Flood Routing for Upstream Reservoirs as a Risk Assessment Tool: Experience of Reservoirs Managed by the Jasa Tirta I Public Corporation, Indonesia

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Reservoirs were mainly designed and constructed in the upstream of each watershed to change the hydrologic characteristics of the basin and decrease the maximum flood discharge. Brantas is an important river basin in the Island of Java, Indonesia, that has used this approach in its water resources management.

However, the issues of flood risk and flood recovery have moved up the political and scientific agendas in recent years following increased frequency and severity in flood incidents and the increased likelihood that this trend will continue as a consequence of climate change (Pryce, Chen and Mackay, 2009). Due to the global climate change, hydrological adversities are drivers to further risk in managing these reservoirs (Arnell, 2004).

Four reservoirs were considered in this paper, namely Karangkates, Selorejo, Bening and Wonorejo. Based on historical floods, a flood-routing routine was conducted for all four reservoirs.

This paper assesses the probability of the flood to exceed the reservoir's