential effective dam safety management is establishing and implementing procedures commensurate with the consequences of dam failure. Dam Owners shall understand and apply to the dam safety management system **(Figure 1)** and provide a structured framework for conducting dam safety operations, addressing identified dam safety issues and deficiencies.

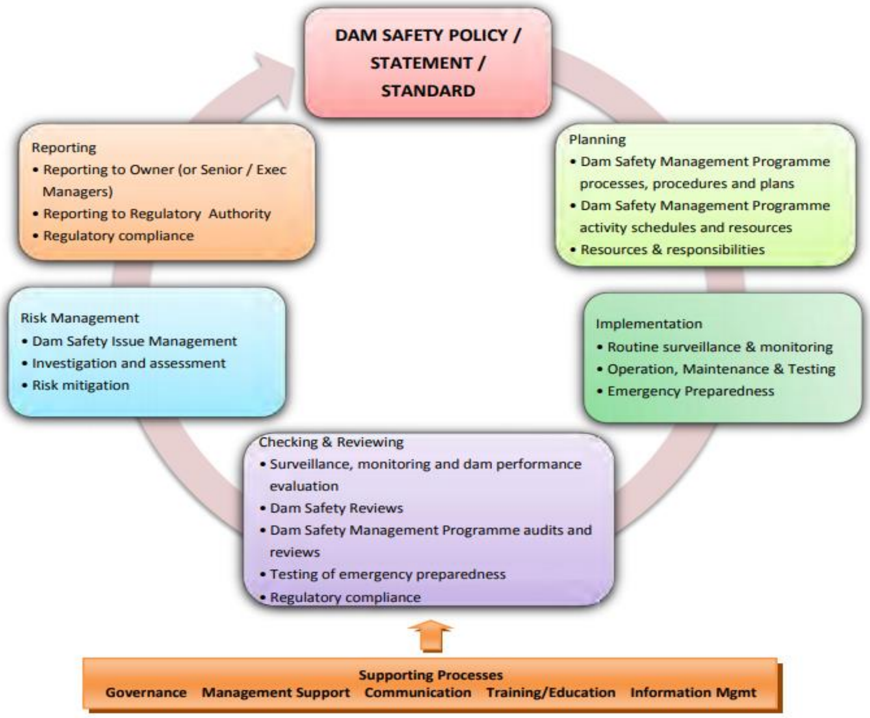


Figure 1: Dam Safety Management Program [6]

The key elements of dam safety management outlined in MyDAMS provide a framework for dam safety activities, decisions, and supporting processes that should be commensurate with the dam hazard rating. It shows the interfacing dam safety activities and cycles throughout the entire life cycle management of a dam. For each dam safety activity, the dam owner must plan and engage the appropriate personnel to implement the dam safety management program elements. The technical requirements and expertise also vary amongst the dam safety activity. It is worth noting that MyDAMS has also outlined the dam risk assessment to be part of a dam safety management program. It allows dam safety decisions to be made based on probabilistic risk criteria.

The appropriate practices that should be considered during the dam reservoir operation are summarised in **Table 1**. Although MyDAMS is not intended to be a design standard or an instruction manual, the implementation and compliance of MyDAMS to all dams in Malaysia are compulsory to achieve its basic safety levels.

Table 1: Dam and Reservoir Operation in Malaysia [2]

Aspects	**Descriptions**
Operating criteria and constraints	- It requires criteria that define operating limits and extensive, reliable data to ensure safe operations within those limits. - Constraints on dam operations should be defined during dam design and reviewed periodically, including maximum safe discharge rates, highest safe reservoir level, physical restrictions on operations, legal constraints on discharge rates and downstream water level.
Data requirements	- They are requiring systems and data to support the operating decisions. - Data should be prepared during the development of documentation, including headwater and tailwater elevations, ways to gauge flow volumes, weather data and access to watershed flow data, information

	on uncontrolled upstream inflows, highest reservoir level, statistics for normal values of inflows, expected inflow design flood (IDF) inflow values and the reservoir elevation during the IDF event.
Operating procedures	- Operating procedures should be defined for normal, unusual or flood, and emergency conditions. - Procedures should be specific enough to define what actions are taken, by whom, and when. - Including the requirement to document operating conditions and activities, such as reservoir water levels, inflows, discharge flows, equipment operations, unusual events, alarms and resulting actions, public activities. - An operations log or record of actions should be maintained.
Flow control	- Information related to flow control system operations should be identified and documented, including manufacturer's information, design reports. - Procedures for supervisory control and data acquisition (SCADA) and water level gauge installation, calibration, maintenance, and repair should be in place. - Critical dam surveillance instrumentation may be linked into the control system to provide real-time indications of potential dam safety issues. - All emergency systems should be identified and documented, including dam-breach early warning systems, emergency power supplies.
Reservoir operation records	- Records and data associated with a reservoir's operation should be recorded and stored securely, including rainfall, reservoir inflows, reservoir lake levels, reservoir outflows, and all functions of gates and valves. - The recording incidents such as unusual loading conditions, operations, and occurrences, together with evaluations and the lessons learned.

The flood risk management operation is worth noting for international best practices on reservoir operation, as in the United States Army Corps of Engineers (USACE) [7]. Four aspects emphasise as follows,

1. Project outflows. The outlet works are designed to manage releases during the evacuation of flood storage, while the spillway is used when the reservoir approaches full pool level and during induced flood surcharge operations.
2. Managing and monitoring outlet and spillway gate regulation. The water manager issues flood regulation schedules and operating instructions, including guidance on total discharge, gate settings, flow rates of change, and the gates and structures to be used.
3. Combined use of outlet works and spillways. Such combined use depends on evaluations of the hydraulic and structural designs at the particular project, including the flow characteristics of the spillway and outlet works concerning the symmetry of flow in the spillway or outlet channel.
4. Free-flow operation of projects with little or no flood risk management mission. Spillways are designed to provide approximately the equivalent capacity of the natural outlet. Outflows may augment the spillway discharge through power units.

3. Case study: Perak River hydropower scheme

3.1 Overview of Perak River basin

The state of Perak is located in the western region of Peninsular Malaysia, bordered by the southern parts of Thailand and other Malaysian states, including Kedah, Penang, Kelantan, Pahang and Selangor, as shown in **Figure 2**. Perak River is the second largest river system in Peninsular Malaysia, with approximately 427 km and a catchment area of 15,180 km². It is the main river to channel water from the inundated areas of the Perak River basin to the Straits of Melaka during the wet season caused by the southwest monsoon, inter-monsoon season and sometimes northeast monsoon at the end of the year. The Perak River basin occupies 71 % of the total land area in Perak State, with hilly terrain found at the northern, eastern and western parts of the river catchment. These upland areas generally range from 1000 m LSD to more than 2000 m LSD in elevation, with some peaks reaching more than 2100 m LSD. The topography is less rugged towards the main drainage lines in the central part of the basin, where most of the land is below an elevation of 75 m and consists of low hills.

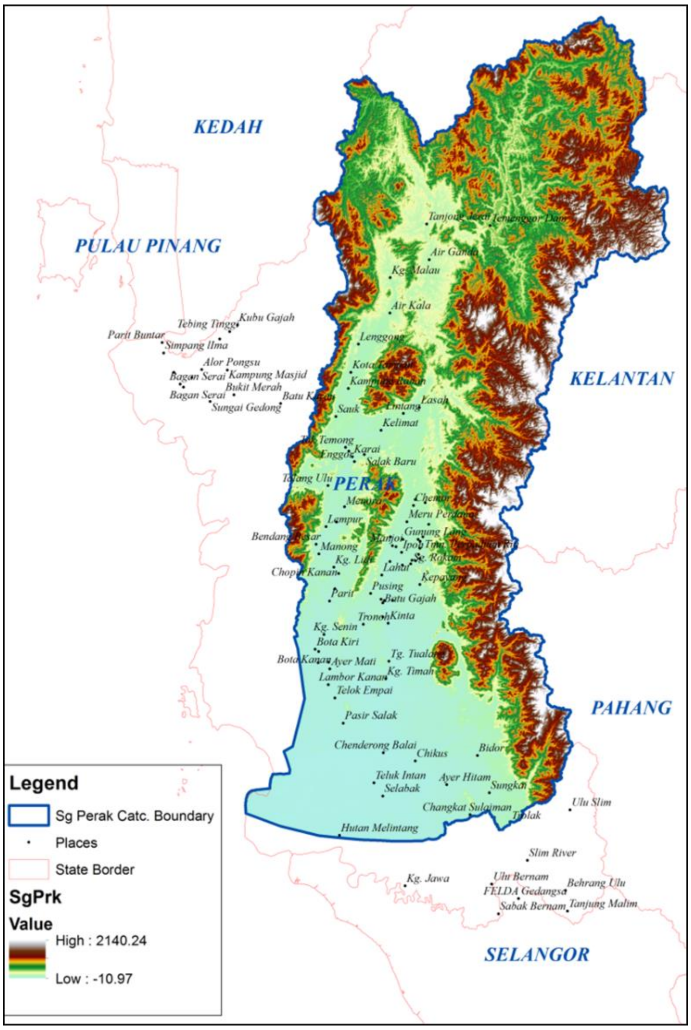


Figure 2: Location of Perak River Basin

Along the upper reaches of the Perak River, a cascade of four dams have been constructed, collectively known as the Perak River hydropower scheme, spanning approximately 115 km [8]. **Figure 3** shows the locations of dams and run-off river hydroelectric stations in the Perak River hydropower scheme. It starts with the Temengor Dam at the uppermost stretch, receiving flows from upstream of Perak River, followed by Bersia, Kenering and Chenderoh Dams, discharging into the river mouth in the southern. These dams were constructed between 1930 and 1983 with different designs and sizes. Multi-functional dams have been used for flood mitigation, water supply and hydroelectric power generation, operated by the Perak River Power Stations (SSJSP). The power plants are built either as peaking or baseload with a combined generating capacity of 1,248 Megawatts (M.W.), among the major assets to TNB Power Generation Sdn. Bhd. (GenCo)[9].

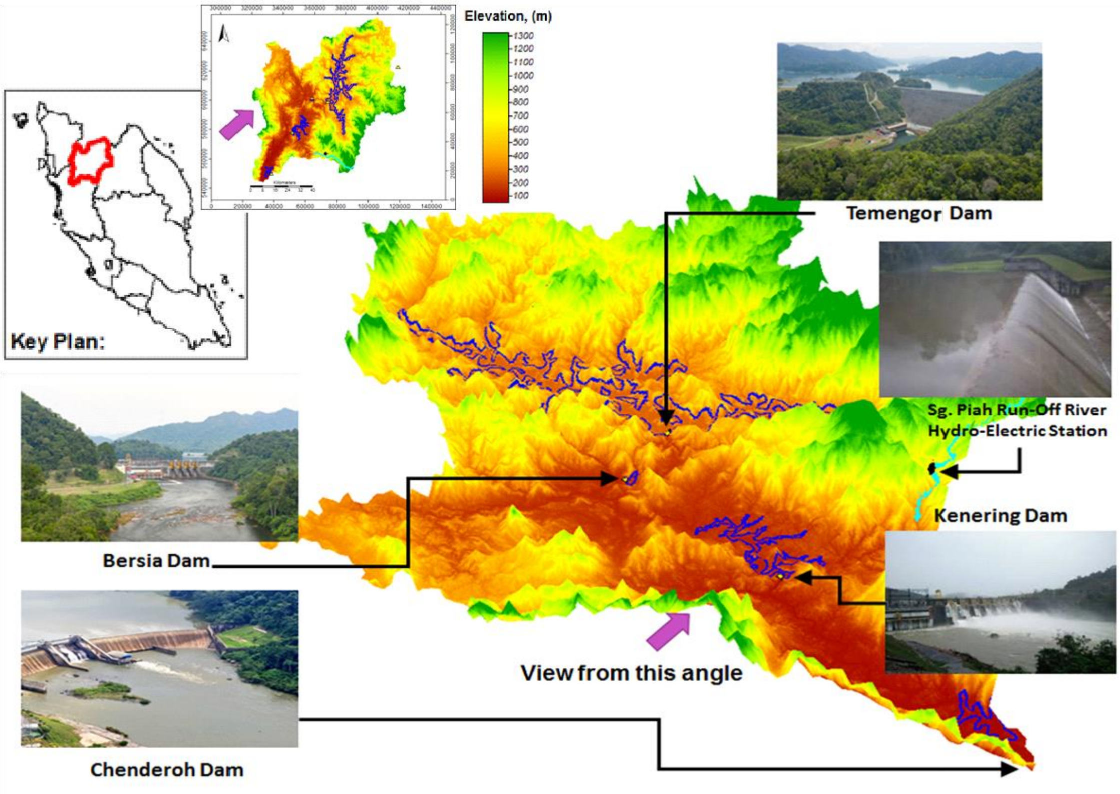


Figure 3: Locations of Dams and Run-off River Hydro-Electric Station in Perak River Hydropower Scheme

Temengor dam is a rockfill dam with 127 m height, with a free-flow U-shape drop inlet with concrete chute and flip bucket spillway. Bersia Dam is a 33 m height concrete gravity dam located approximately 20 km downstream of Temengor Dam and equipped with a controlled radial gates spillway. Kenering dam is a 48 m-high concrete gravity/earth & rockfill dam with radial gates spillway. In contrast, Chenderoh Dam is the oldest of the four dams in the Perak River hydropower scheme, located just upstream of Kuala Kangsar town. It is a 32 m concrete hollow buttress dam with a gated spillway.

3.2 Historical and projected future rainfall characteristics

The Malaysian Meteorological Department (MMD) reported that the annual temperature for Peninsular Malaysia shows a positive trend from 1969 to 2015, with temperatures ranging from

21 °C to 32 °C. As a tropical country situated just north of the equator, the characteristics of the Malaysia climate are uniform temperature and high humidity throughout the year, with an annual average rainfall of 2,420 mm for Peninsular Malaysia and 3,230 mm for East Malaysia (Sabah and Sarawak) [10]. The spatial distribution of the annual rainfall amount in 2019 for Malaysia is as shown in **Figure 4**.

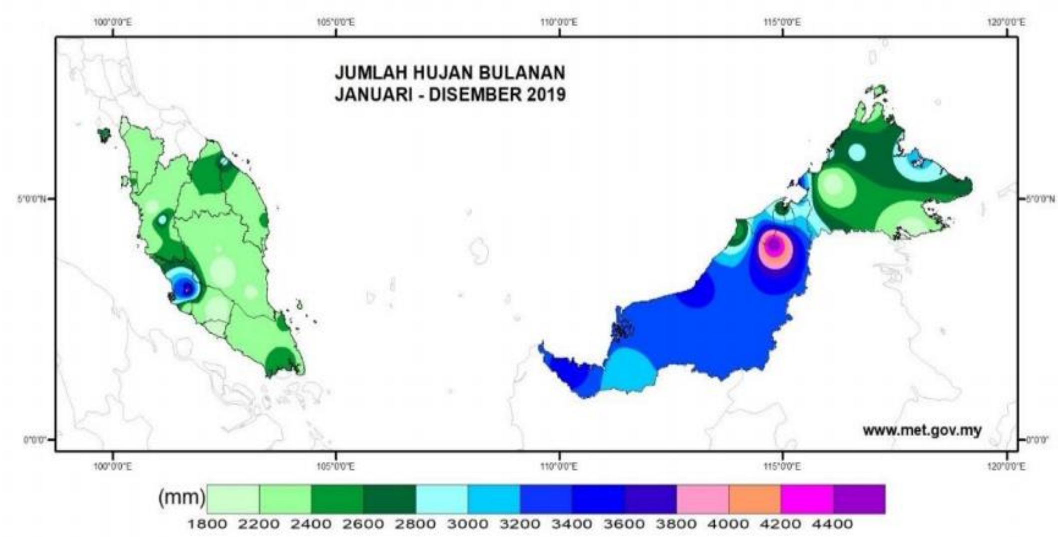


Figure 4: Spatial Distribution of Annual Rainfall in 2019

The Regional Hydro-Climate Model for Peninsular Malaysia (RegHCM-PM) was developed by the National Hydraulic Research Institute of Malaysia (NAHRIM) to represent future climate predictions in Malaysia. The RegHCM-PM model downscales the climate simulations of the Canadian Climate Center general circulation model CGCM1 at a global scale with a very coarse spatial resolution (~410 km grid resolution over the region encompassing Peninsular Malaysia) to the Peninsular Malaysia region at 9 km spatial resolution. The RegHCM-PM has been upgraded to RegHCM-PM2 as a new model. This new model can quantify the impact of the complex topographical and land surface features on its climate condition using a smaller grid of 6 km RegHCM-PM2 of Peninsular Malaysia.

A study by NAHRIM on the daily projected rainfall computed from the ECHM5 climate model showed that the ECHM5 climate model yielded more promising results than the other climate models (CCSM3 and MRI) in the west coast of Peninsular Malaysia [11]. The adopted projected future rainfall originated from the "A1B1" scenario, representing the most plausible scenario, which describes a future world with rapid economic growth, a global population that peaks in mid-century and declines after increasing cultural and social interactions. This technological emphasis scenario is on balance across all energy sources, which not relying too heavily on any particular energy source. The average annual rainfall amount between historical and projected rainfall from 2001 to 2060 is illustrated in **Figure 5**. It is observed that the historical and projected average annual rainfall amount is about 1909 mm and 2345 mm, respectively, indicating the study area will be receiving more rainfall in the near and mid future than the historical observed rainfall.

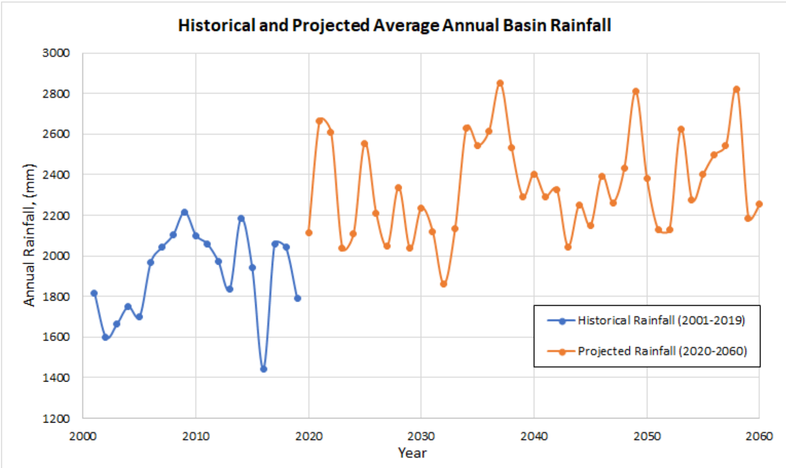


Figure 5: Historical and Projected Average Annual Rainfall in Perak River Hydropower Scheme

4. Best Practices to minimise the impact of reservoir operation

To increase the safety and functionality of existing hydroelectric dams in the Perak River basin, TNB GenCO as a dam owner has strengthened the operation and management capacity and reservoir operation for dam safety of existing hydroelectric dams in the Perak River basin. The beneficiaries include populations in the downstream areas that would be at risk of dam failure.

4.1 Temengor Inflow Forecasting System

One of the operational initiatives by SSJSP is to have additional time to plan a response to flood events. This task should result in operations being undertaken with a better understanding of dam safety risks. Temengor Inflow Forecast System (TIFS) would provide a lead-time so that dam owners could provide early information and or warnings for public safety to downstream communities in the event of a significant flood release from the dam storage. This project involves developing a short-term inflow forecasting system to forecast inflows and water levels in the Temengor reservoir. It should result in operations being undertaken with a better understanding of dam safety and downstream flooding risks. It allows better planning of reservoir drawdowns to mitigate spill risk by allowing adequate storage space. The additional lead-time enables the dam operator to provide advance information or warnings to relevant authorities and downstream communities in a large flood release from their storage.

The inflow forecasting system should be designed by reflecting on and addressing the needs of dam operators and managers – providing high forecasting accuracy, timely issuance of forecasts, high reliability of forecasting and warning systems and clear communication of the system outputs to decision-makers. High-level system requirements include modelling inflows and lake levels and simulated rivers, lakes, and reservoirs responses to short-term weather changes. Adequate monitoring equipment such as rainfall stations, water level stations and other hydrometeorological equipment shall be made available in the catchment to provide enough information as input data to the reservoir inflow modelling system. Furthermore, a rainfall forecast would be required to give sufficient lead-time between 5-7 days, obtained from the meteorological service. Interactive and real-time forecast display is mainly needed for flood forecasts into Temengor reservoir and will be used to optimise the accurate forecast of the future TIFS during flood operation.

TIFS developed for the Perak River Hydropower scheme can predict the incoming inflow and lake level in the Temengor reservoir. Prior to the system design, essential information such as forecast time, operating issues and requirements, system interface, warning elements, communication and information and technology system were discussed and identified. TIFS involves the integration of all required elements; from real-time hydrological data such as water level and rain gauges, followed by integration with live-feed information on lake level, turbine and spillway releases available from the SCADA system, which form the main input to the hydrological model which runs on schedule.

4.1.1 Monitoring equipment and data storage

Hydrological monitoring equipment on rainfall and water level were installed and upgraded in the Temengor catchment. Due to limited network availability in the catchment, the data was transmitted by satellite technology, INMARSAT. Data was being transmitted to servers located at SSJSP. There are two servers in operations used for receiving telemetry and forecast data. The forecasting server will be used to take data from the telemetry server and store it on the hydrometric database to be available to the forecasting model [12]. Operators will consider the outputs from the inflow forecasting system as an input for decisions in operation responded to floods. Forecasting system outputs and automated warnings should be secured and only sent to or accessed by selected staff. The input data of rainfall forecast will come from the MMD and historically generated ensembles. TIFS measures real-time rainfall as well as water level, while the web-based display system will include real-time dam release and lake level measurements using TNB SCADA data.

4.1.2 Reservoir inflow forecasting model

The reservoir inflow forecasting model is developed on the Aquarius Forecast™ model platform. This Aquarius Forecast™ software is specifically designed for real-time modelling applications and has been proven to be successful and reliable in flood operations. The model is linked to the Ajenti Data Management system and Aquarius™ hydrometric database. Ajenti™ DataBridge does the data synchronisation, scheduling, and management. The forecasting model includes catchment run-off process modelling using the GR4H model, channel routing model, storage routing algorithm and reservoir operating rules. TNB-FS uses a conceptual rainfall-runoff model to simulate inflow and level pool routing for the storage model. Finally, the automated alerts will be displayed, with information obtained from monitoring stations, forecast models and SCADA systems.

Once the model is run in forecast mode, the outputs such as forecast reservoir water level, total inflow at the reservoir outlet, total outflow (including release and spill) from the dam, the average catchment rainfall, inflows at water level stations, and the number of missing data at each time step generated. The hourly execution of models is managed using Ajenti Data Bridge, which is finally archived in Ajenti Data Management System for display on the dashboard. The various inputs/outputs and modelling components of TIFS are shown in **Figure 6**.

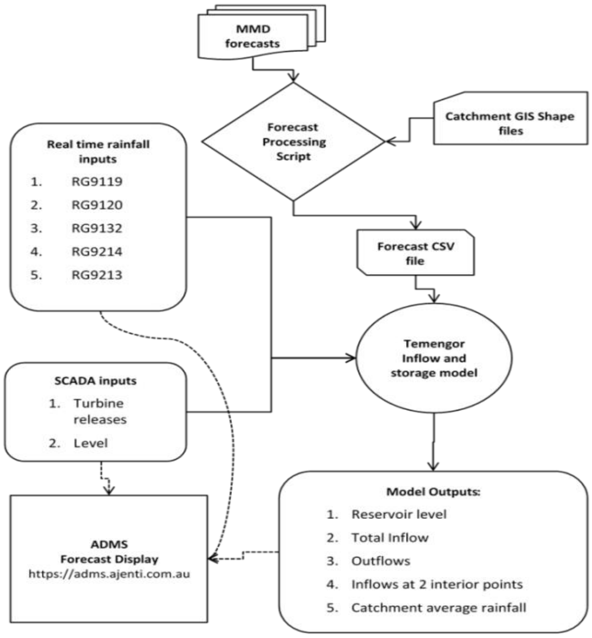
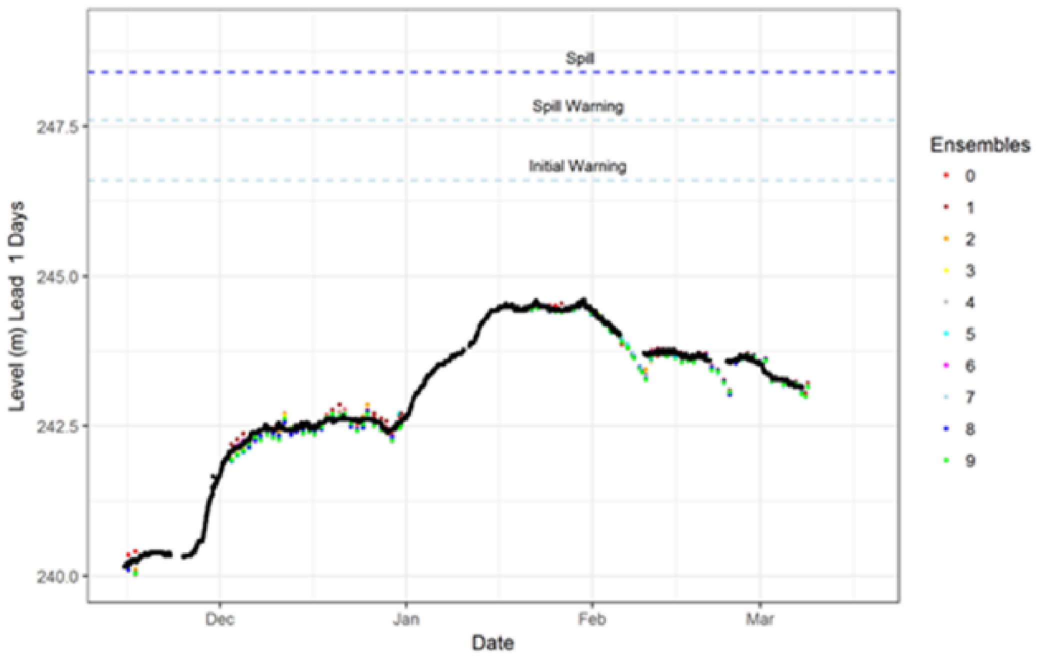


Figure 6: Inputs and Output Schematic of Forecast Model



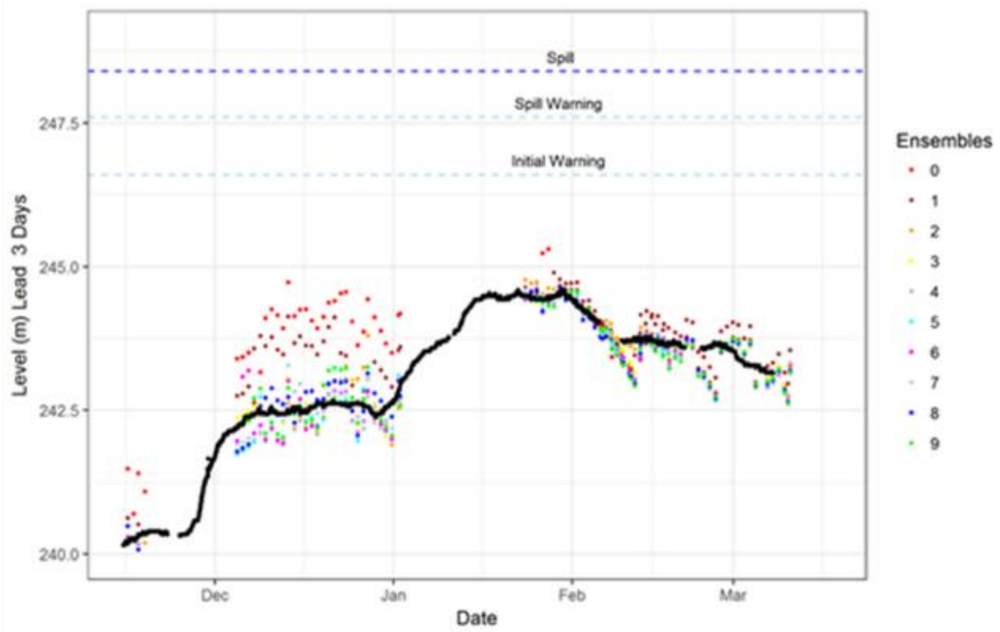


Figure 7: Example of Forecast Result for Lead Time of 1 day and 3 days [13]

The black line in the figures refers to the observed lake level, while the coloured dots are the forecast ensembles generated by the model (**Figure 7**). A perfect forecast would have all ensemble points coinciding with the observed lake levels. In general, the analysis shows that the forecast ensembles cover the observed lake levels well.

4.1.3 Forecast dissemination

TIFS can be viewed using a dedicated web address and accessible by selected SSJSP personnel using a unique I.D. and password. The relevant personnel are allowed different levels of access for maintenance and security purposes. The information displayed on the dashboard contains a live feed on the forecast lake level and releases from Temengor, which should provide sufficient information to the operators during monsoon season to support any decision on Emergency Response Plan (ERP). The typical overall display from the system website is shown in **Figure 8**.

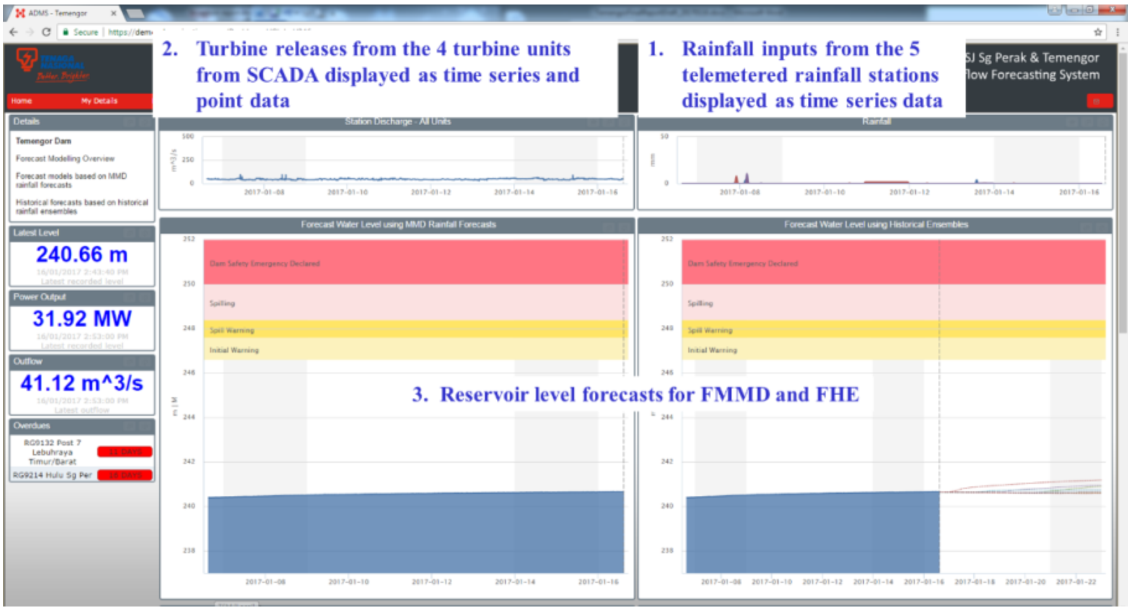


Figure 8: Overall Display of Temengor Inflow Forecast System

4.2 Review of Probable Maximum Precipitation and Probable Maximum Flood under Climate Change Impact

The current practice in the design of dams is to use the inflow design. It is deemed appropriate for the hazard of the dam, reservoir, spillway and outlet shall be capable of accommodating the safe flood flow without risking the loss of lives or endangering downstream areas.

Earlier dams have been designed and operated under the assumption of stationarity of a design storm value, known as Probable Maximum Precipitation (PMP), to derive the Probable Maximum Flood (PMF) for spillways of large dams where no risk of failure can be accepted. These estimates have also been used in defining the extent of flood plains at risk in extreme flood conditions [13]. There are indications that global climate change can potentially influence the regional climate and, more specifically, the rainfall and temperature. Thus, a study to revise the PMP- PMF values by using notable storms and considering the potential effects of climate change on PMP and PMF estimates has been done for TNB Hydroelectric Scheme [1].

Due to climate change impacts, some of the revised values of PMF have exceeded the original design values. Thus, structural and non-structural measures are used to reduce risks of life, property, and the environment from dam failure. It is vital to consider the international best practices and case studies on rehabilitation exercises to acquire valuable knowledge on cost-benefit analysis in considering various available options to meet the economic justification of mitigation measures options. For example, a Risk-informed approach and revised PMP using dynamic methods as the USA Dam industry practises can be implemented to save cost and improve public safety.

4.3 Dam Break and Socio-Economic Study

It is part of the requirement of MyDAMS to conduct the dam break study and socio-economic impact analysis. This study has been done for all TNB hydropower dams to produce dam-break flood hazard maps and quantify the socio-economic impact due to dam failure (**Figure 9**).

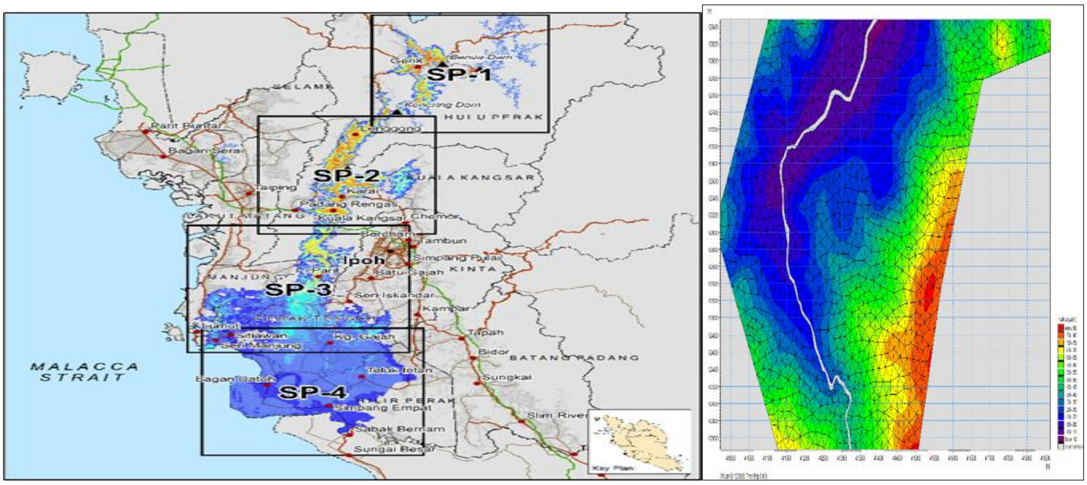


Figure 9: Example of a flood hazard map for Sg. Perak

Pertinent information was extracted from the modelling result, such as dam breach peak outflow, inundated area, flood extent distance and affected villages. This information is also used as input to set triggering levels for ERP included in the Dam Safety ERP (DSERP) Manual and shared with relevant agencies, which can be referred during an emergency, especially for the community evacuation at the affected area. The output will be augmented to generate a decision-making tool to predict the best possible evacuation route and forecast casualties. The prediction tool is via life safety modelling, thus establishing an appropriate early warning system to alert communities about incoming disasters through sirens or strobe light [4].

4.4 Dam Safety Emergency Response Plan

The Dam Safety Emergency Response Plan (DSERP) Manual provides a detailed contingency program that includes actions that must be taken to control and/or minimise an emergency impact. The program has its research activity focusing on developing the Emergency Response Plan (ERP) for all TNB hydropower dams. The effectiveness of the completed manual was tested during a tabletop exercise involving dam personnel and various agencies. Ensuring all parties are familiar with their roles and responsibilities is very important, including an action plan during emergency conditions. Therefore, a series of seminars and hands-on exercises are conducted to achieve the program objectives, including drill exercises and standard operation procedure (SOP) guideline workshops with local agencies and tabletop exercises. **Figure 10** shows an example of the Tabletop Exercise conducted by TNB.

Figure 10. Example of Tabletop and Evacuation Exercise conducted by TNB [14]

4.5 Integrated Community Based Dam Disaster Management

The TNB hydropower schemes have a program that involves all TNB hydropower schemes, authorities and communities on a bigger scale. The dam owner and authorities play an integral role in increasing nearby communities' awareness of the hydroelectric infrastructure. Considering the risk faced by the downstream community, TNB realised that community-based efforts should be highlighted for anticipating any untoward incidents. TNB has formulated an integrated community-based disaster management program (ICBDM) with an aspiration of empowering the community-based effort on how to take ownership of life-saving should any disasters occur. The program consists of several technical and non-technical elements. All the technical elements will be utilised to be the feeder for the second stage of the non-technical based initiative. The two feeders are the community-based training and awareness program (CBTAB), and the multi-stakeholder engagement program (MSEP). The community-based training and awareness program encompasses the initiatives to educate the school children, teenagers and adults on the importance of a dam safety program. This initiative will create a platform for the community to be prepared for the dam-related disaster. Finally, all the earlier initiatives will be tested on their success rate by having all the generated outputs as a feeder to the multi-stakeholder engagement program. This program involved all TNB hydropower schemes, authorities and communities on a bigger scale.

4.6 Risk-Informed Decision Making for Sustainable Dams

Risk assessment and risk-informed decision making (RIDM) can be used to drive the decision process for dams prioritisation to take action on risk reduction. These practices are in use by many countries to evaluate existing infrastructure. The risk-based analysis is a potentially relevant approach for assessing economic feasibility, social safety, and dam rehabilitation priority. In this regard, the novelty is to develop a fully integrated dam risk model that can consider possible risk factors, various potential failure modes, and potential damage costs in a statistical framework within the A.I.s. Much focus is placed on a fully integrated probabilistic dam risk analysis approach.

4.7 Automatic Dam Safety Management System in IR 4.0

Several dam safety management systems worldwide include MISTRAL from Italy, ESMHS from Egypt, and PAEWEB from Brazil. However, the existing system problem is: 1) expert systems are designed only for specific dams, 2) developed for dam safety experts, and 3) all necessary failure states are not covered. For these reasons, a Dam Safety Smart Management System (DS-SMS) as part of digitalisation in the IR 4.0 was initiated and developed by TNB. This project proposes an expert system to evaluate dam safety for 12 large hydropower dams in Malaysia. The proposed expert system is implemented within the Dam Safety Remote Monitoring System currently operated by Tenaga Nasional Berhad (TNB). The system automatically evaluates all failure modes for 3 major dam types and operates 24 hours a day. The proposed DS-SMS is expected to be fully operational by 2022 to improve dam safety management and enhance public confidence in dam safety.

5. Strategic Dam Operator Competencies Program

All dam owners must have a strategic building capacity for sustainable development through formal and informal curricula. The following elements are recommended to support the sustainable dam safety program and capacity building in dam engineering and safety:

a) To establish the capacity building (public-private-academia) for dam engineering, involving parties that have interests in dam engineering and dam safety to be in line with ICOLD and other international recognised dam societies:

b) To develop the guidelines and bulletins for state-of-the-art dam engineering and safety to ensure that dams are built and operated safely, efficiently, economically, and environmentally sustainable and socially equitable.

c) To promote conferences, short courses, workshops and encourage stakeholders to contribute national issues and best practices in planning, development, maintenance and operation of dams and reservoirs.

d) To promote a program of Emergency Action Plan (EAP) implementation, compliance and exercise for all high and significant hazard potential dams

e) To promote public awareness and outreach of the benefits and risks related to the dam.

6. Conclusions

There is an urgent need to implement the procedures in dam-reservoir operation as stipulated in MyDAMS that provide multiple benefits for safe communities and a resilient environment. The Government of Malaysia has rightly put a national dam safety management guideline to ensure holistic and sustainable dam safety management, primarily operational decision making. The TNB and GenCO are supported by the Malaysia Government on implementing MyDAMS Guidelines in their hydropower dam operations. It is high time for Malaysia to connect within transdisciplinary in taking action due to lack of dam expertise. Malaysia needs a prominent action on closing the gap in the dam engineering field. Dissemination program and knowledge sharing in the capacity building locally and internationally shall make a comprehensive routine program through cross-cutting activities platform. This effort is crucial in realigning the sustainable development goal 6 (SDG 6) backtrack to the UNESCO Global Agenda by 2030.

Acknowledgement

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7. References

[1] McClelland, D.M., and Bowles D.S. 2002. Estimating life loss for dam safety risk assessment: A review and new approach, IWR report 02-R-3, Institute for Dam Safety Risk Management Utah State University, Logan.

[2] DID. 2017. Malaysia Dam Safety Management Guidelines (MyDAMS). Department of Irrigation and Drainage, Kuala Lumpur, Malaysia.

[3] Nor Hisham Mohd Ghazali. 2019. Dam Management in Malaysia: Institutionalizing Dam Safety. Keynote Speech. International Conference on Dam Safety Management and Engineering, Malaysia.

[4] Sidek, L. M., Yalit, M. R., Shah, M. R. M., Omar, R. C., Ahmed, A. N., Basri, H., & Harun, A. 2019. Dam Break Modelling and Flood Hazard Mapping for Cascading Dams in Sungai Perak Hydroelectric Scheme. In the International Conference on Dam Safety Management and Engineering (pp. 368-382). Springer, Singapore.

[5] DWS. 2012. Dams distribution in Malaysia. Department of Water Supply, Kuala Lumpur, Malaysia.

[6] DHI. Dams and reservoirs [Online]. Available https://www.dhigroup.com/areas-of-expertise/surface-and-groundwater/dams-and-reservoirs [Accessed August 10, 2021].

[7] USACE. 2017. Management of Water Control Systems (EM-1110-2-3600). U.S. Army Corps of Engineers, Washington, DC.

[8] DID. 2011. National Water Resources Study (NWRS) 2000-2050. Department of Irrigation and Drainage, Kuala Lumpur, Malaysia.

[9] Syazuan, M and Kamarulzaman. 2016. Sungai Perak energy management system:

Improvement of efficiency and reliability of Sungai Perak Hydropower plant through modernisation of Scada system. ARPN Journal of Engineering and Applied Sciences 11(6): 4036-4039.

[10] Ahmad, F, Ushiyama, T, Sayama, T. 2017. Determination of Z-R relationship and inundation analysis for Kuantan River Basin. Malaysian Meteorological Department, Kuala Lumpur, Malaysia.

[11] Azuhan Mohamed. 2017. Hydrological Climate – Impact Projections in Malaysia. National Hydraulic Research Institute of Malaysia (NAHRIM)

[12] H Basri, LM Sidek, L H C Chua, A Z Abdul Razad and M S Kamarulzaman. 2019. Hydrometeorological monitoring for hydropower reservoirs in remote areas. IOP Conf. Series: Earth and Environmental Science 257 (2019).

[13] Razali, J., Sidek, L. M., Marufuzzaman, M., Rakhecha, P. R., Radzi, M. M., Hossain, M. S., & Zawawi, M. H. 2019. PMP Driven Probable Maximum Flood for 4 Dams in Sungai Perak Hydroelectric Scheme. In the International Conference on Dam Safety Management and Engineering (pp. 76-89). Springer, Singapore.

[14] Lariyah, M. S., Hidayah, B., Thiruchelvam, S., Rahsidi, S. M., Zailti, A. R. A., & Zuraidah, A. 2014. Implementation of dam safety management program in Malaysia: From theory to practice. In Structural, Environmental, Coastal and Offshore Engineering (pp. 583-588). Trans Tech Publications Ltd.

Showcasing selected reservoirs and their operations in the Philippines

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Abstract
The Philippines has over a hundred dams and about fifty (50) of them are of moderate to large sizes. There are about ten (10) major ones which are classified as multipurpose dams for domestic water supply, irrigation, hydropower generation and flood control. This paper showcases three major reservoirs in the Philippines namely Angat Reservoir on its competing water uses, the San Roque Dam flood operations during Typhoon Parma in 2009, and the Pulangi Hydropower IV Dam with sediment flushing facilities as an illustration of a sustainable reservoir development.

Key Words: *multipurpose reservoir, competing water use, reservoir operations, sustainable reservoir development.*

1. Introduction

Dams and reservoirs play a key role in sustaining human civilization through collection and storage of water for drinking and irrigation, producing energy and mitigating flooding. Today dams remain an essential component of development in response to the world's increasing water demands, energy requirements, through buffering impacts of climate change and variability, and if designed properly as a renewable resource for hydropower generation, to minimize carbon emissions.

On the other hand, dam safety is equally important considering that a catastrophic event such as dam failure can cause significant loss of life and damage to the downstream community. Thus, it is important emphasize that there is a need for effective dam safety programs to prevent catastrophic dam incidents such as dam failures or even incidents resulting from unsafe dam operations such as massive spillway releases to avoid dam overtopping.

Equally important is the safe operations of dams and reservoirs as a component of dam safety which is associated to negative impacts or hazards caused by unsafe operations of dams during emergency or flood operations conditions. For instance, the ability to operate dams under emergency conditions is to balance its flood control function which is a short-term, almost real-time objective (i.e., when to contain or when to release the floodwaters) in contrast to water conservation for domestic water supply or irrigation which is a medium-term or seasonal objective to save water for the dry season.

This paper showcases three major reservoirs in the Philippines to illustrate their unique features and implications to reservoir operations under normal conditions and emergency operations. In particular, these are as follows: (1) Angat Reservoir as a multipurpose reservoir and its competing water uses by virtue of its physical or design configuration and water rights allocation; (2) San Roque Dam flood operations during Typhoon Parma in 2009; and, (3) Pulangi Hydropower IV Dam with sediment flushing facilities for long-term, sustainable reservoir development. The next section below briefly shows the dams and reservoirs in the Philippines.

2. Dams and Reservoirs in the Philippines

There are over a hundred dams in the Philippines and about fifty (50) of them are of moderate to large sizes which are displayed in **Figure 1**. Referring to **Figure 1**, most of the dams are owned and operated by the National Power Corporations (NPC) and the National Irrigation Administration (NIA). The major dams in the Philippines with storage capacities of more than 500 MCM (million cubic meters) are only found in Luzon Island (upper portion of Fig. 1).

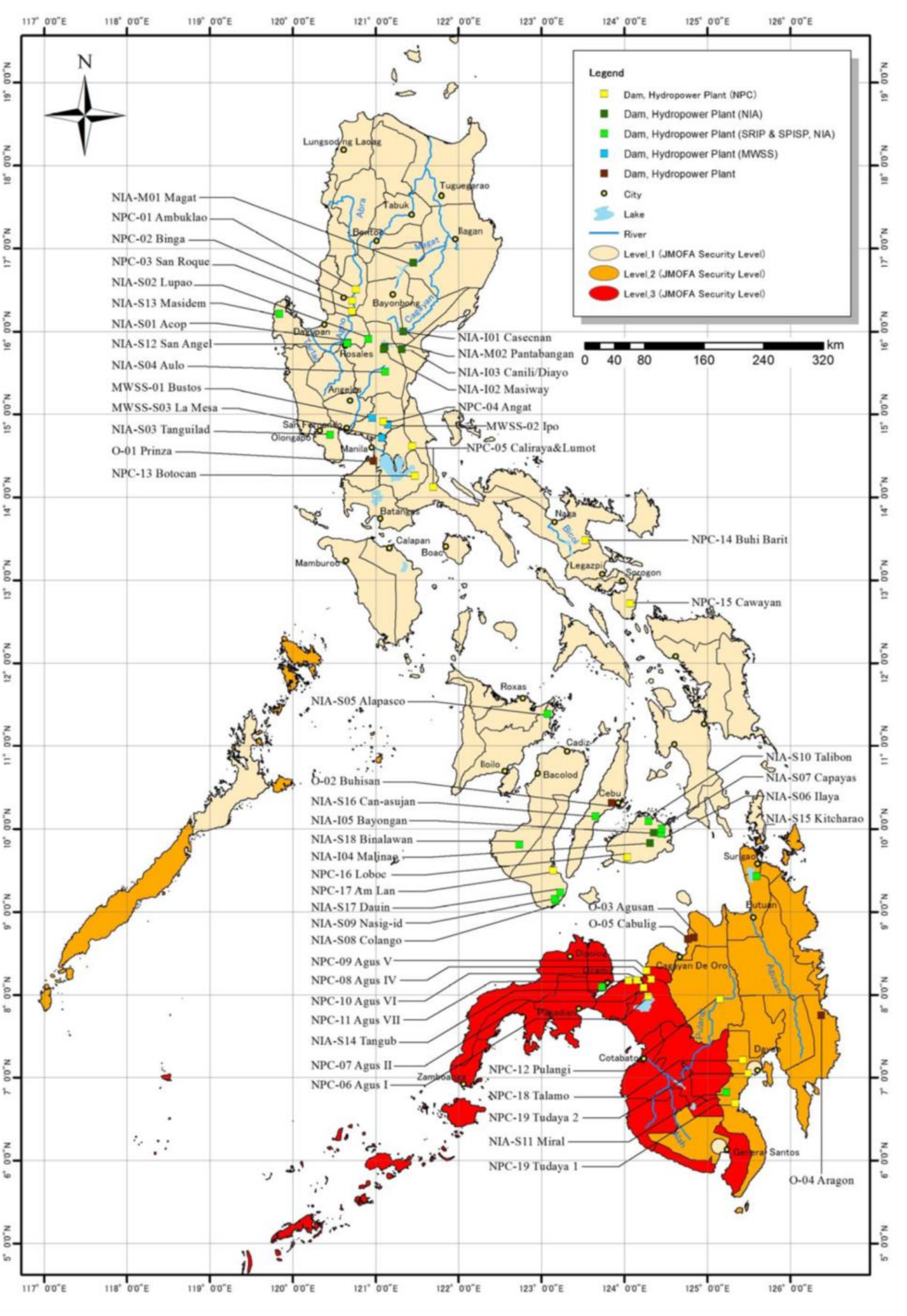

Figure 1. Location of various dams in the Philippines. Taken from [1].

For the three reservoirs illustrated in this paper, **Figure 2** shows pictures of the Angat Dam, San Roque Dam and Pulangi HP IV Dam. These dam/reservoir systems are showcased in the next sections and their locations are indicated in **Figure 1** as NPC-04 Angat, NPC-03 San Roque and NPC-12 Pulangi, respectively.

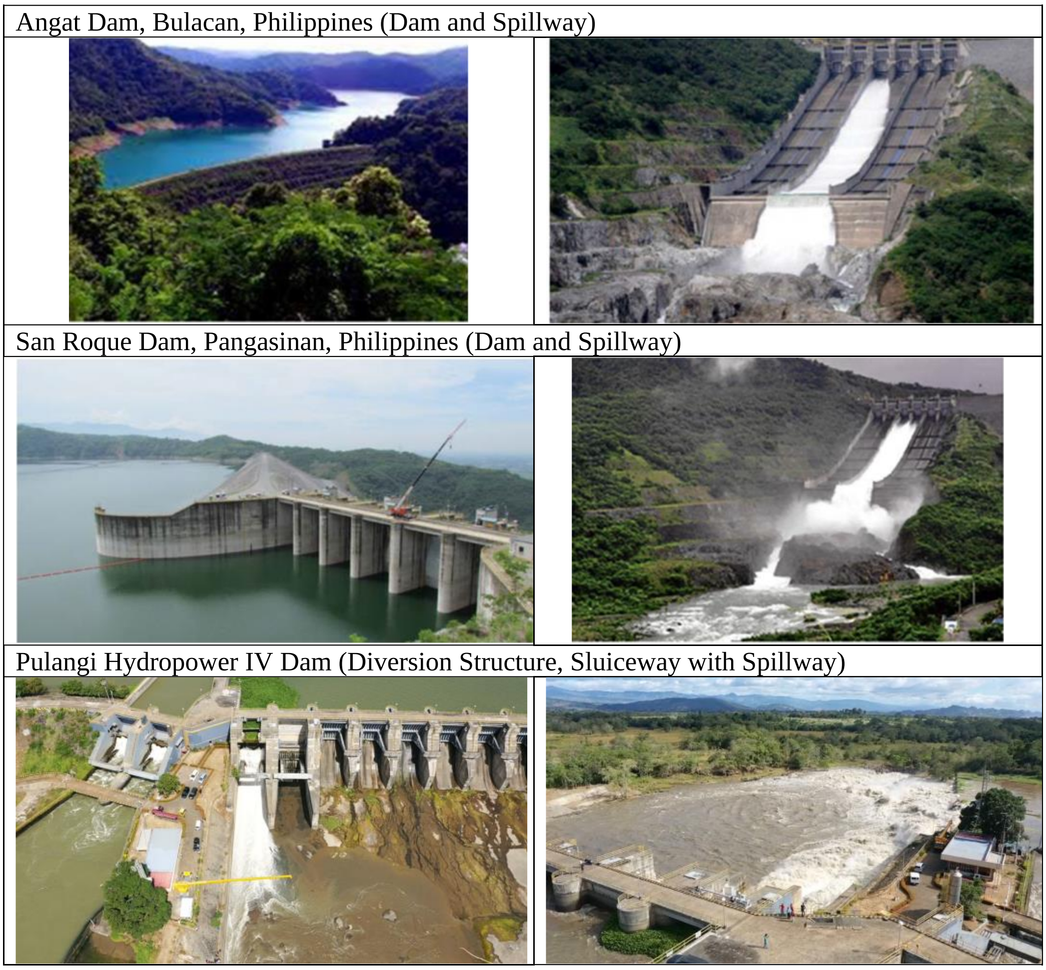

Figure 2. Pictures of Angat Dam, San Roque Dam and Pulangi HP IV Dam in the Philippines.

3. Competing Uses of Angat Reservoir: By Virtue of Its Physical Configuration and Water Rights Allocation

The Angat Reservoir is a multipurpose reservoir for Metro Manila's domestic water supply under the Metropolitan Water Supply and Sewerage (MWSS), Bulacan's Angat-Maasim irrigation demand for about 24,000 ha of rice land under the National Irrigation Administration (NIA) of the Angat-Maasim River Irrigation System (NIA-AMRIS) including hydropower generation and certain flood control function. Showcased here the issue of competing water uses of Angat Reservoir.

With regard to the physical (or design) configuration of the Angat Reservoir system as shown in **Figure 3**, the main hydropower plant (HP) generation with a capacity of 200 megawatts (MW) is through releases to NIA for irrigation. The auxiliary HP generation with a capacity of 46 MW is through releases to MWSS for domestic water supply. However, twice as much power can be generated at the main HP compared with the auxiliary HP for the same flow discharge, since at, say, a reservoir elevation of 205 meters (m), the head for power generation for the main HP is 187.5 m (that is, 205 – 17.5 m tailwater elevation), while that for the auxiliary HP is 104 m (that is, 205 – 101 m tailwater elevation at Ipo Dam).

With regard to NIA and MWSS water rights, originally, after Angat Dam was built in 1968, NIA had 36 cubic meters per second (CMS), while MWSS had 22 CMS, a total of 58 CMS, which is the amount equal to the water rights granted to the National Power Corporation to operate Angat Reservoir for its hydropower generation objectives provided that the MWSS (domestic water supply) and NIA (irrigation) water rights or allocations are satisfied on a long-term, average daily basis. The long-term average is emphasized here, because NIA has seasonal water requirements in contrast to MWSS, which is fixed on a daily basis. However, since 2000, with additional water from the Umiray River through transbasin transfer (a separate watershed from Angat), the water rights situation has evolved into the following: (i) MWSS water rights became 46 CMS, which is the sum of the original 22 CMS plus 15 CMS referred to as conditional water rights from NIA plus 9 CMS from the Umiray River; (ii) NIA-AMRIS water rights were reduced to 21 CMS, which is the original 36 CMS minus 15 CMS; and (iii) Bulacan bulk water rights are 3 CMS, which comes from the Umiray River transbasin transfer. The above water rights allocation is based on the long-term average inflow of the Angat and Umiray watersheds of 70 CMS.

In view of the above change in water allocation and priority, 200 MW capacity of the main HP of Angat is seldom utilized, since NIA's allocation has been reduced to 21 CMS from its original 36 CMS. Also, in accordance with the Philippine Water Code, during water shortage conditions, the order of priority of water delivery from a multipurpose reservoir like Angat is to first satisfy domestic supply, followed by irrigation demand and hydropower that is incidentally generated.

This illustrates the case where with changing water demands and priorities for domestic water supplies (with 46 MW powerplant) as opposed to irrigation (with associated 200 MW power plant), the original hydropower capacities of Angat Reservoir can no longer be fully utilized. Yet, as electric (hydropower) generation is definitely needed especially during peak power demand during the day, reservoir operations for the day on hourly basis can be challenging for the operators.

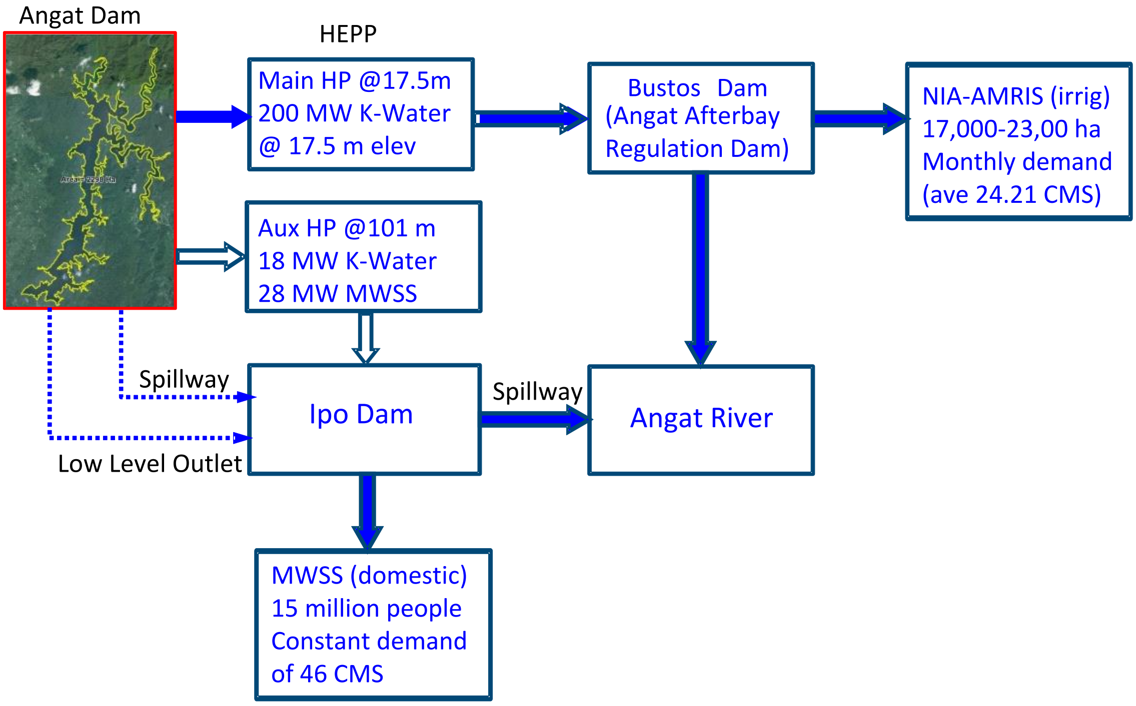

Figure 3. Physical components and water demands of the multipurpose Angat Reservoir system with Bustos and Ipo Dams for domestic water supply, irrigation water supply, hydropower generation and flood control. Taken from [2].

4. San Roque Dam Flood Operations During Typhoon Parma in 2009

San Roque Multipurpose Dam was completed in 2002 to provide water storage for irrigation and hydropower, flood control and its unique function for water quality control by capturing sediments to minimize turbidity in its irrigation water releases. Its hydropower plant has a total installed capacity of 402 MW. Ancillary structures of the dam include the spillway, intake for power tunnel and intake for low level outlet. The maximum water operating level is 290.0 m and its flood allocation storage is between 280 and 290 m. This section illustrates how San Roque Dam was operated during Typhoon Parma as the narrative below was essentially taken from Tabios [3] and likewise Tabios et al. [4].

During Typhoon Parma in October, 2009 which came in and out three times in Northern Luzon wreaked havoc especially in the Lower Agno River Basin of Pangasinan downstream of the San Roque Dam. As shown in **Figure 4**, forecasting the track of Typhoon Parma was quite a challenge since at 2AM October 4 in 2009; Parma was heading out after hitting the San Roque Dam area the day before. But then, at 8AM on October 4, PAGASA (weather service agency of the Philippines) forecasted that it was coming back and only to reverse its forecast at 8 PM on October 4 and 2PM on October 5 that Parma was heading out. In fact, at 10 AM on October 6, PAGASA stated that there *is no major disturbance expected to affect the Agno River Basin within the next 24 hours* implying that Parma was not coming back. But barely four hours later, PAGASA announced at 2 PM on October 6 that Parma was definitely coming back. The next day and especially on October 8-9 as shown in **Figure 5**, San Roque Dam had to make significant spillway releases before the dam was overtopped which caused the devastating flooding in the Lower Agno River Basin especially in the towns of San Manuel, Tayug, Rosales, Alcala and Villasis in Pangasinan.

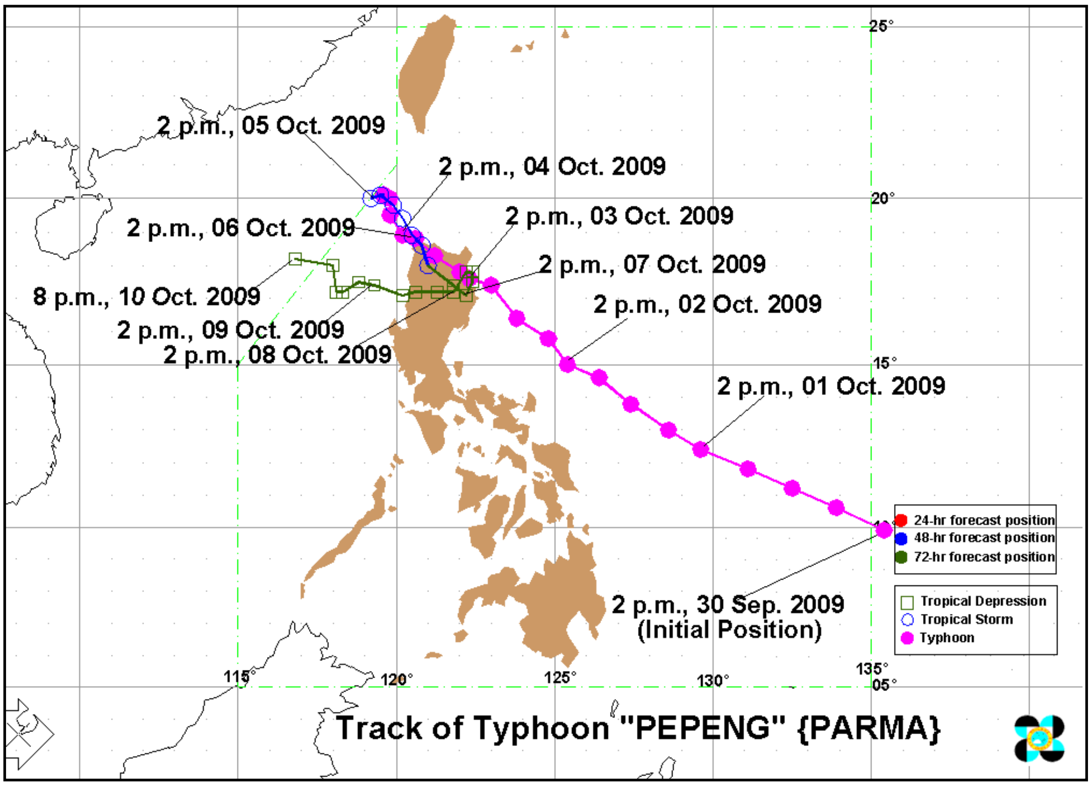

Figure 4. Tract of Typhoon Parma, locally called Pepeng during the period October 1-10, 2018 from PAGASA. Taken from [4].

It is important to emphasize that during the period between October 5 and 7 with the dam reservoir already above 284 m (290 m is maximum operating level) and rising, the dam operators still made the decision not to spill/release from the reservoir. Two factors influencing the decision whether to release now or later are as follows: 1) that spilling reservoir water at that instant would free more flood control storage space for future use (the already predicted return of Parma); the downside of such an action would be that it could exacerbate the flooding downstream of the dam; or, 2) not spilling water would attenuate the flooding downstream of the dam; the downside of such an action would be that there would be very little flood control storage to attenuate any prospective flood inflow.

On hindsight, the dam operators actually waited too long to make significant pre-emptive releases during the period between Oct. 5 and 7, 2009. It would have been perhaps too soon if it were done on October 5 which was one day after the first passage of the typhoon. On October 6, the press release made by PAGASA at 10AM that day stating that *with no major disturbance expected to affect the [Agno River] Basin within the next 24 hours, the present condition does not necessitate the operation of its spillways* would have directly influenced the dam operators not to make significant pre-emptive spillway release. However, with the typhoon track forecast bulletin issued by PAGASA four hours later at 2 PM on October 6 indicating that Typhoon Parma was definitely coming back, this should have signaled the dam operators to make significant pre-emptive spillway releases already. Yet they did not, but waited until 1AM on October 7, and even then, released water at an insignificant rate of 215 m^3/sec – increasing the rate at infinitesimal amounts, so that that by 10 AM of October 8, or almost forty-eight hours later, the release was still only at 800 m^3/sec.

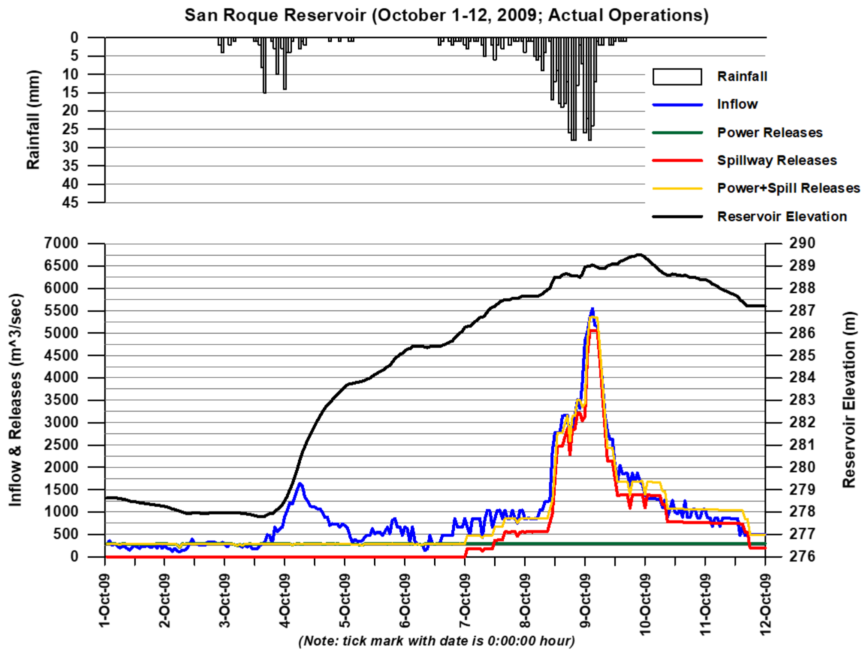

Figure 5. Time series plots of observed rainfall, reservoir levels, inflows and spills of San Roque Dam during Typhoon Parma provided by NAPOCOR. Taken from [3].

What would have happened, if the pre-emptive spillway releases had been made earlier, and in greater amounts? An illustrative optimization-simulation study was conducted to find out. Two reservoir operation cases are illustrated here as follows: (1) Spills or (pre-emptive releases) are made after 8AM October 5 and when the reservoir elevation (specified threshold elevation) is above 280 m; and, (2) Spills or (pre-emptive releases) are made after 8AM October 5 and when the reservoir elevation is above 282 m.

In these optimization-simulation runs, the objective function is to minimize the maximum spillway releases (n.b., turbine releases are at maxima) starting at the specified pre-emptive release time (e.g., 8AM, October 5) provided that the reservoir elevation is above the specified threshold elevations (e.g., 280 m). The major constraint in the optimization model is the physical system constraint (i.e., reservoir hydrologic routing equation, reservoir storage-elevation relationship and spillway rating curve) defined by the simulation model. For the case of 8AM, October 5 pre-emptive release time (simulation ending at midnight of October 12), the optimization model calculates (optimizes) a total of 161 hourly spillway flows and for the case of 8AM, October 6 pre-emptive release time, a total of 137 hourly spillway flows. Note that these are considerable number of decision variables (hourly spillway flows) to calculate (optimize) if done manually thus the need for a mathematical, computerized optimization-simulation model.

Figure 6 shows the results of optimization-simulation model runs for Cases 1 (top figure) and 2 (bottom figure). These figures show the time series plots of rainfall, inflows, power releases, spillway releases, power plus spillway releases and reservoir elevations of San Roque Dam using the optimization-simulation model. It is seen that when the spillway pre-releases were made at those particular times and threshold reservoir elevations, there was a spike of spillway release that almost reached as high as 2,500 m^3/sec to bring down the reservoir elevations to the threshold elevations. The maximum spillway discharges reached about 2,700 m^3/sec or a total reservoir outflow (spillway plus turbine releases) of about 3,000 m^3/sec for the optimization-simulation cases compared to the actual case of 5,101 and 5,361 m^3/sec, respectively. The maximum reservoir elevations reached 286.51 and 287.90 m for Cases 1 and 2, respectively since early pre-emptive spillway releases. Note that in the actual case, the maximum elevation of 289.50 m was reached which was almost at the top elevation of the spillway gate of 289.6 m. Operating the reservoir at elevations of 288 m or higher is already at risky levels that could result in overtopping and possibly damaging the spillway structure even if water levels are still way below the dam crest elevation of 295 m. Of course, overtopping of the dam itself and especially resulting to a dam-break would be very catastrophic and damaging to the communities downstream of San Roque Dam since flood waves generated could be as high as tens of meters and spreading a hundred kilometers or so.

In any case, the results of these simulations show that early and significant pre-emptive spillway releases (rather than wait-till-the-last-minute attitude) would have alleviated flooding in Carmen-Rosales, Asingan, Sta. Maria and Tayug (towns downstream of San Roque Dam) which can only be flooded if the discharge in Agno River is about 3,000 m^3/sec which are less than 3,000 m^3/sec.

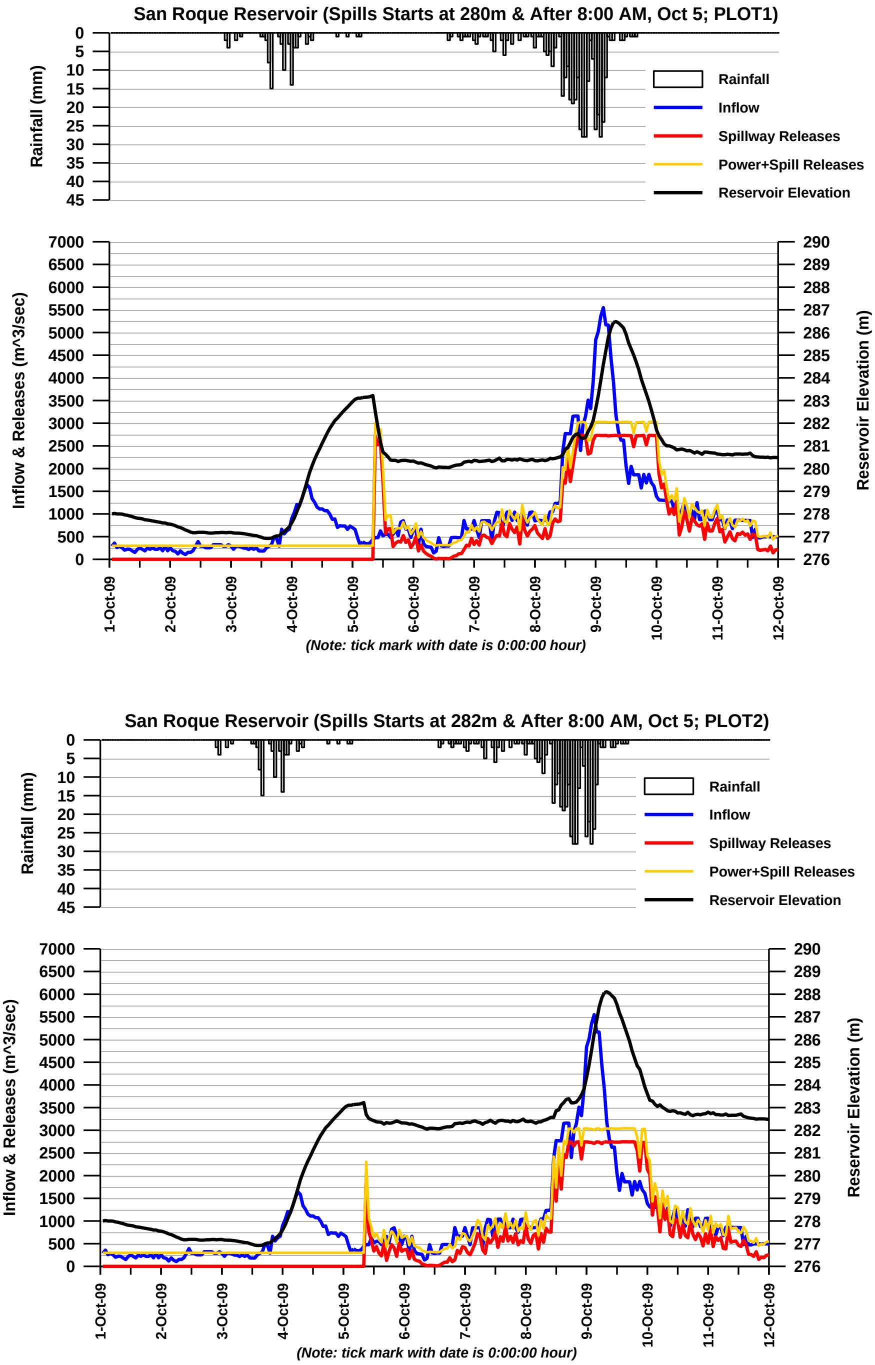

Figure 6. Time series plots of rainfall, inflows, power releases, spillway releases, power plus spillway releases and reservoir elevations of San Roque Dam using the optimization-simulation model. The top (Case 1) and bottom (Case 2) figures are plots when spillway releases are made after 8AM on October 5, 2009 when the reservoir elevations are above 280 m and 282 m, respectively. Taken from [3].

5. On Sustainable Reservoir Development: Pulangi HP IV Reservoir with Sediment Flushing Facility

The multipurpose Angat Reservoir/Dam system for domestic water supply, irrigation water supply, hydropower generation and flood control or the multipurpose San Roque Reservoir for irrigation water supply, hydropower generation, flood control and water quality control were designed with a finite life of about 70 years due to reservoir sedimentation. Thus, it is not quite a renewable resource and once it gets filled-up, it is a major effort to decommission or remove it. Another major issue with reservoirs is that it could adversely impact the river downstream of the dam due to the change (lack thereof) in sediment supply (suspended and bedload) thus altering the natural river landscape (form and alignment) and consequently the downstream river ecology and ecological integrity [5]. In this case, the river downstream will starve from seasonal supply of sediments that is responsible for maintaining stable channels that prevents too much erosion or sedimentation. In any case, there are possible measures or management strategies to minimize such adverse impacts such as the proper location of reservoir site, watershed erosion control, and reservoir sedimentation management strategies that includes sediment flushing or sluicing [6].

The Pulangi Hydropower Plant IV reservoir in Maramag, Bukidnon exemplifies a sustainable reservoir design which is the only large-scale reservoir in the Philippines with a sediment flushing facility to prevent or minimize reservoir sediment accumulation. **Figure 2** given earlier for Pulangi HP IV dam actually shows the sediment flushing operations conducted in last January 2020. The photo on the left-hand side shows the start of flushing operations with the opening of the bottom sluice gate (3rd gated structure from the left) and the photo on the right-hand side shows sediment flushing when both bottom sluice gates have been opened.

From Tabios [3], **Figure 7** shows a time series plot of the sediment flushed and reservoir capacity over a 360-day simulation study. The beginning time (in days) is January which started at around 38.5 MCM, approaching around 37.7 MCM in March-April (dry months) and gaining reservoir capacity at about 40 MCM in July-October (wet months) and settling back to 39.3 MCM at the end of the year. A net sediment volume of 0.8 MCM was removed (flushed out) during the 360-day simulation. The Pulangi Reservoir annual sediment inflow is about 1.0 MCM a year so if more sediment flushing operations are conducted in a year, the net sediment accumulation will be zero.

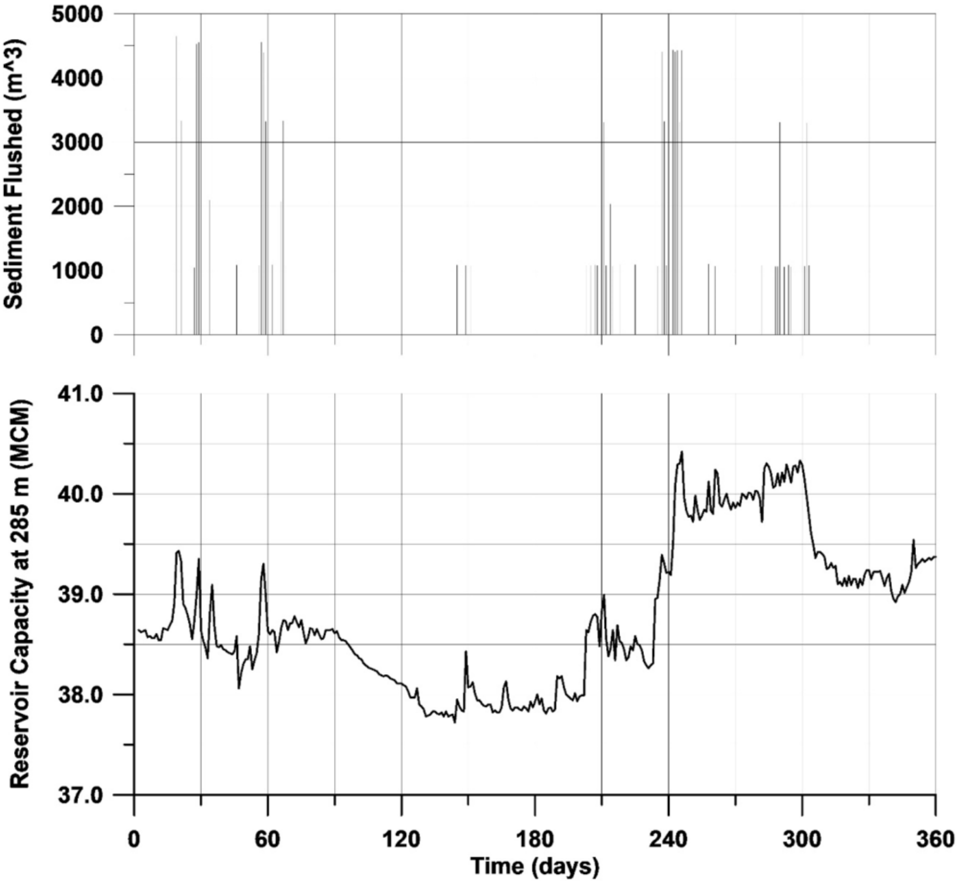

Figure 7. Time series plots of sediments flushed (m3) and reservoir capacity (in MCM, million m3) for a 360-day simulation period with fifty-seven (57) 12-hr flushing operations in Pulangi HP IV Reservoir. Taken from [3].

6. Summary and Conclusions

To recapitulate, this paper has illustrated the following: (1) Angat Reservoir as a multipurpose reservoir and its competing water uses by virtue of its physical or design configuration and water rights allocation; (2) San Roque Dam flood operations during Typhoon Parma in 2009; and, (3) Pulangi Hydropower IV Dam with sediment flushing facilities for long-term, sustainable reservoir storage.

For the case of the competing water uses of Angat Reservoir for domestic water supply and irrigation demand, it is essentially constrained due to the physical configuration of the system and because of changes in increased water allocation and prioritization of domestic water supply over irrigation water supply brought in recent years. This has subsequently compromised hydropower generation which may be unfavorable to recent privatization of the hydropower asset. On the other hand, irrigation water demand has actually been reduced due to urbanization (conversion of rice paddies to residential/commercial lands) as well as the seasonal flooding in the NIA-AMRIS irrigation area thus leading to the transfer of water rights allocation from NIA to MWSS due to unused NIA water rights (demand).

In the case of San Roque Dam, it would require a review and improvement of its reservoir operating rules for normal and emergency operations (under flood control conditions). In particular, the operation rules or protocol for multi-purpose reservoirs, especially San Roque Dam as suggested by Tabios et al (2010), must be three-tiered as follows: (1) a long-term reservoir operation rule which may be based on monthly or seasonal purposes such as hydropower generation and irrigation releases; (2) a medium-term operation rule which is to fine tune the water allocation based on seasonal (monthly or weekly) outlook or forecast of weather or climatic conditions; and, (3) a short-term (almost real-time) operation rule especially under emergency or flood control conditions which is based on dynamic, anticipatory, control-feedback flood operation model with rainfall-runoff forecasting model.

Finally, as illustrated for the case of Pulangi Hydropower IV reservoir, a sustainable reservoir as a renewable resource with almost infinite life must be built with proper sediment control (i.e., reducing watershed sediment yield; rerouting sediments; sediment removal by dredging or hydraulic flushing). With sediment flushing operations in particular, the river downstream is not starved of sediment supply (carrying nutrients to support flora/fauna), so as not to compromise the ecological integrity of the river. As such the reservoir must be designed and operated by adopting life cycle management approach.

7. References

[1] Nippon Koei, 2019, The Study for Restoration and Upgrading Dams Under Operation in the Republic of the Philippines, Report to Ministry of Economy, Trade and Industry, Japan.

[2] Tabios, G. Q. III. (2016). Competing Water Uses of Angat Multipurpose Reservoir with Increased Domestic Water Demand under Future Reservoir Sedimentation and Climate Change, In Water in Agriculture: Status, Challenges, and Opportunities, edited by Stephen J. Banta, Published by The Asia Rice Foundation, College, Laguna, pp. 73-90.

[3] Tabios, G.Q. III (2020), Water Resources Systems of the Philippines: Modeling Studies, Springer Nature, Cham, Switzerland.

[4] Tabios, G.Q. III, S.C. Monsod, C. Arcilla, R.S. Momo, G.J. Rabonza, C.S. Salazar, M.S. Chiu, P.D. Nilo, P.M. Ordona, M.A. Loyzaga and W.B. Connell. (2010). San Roque Dam during typhoon Pepeng of October 2009, Report of Investigating Committee Created under Department Order DO2009-10-0015 of Secretary Angelo T. Reyes, Department of Energy, Republic of the Philippines.
[5] Kondolf, G.M., Y. Gao, G.W. Annandale, G.L. Morris, E. Jiang, J. Zhang, Y. Cao, P. Carling, K. Fu, Q. Guo, R., Hotchkiss, C. Peteuil, T. Sumi, H.W. Wang, Z. Wang, Z. Wei, B. Wu, C. Wu, and C.T. Yang, 2014, Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future 2(5). DOI:10.1002/2013EF000184.
[6] Annandale, G.W., G.L. Morris, and K. Pravin, 2016. Extending the Life of Reservoirs, Sustainable Sediment Management for Dams and Run-of-River Hydropower. International Bank for Reconstruction and Development/The World Bank, Washington, DC.

Assessing reservoir system operation for downstream flood regulation, a case study for the Red River - VietNam

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Abstract
Flooding is considered one of the most dangerous disasters in VietNam that causes huge damage to lives and properties. To regulate flooding especially in downstream cities, upstream dams, and reservoirs play an important role. The Red River basin is the second largest river basin of VietNam with a total area of 155,000 km2 in both VietNam and China. In the river basin, floods occur almost every year especially in the Red River delta where the Hanoi capital is located. This causes large-scale flooding and inundation in the delta and leads to serious damages and loss of human lives. This study provides general operation rules of dams and reservoirs in Viet Nam and assesses the operation status of the reservoir system in the Red River basin, especially the one in the inter-reservoir operation procedure.

Key Words: reservoir operation, inter-reservoir, flood control, Red River, Viet Nam.

1. Introduction

Over thousands of years, people have built dams and reservoirs for flood control, water supply, irrigation, electricity generation, industry, and recreation [1] (WCD, 2000). The dams and their total volume has significantly increased in the last 60 years, reaching 50,000 large dams those higher than 15 m [2]. The total cumulative storage capacity of 7000 to 8300 km3 [3] [4] is approximately 10% of the freshwater in all the natural lakes on Earth [5]or one-sixth of the annual river flow to the oceans [6].

Reservoirs and dams play an important role in water resources management including reducing flooding, ensuring water safety and power supply. These missions have greatly benefited human society in many ways, improving human health, expanding food production, and economic growth. Although it plays a very important role and is invested in planning and resources for construction, reservoirs generally fail to achieve their design goals, both in terms of economic profit and in minimizing negative impacts [1][7]. Reservoirs and dams, especially large ones, can also cause significant costs and damage to human society including migration, resettlement, and water security, ecology, and environmental sanitation. These damages are often not fully assessed in the pre-feasibility stage. In addition, multi-purpose reservoirs also have potential contradictions in satisfying opposing objectives. Therefore, the problem of reservoir management and operation is increasingly concerned by scientists as well as managers. Reservoir operation is a challenging problem that requires determining the balance between conflicting decisions over time and water users. These conflicts may be specified into three types: (1) conflicts in limited storage of reservoirs to satisfy multiple purposes; (2) conflicts in release time to meet requirement; (3) conflict in daily discharge with downstream.

Most of Viet Nam's territory is at the high mountains in the upstream, the midland, and flat plains in the downstream, so most provinces and cities have the potential for reservoir construction for different purposes such as hydroelectricity, irrigation, domestic water supply, and single or multiple objectives. The first single-purpose reservoirs had been built in 1960 e.g. Dai Lai and Suoi Hai reservoirs. The earliest multiple purpose reservoirs constructed for flood control, power generation, and water supply are Thac Ba in 1964, Hoa Binh in 1979, and Dau Tieng in 1981. In Viet Nam, there are about 6,500 reservoirs with a total storage of approximately 11 billion m3. In which, 560 reservoirs have a storage capacity of over 3 million m^3 [8]. The reservoirs in Viet Nam are both natural and man made, located from North to South of the country. These reservoirs are constructed for irrigation, flood regulation, electricity generation, aquaculture, tourism, recreation, and the environment as well. Under the change of climate and natural disasters, the role of the reservoirs especially flood regulating reservoirs has been more important.

2. General dam reservoir operation method in Viet Nam

2.1 Purpose of dam reservoir operation

Viet Nam has more than 6,500 reservoirs. Most of the reservoirs were initially built and operated according to the single-reservoir operation process. In 2010, the VietNam Government issued Decision No. 1879/QD-TTg approving the list of hydropower and irrigation reservoirs in river basins that have inter-reservoir operating procedures. Accordingly, 61 large irrigation and hydropower reservoirs in eleven river basins must be operated according to the inter-reservoir operation process, including Red River, Ma river, Ca river, Huong river, Vu Gia -Thu Bon River, Tra Khuc river, Kone - Ha Thanh River, Ba river, Dong Nai river, Se San river and Srepok river [11]. Currently, the Viet Nam Ministry of Natural Resources and Environment (MONRE) has completed the process of developing inter-reservoirs procedures of these eleven river basins. By 2020, a large multipurpose reservoir system has been built quite completely on major river basins of Viet Nam. Among the inter-reservoir systems, the reservoir system of the Red River basin plays an important role in socio-economic development not only for the Northern Delta in supplying water for domestic use, industry, irrigation, transportation, and flood control but also for the whole country in electricity generation.

According to the data of the Ministry of Industry and Trade [9], by 2010, the total capacity of installed hydropower plants was over 20,600 MW, accounting for 30% of the total capacity of power plants in the whole country. The equivalent electric production of hydropower is about 100 billion kWh [10].

For large hydropower projects in Viet Nam, the following objectives can be categorized:

- Hydroelectric projects in the North: Hoa Binh, Son La (Da river), Tuyen Quang (Lo River), Thac Ba (Chay river) besides generating electricity also preventing floods for downstream, replenishing water sources, facilitating downstream waterway traffic, developing aquaculture in reservoir surface. The Cua Dat hydropower project (Ma - Chu River), Ban Ve (Ca river) also have the above tasks, in which Ban Ve hydropower plant also has the task of pushing salinity for the downstream.

- Hydroelectric projects in the Central and Southern regions: besides generating electricity and aquaculture, also supplementing water sources for the downstream such as pushing salinity (Tri An hydroelectricity on Dong Nai River). This multipurpose hydroelectric project would contribute to climate change adaptation and the clean development mechanism (CDM).

In general, operation objectives are determined according to the period of flood season and dry season. Most of the reservoirs in the inter-reservoir operation process are specified with specific objectives as follows:

1. During the flood season:

a) Ensuring the dam's safety.

b) Ensure flood control for downstream.

c) Ensure power generation efficiency.

2. During dry season:

a) Ensuring the dam safety;

b) Ensure minimum flow in the river and minimum water demand downstream;

c) Ensure power generation efficiency.

2.2 Basic method & rule for dam reservoir operation

According to Steering Committee No. 35 of Ministry of Industry and Trade, the reservoirs operated according to inter-reservoir operational procedures need to follow the below rules to reduce flood downstream:

- Operate the reservoir with the total discharge volume not greater than the inflow at any case until the flood peaks or all the gates are fully opened.

- The operation of flood reduction for the downstream must ensure that there is no abnormal flow that directly threatens the lives and properties of people in the riverside areas downstream of the reservoirs; In case of causing damage.

- During flood season operation when not participating in flood reduction operation for downstream, the water level of reservoirs must not exceed the prescribed maximum before-flood water level.

- During the operation, it is necessary to regularly monitor and update information on weather, rainfall, and flood conditions; water level at hydrological stations; water level and flow to the reservoir and forecast report for real-time operation.

At the end of the process of reducing flood downstream, operating in unusual situations, or operating to ensure safety, the reservoir's water level must gradually be operated to the prescribed maximum before-flood level.

From the above general rules, according to the designed purpose of reservoirs and operation cases, the specific rules for reservoir operation are below:

- Single reservoir: For the reservoirs that are not designed with flood capacity, the reservoir will operate according to storage capacity, inflow, and the operation chart. The reservoirs maintain operation at a high water level that is close to the upper bound of the operation chart to maximize operational efficiency. For a reservoir that has a flood capacity, this volume will be maintained for most of the flood season, usually only allowed to accumulate during the late flood period.

- Inter-reservoir: the reservoirs will be regulated to ensure water supply, reduce floods for downstream areas. The operation procedure is evaluated at the discharge control points (e.g. hydrological stations). Depending on the characteristics of the reservoir system (parallel or series), the role of the reservoir in flood regulation will be decided. In case that the reservoir needs to determine flood capacity, its volume and storing stages are defined based on observed and forecast reservoir capacity and inflow in different periods of flood season i.e., early, main, and late floods. In addition, cascade reservoirs also consider water level observation and forecasting at control points compared to flood water alarm (Decision No.05/2020) to decide operation rules in flood season [12].

3. Dam reservoir operation in the Red River

3.1 Overview of the Red River

General description

The Red River (Hong River) is the second-largest river basin in Viet Nam. The river is a transboundary river with a length of 1,149-kilometer flowing from Yunnan (China) through 17 provinces of northern Viet Nam to the Gulf of Tonkin. The river basin's total area is about 155,000 km2, in which 72,700 km2 (46.9% area) is in Viet Nam territory and 82,300 km2 upstream countries including China and Lao PDR Nam [13]. The river in Viet Nam includes three main tributaries, i.e., Thao, Da, and Lo rivers, joining at Viet Tri city and flowing through Ha Noi, the capital of VietNam (**Figure 1**).

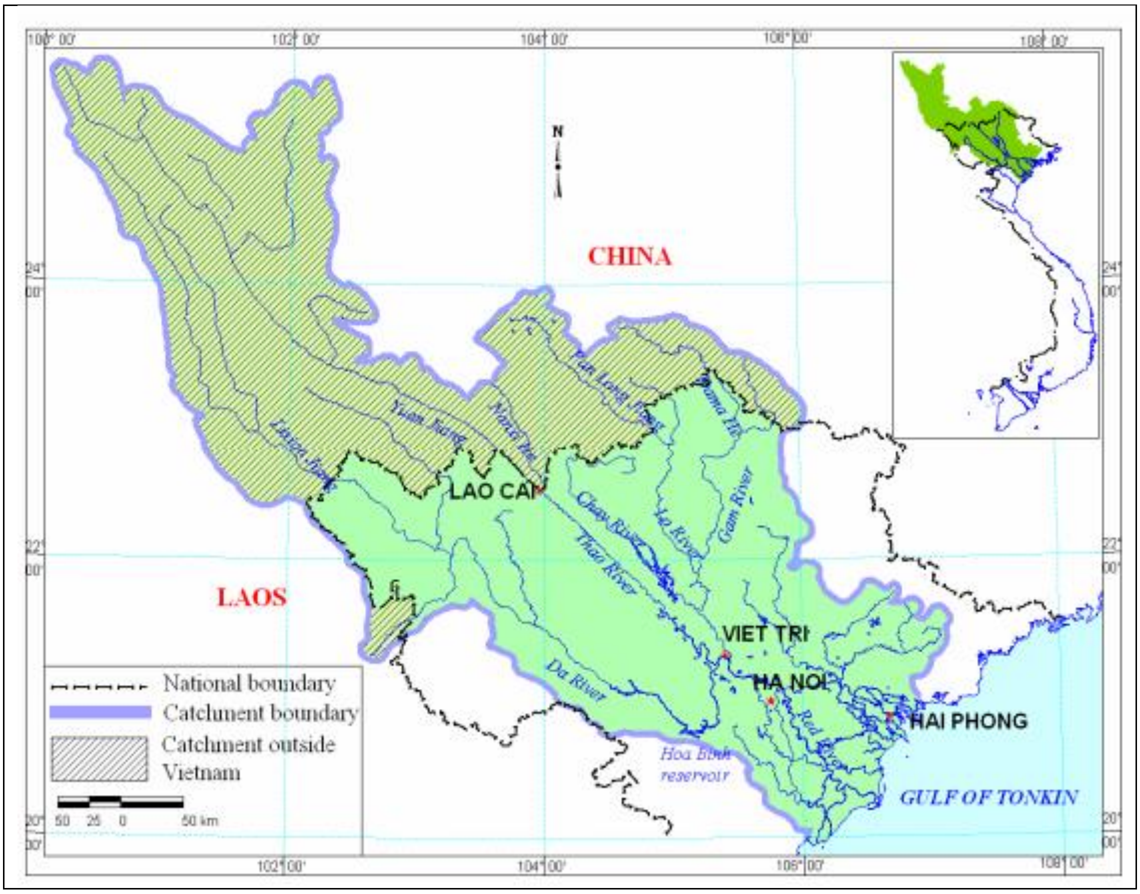

Figure 1: Map of Red River [Ngo Le Long]

Geography

The Red River basin has a steep slope from Northwest to Southeast. The terrain is mostly mountainous, accounting for about 70% of which the area with an average altitude above +1000 m accounting for about 47%. The basin can be divided into three topographical regions: the Northeast, the Northwest, and the Northern Delta. The most important of which is the Northern Delta region, which is a large delta region with an area of about 21,000 km2 (located between the Northwest and Northeast mountains).

Rainfall

The tropical monsoon climate dominates the Red River basin with a cold-dry winter and a hot-wet summer. The climate is strongly impacted by topography causing uneven distribution in both space and time.

The average annual rainfall of the basin is about 1,900 mm with several intense rainfall locations around 4,000 mm (Bac Quang in Lo branch, Hoang Lien Son in Da branch) [14]. Rainfall patterns in the Red River basin are strongly seasonal and spatial variations. The wet season is from May to October, accounting for approximately 80% of annual rainfall, the remainder is in the dry season, from November to April (**Figure 2**).

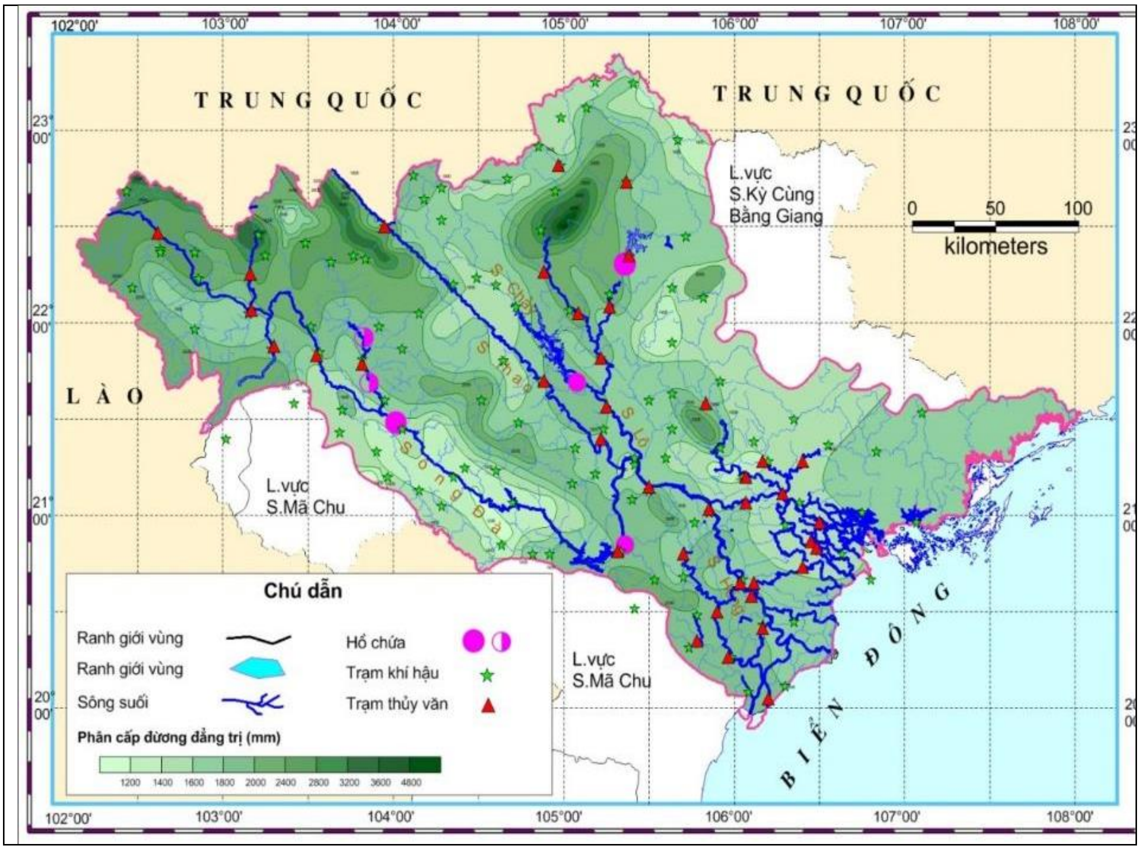

Figure 1: Map of annual rainfall in the Red River basin (part of Viet Nam)

Hydrology and water resources

The water resource of the Red River basin is at the second rank of the national river basins. The total annual discharge volume at Son Tay station is around 120 km3, corresponding to an average discharge of 3,800 m3/s or 26.5 l/s.km2, accounting for about 16% of the total runoff volume of the whole country. Due to rainfall distribution, the water resources of Thao River, the main branch of the Red River, is lower than the two others i.e. Da and Lo Rivers. The seasonal flow is also significant in the basin. The flood season is from June to October with 70-78% of the total annual flow. The dry season lasts for seven months with around 22-30% of the total annual flow.

Dams and reservoirs

The basin is located in high mountain ranges with narrow valleys and steep rivers. Due to high hydropower potential, many dams and reservoirs have been built along the mainstream and tributaries of the Red River in both China and VietNam territory. In China, the eleven cascade reservoirs were approved in 2011 [15] in which six reservoirs are in planning or designing and the other five have been operated or under construction.

In Viet Nam territory, there are 2,499 dams and reservoirs have been constructed for different purposes of water use (Directorate of Water Resources, 2007). Most of the waterworks are for irrigation and water supply. The Red River basin has seven large reservoirs that are determined as an inter-reservoir operation. The four main reservoirs are Son La and Hoa Binh (in Da river), Thac Ba, and Tuyen Quang (in Lo River) are for both water supply and flood regulation (**Figure 3**). These upstream reservoirs are operated following operation rules promulgated in Decision No.740/QD-TTg (dated June 17, 2019) for operating inter-reservoir in the Red River basin to lower water level at Hanoi station to 13.1 m for 300-year flood and 13.4m for 500-year flood [16]. The major parameters of cascade reservoirs in the Red River basin are listed in **Table 1**.

Table 1: Major parameters of inter-reservoir in the Red River basin

Parameters	**Hoa Bình**	**Son La**	**Lai Chau**	**Tuyen Quang**	**Thac Ba**	**Ban Chat**	**Huoi Quang**
Maximum water level (m)	122	217.83	297	122.55	61	477.31	371.77
Normal water level (m)	117	215	295	120	58	475	370
Dead water level (m)	80	175	265	90	46	431	368
Total storage capacity (10^9 m^3)	9.862	9.260	1.215	2.260	2.940	2.137	0.184

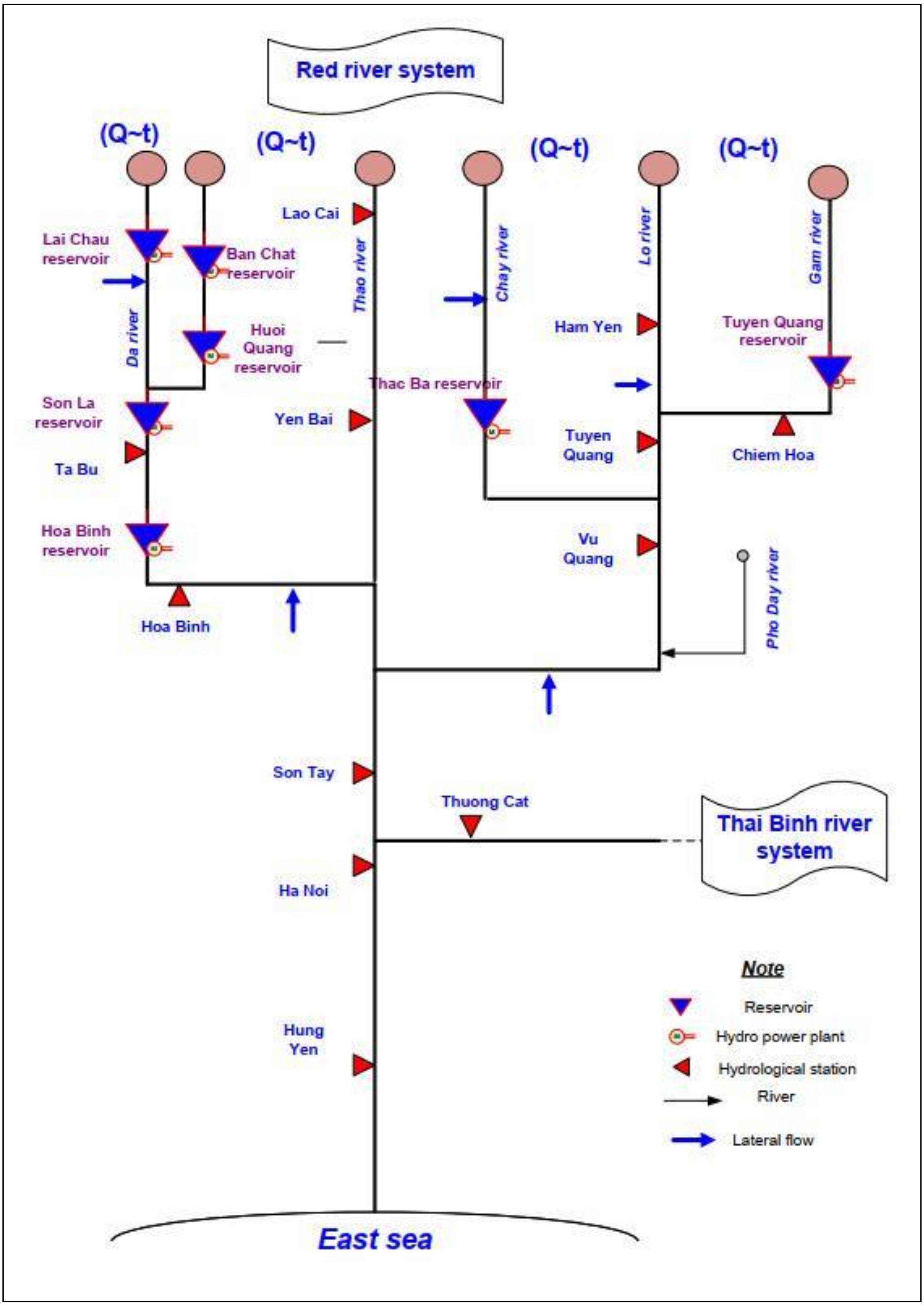

Figure 3: Schematic map of reservoirs and hydrological station in the Red River basin

The regulation of the upstream reservoirs of the Red River (in China territory) is one of the factors that change the flow distribution and the flow characteristics in the lower Red River. The flow in the flood season tends to decrease, the flood water level in Hanoi station in the last decade is mostly lower than water level alarm 1. By estimating, the upstream reservoir system has reduced the flood from 1.1 to 4.2m. The dry season from January to February is when the peak water demand and the pouring period of rice. The main water use period in agriculture in the Red River, usually from December to April. The reservoir system especially Son La and Hoa Binh will supply a large amount of water to downstream to increase water level at head waterworks. In other months of the dry season, the reservoir system mainly operates according to power demand resulting in the lowest water level in the history records. Since 2000, to maintain a proper water level for the pouring period of rice i.e. water level at the Ha Noi about 2.0-2.3m, the upstream reservoirs need to increase the discharge flow to the downstream. Recently, the average amount of flow is about 2 to 6 billion m3 [17].

3.2 Science and technology to support the dam reservoir operation

Reservoir operation is one of the most important water resources planning and management issues in the Red River basin. The operations strategies of reservoirs in the basin are determined by controlling release discharge to meet the demands of stakeholders. The main objectives of cascade reservoir operation in the Red River basin are flood control, hydropower generation, and water supply. These objectives often consist of conflict and inequality. Popular approaches are flood forecast, operation optimization, hydrological, and hydraulic simulation to define the guiding strategies.

Nguyen et al. [18]developed flood outlook stochastic-based approaches at Hoa Binh, Yen Bai, Tuyen Quang, and Hanoi stations. Since 2001, statistical models such as moving average (MA), auto-regression (AR), and ARIMA have been applied to do long-term flood forecasts in the mainstreams of Red River. Bui [19] developed a technique to forecast flood inflow to major reservoirs in the river basin. The study adopted the MARINE model for short-term flood forecasting and the statistical model for long-term flood forecasting.

Anumerical models are used to simulate the hydrological and hydraulic regimes in reservoir operation problems. The hydrological models include dump and semi-distributed hydrological models such as HEC-HMS, MIKE Nam, SWAT, TOPMODEL. The hydraulic models are both 1-D and 2-D software such as MIKE 11, MIKE 21, HEC-Ras. Some simulation tools such as HEC-Resim, MIKE Basin can be used to route through reservoirs.

Recently, some authors have determined reservoir operation rules using optimization techniques. The heuristic algorithms such as linear programming, nonlinear programming, and dynamic programming [20][21][22] are applied to maximize the benefit of inter-reservoir operation in the Red River basin. Some metaheuristic algorithms have been applied to optimize operation rules to meet objective functions. Simulation-optimization methods were conducted using MIKE 11 and Shuffled Complex Evolution (SCE) to optimize the operation rule of the Hoa Binh reservoir satisfying multiple purposes [23][24]. A simulation-based optimization method is used to develop and to solve multi-objective optimization for cascade reservoirs in Red River,. The multi-objective evolution algorithm (MOEA) and non-dominated sorting genetic algorithm II (NSGA II) [25] were combined with the MIKE package in the MATLAB programming environment to maximize irrigation and electricity generation.

3.3 New aspect of operation under climate change

In recent years, advanced approaches have been explored to improve reservoir operation efficiency to meet the proper demand of stakeholders in the climate change context. The advances in water management in the Red River basin can be classified into the following categories:

Advances in rainfall and flood forecast

With the development of technology, rainfall forecast quality is also improved. The forecast from the numerical weather prediction model is localized and corrected by comparing with observed data. Nguyen and Bae [26] generated ensemble precipitation predictions (EPPs) to forecast rainfall and flood by considering radar rainfall observation with spatial rainfall correction. This approach has been adopted to do forecasting services in Viet Nam National Center for Hydro-Meteorological Forecasting (NCHMF).

Trinh [17] developed a flood forecasting tool by adopting an artificial neural network (ANN) to improve operation inter-reservoir in Red River. The climatic factors including local rainfall and global features such as ENSO and Pacific Subtropical High are involved to train the ANN. The author integrated the new techniques with a traditional seasonal base flow to improve flood forecasting to forecast floods in the long term. Based on the seasonal base flow of the Red River, the flood peak is defined and then the reservoir is real-time operated.

Hybrid algorithms optimization reservoir operation

Recent studies in optimizing reservoir operation focus on coupled optimization algorithms with machine learning techniques. The method aims to improve the global optima considering big-data processing. The AI-based method is combined with multi-objective algorithms (MOGA, NSGA-II) to optimize operation rules of Hoa Binh reservoir to regulate downstream flooding and to maximize hydropower generation [27].

4. Administrative and legal framework

Reservoirs in Viet Nam mostly are for irrigation and power generation. Most of the irrigation reservoirs are invested by the Viet Nam Government and the Ministry of Agriculture and Rural Development (MARD). The Provincial People's Committees are the management agencies. Depending on the reservoir storage volume, the operation procedures may be issued by the MARD or the province. Most of the four hydropower reservoirs are managed by the Ministry of Industry and Trade (MOIT). The operation rules are decided by either the MIT or the province, depending on the capacity and importance of reservoirs. Suppose the reservoirs impact significantly on flooding, drought, and water use in the downstream and the whole basin as well. In that case, the Ministry of Natural Resources and Environment (MONRE) is responsible for developing the inter-reservoir operation process to minimize the negative impact downstream and harmonize, improving the efficiency of water use among sectors.

The legal framework for building an overall reservoir operation process must comply with the government's regulations in Decree 114/2018/ND-CP on dam and reservoir safety management [28]. For irrigation reservoirs, the reservoir operation process will be specified in Circular 05/2018/TT-BNNPTNT of the MARD [29]. For hydropower reservoirs, the reservoir operation process will be specified in the Circular

No. 09/2019/TT-BCT of the MOIT [30].

The contents of the operating procedures established for the single reservoir and inter-reservoir generally include the following:

- General provisions
- Reservoir operation during the flood season (include the main content of the operation period, operation priority, and specific regulations on storage and release discharge)
- Reservoir operation during the dry season (include the main content of the operation period, operation priority, and specific regulations on minimum water supply)
- Responsibility for communication
- Responsibilities of agencies and organizations
- Particularly for the single reservoir operation procedure, there will be additional content of operating regulations for sluices, bottom, and surface gates.

5. Discussion and Conclusion

It is undeniable that, in the process of formation and development over the past decades, irrigation and hydropower reservoirs in Viet Nam have performed well their roles and missions, contributing a lot to the development of natural resources, clean energy and is a factor promoting socio-economic development of the country. However, in the current operation, in flood season operation, most of the reservoirs maintain a fixed volume of flood reduction during the whole flood season or in different flood periods (early flood, main flood, and late flood season). This led to a waste of water resources, especially in the context of climate change and abnormal changes in hydrometeorological characteristics. This issue is expected to be overcome with the advances in rainfall and flow forecasts.

Besides, the conflicts among water sectors such as agriculture, hydropower, and flood control have been occurring and become stronger. For example, when agriculture requires large water demand, the electricity demand of the system is not high, which leads to low efficiency of electricity generation. Synchronous and interdisciplinary studies are crucial. Furthermore, optimization is considered as one of the most effective solutions to address reservoir operation problems.

6. References

[1]. WCD, “Dams and development: a framework for decision making,” 2000.

[2]. Berga L, et al. 2006. Dams and reservoirs, societies, and environment in the 21st century. Proceedings of the International Symposium on Dams in Societies of the 21st Century; 18 Jun 2006; Barcelona, Spain. London, UK: Taylor and Francis Group.

[3]. Vörösmarty CJ, Meybeck M, Fekete B, “Anthropogenic sediment retention: major global-scale impact from the population of registered impoundments,” Glob. Planet Chang., vol. 39, pp. 169–90, 2003.

[4]. Chao BF, Wu YH, “Impact of artificial reservoir water impoundment on global sea level,” Science (80)., vol. 320, pp. 212–14, 2008.

[5]. Gleick PH. 2000. The world’s water 2000–2001: the biennial report on freshwater resources. Washington, DC: Island Press

[6]. Hanasaki N, Kanae S, “A reservoir operation scheme for global river routing models,” J Hydrol, vol. 327, pp. 22–41, 2006.

[7]. Labadie J. W. “Optimal operation of multireservoir systems: state-of-the-art review,” J.

Water Resour. Plann. Manag., vol. 130, no. 2, pp. 93–111, 2004.
[8]. Department of Water Resources Management. http://dwrm.gov.vn/index.php?language=vi&nv=news&op=Tai-nguyen-nuoc/Con-so-binh-luan-6-500-ho-chua-thuy-loi-4543
[9]. The Ministry of Industry and Trade (2011). Evaluation report on strategy environment for the national electricity development Project 2011-2020, Considering 2030 (QHD VII). Hanoi, p.262
[10].https://en.evn.com.vn/d6/news/Overview-of-hydropower-in-Vietnam-66-163-1514.aspx
[11].Decision No. 1879/QD-TTg dated 13/10/2010 of the Prime Minister approved the list of irrigation and hydropower reservoirs in river basins must construction of inter-reservoirs operation process
[12].Decision No. 05/2020/QD-TTG dated 31/01/2020 of the Prime Minister promulgating water levels in accordance with flood warning levels on rivers nationwide
[13].Tran T.X. et al. (2012). "Water Resources in major river basins of Viet Nam". Science and Technology Publishing house, Hanoi.
[14].Trinh, T.P. (2012), Ministrial project "Research on methods to identify and forecast potential surface water sources for annual water resource potential notification and testing in the Red River basin".
[15].Xin Wen et al., Future changes in Yuan River ecohydrology: Individual and cumulative impacts of climates change and cascade hydropower development on runoff and aquatic habitat quality, Science of The Total Environment, Volume 633, 2018, Pages 1403-1417,
[16].Decision 740/QD-TTg of the Prime Minister on promulgating the procedure of inter-reservoir operation in the Red River basin
[17].Trinh, T.P. (2017), Ministerial project "Research and develop technology to identify large floods and dry season flows in the Red River basin to improve the efficiency of inter-reservoir operation".
[18].Nguyen, L.C. (2001), Ministerial project "Developing options for long-term assessment of annual flood peaks in major rivers in Viet Nam".
[19].Bui, D.L (2016), Ministerial project "Research and develop technology to predict flood flows to reservoirs on the Red River system"
[20].Ha, V.K. and Le B. T. (2003), "Applying two-dimensional dynamic programming to determine the optimal mode of the terraced power generation reservoir system, and testing it for the system of three terraced reservoirs of the Da River".
[21].Ha, N.H. (2007), Project "Develop a set of programs to optimize the inter-reservoir system to ensure real-time flood prevention and power generation"
[22].Ho Ngoc Dung, Ha Van Khoi, Ho Sy Du (2017) Ung dung thuat toan quy hoach dong cho bai toan van hanh toi uu bac thang ho chua thuy dien. Journal of Water resources engineering and environment Vol 59 (Vietnamese).
[23].Long Le Ngo, Henrik Madsen, Dan Rosbjerg, Simulation, and optimization modeling approach for operation of the Hoa Binh reservoir, Viet Nam, Journal of Hydrology, Volume 336, Issues 3–4, 2007, Pages 269-281
[24].Bertrand Richaud, Henrik Madsen, Dan Rosbjerg, Claus B. Pedersen and Long L. Ngo (2011) Real-time optimization of the Hoa Binh reservoir, Viet Nam. Hydrology Research (2011) 42 (2-3): 217–228.
[25].Nguyen L.X., Tran T.D., Hoang S.T., Nguyen P.T. (2021) Optimized Operation of Red-River Reservoirs System in the Context of Drought and Water Conflicts. In: Babel M., Haarstrick A., Ribbe L., Shinde V.R., Dichtl N. (eds) Water Security in Asia. Springer Water. Springer, Cham. https://doi.org/10.1007/978-3-319-54612-4_53
[26].Hoang-Minh Nguyen, Deg-Hyo Bae, An approach for improving the capability of a coupled meteorological and hydrological model for rainfall and flood forecasts, Journal of Hydrology, Volume 577, 2019, 124014,

[27].Francesca Pianosi, Xuan Quach Thi, Rodolfo Soncini-Sessa, Artificial Neural Networks and Multi-Objective Genetic Algorithms for water resources management: an application to the Hoa Binh reservoir in Viet Nam, IFAC Proceedings Volumes, Volume 44, Issue 1, 2011, Pages 10579-10584
[28].Decree No. 114/2018/ND-CP dated September 04, 2018, of the Government on dam and reservoir safety management
[29].Circular No. 05/2018/TT-BNNPTNT of the Ministry of Agriculture and Rural Development dated May 15, 2018, Detailing a number of articles of the Law on Hydraulic Work
[30].Circular No. 09/2019/TT-BCT of the Ministry of Industry and Trade dated July 8, 2019, on hydropower reservoir safety management

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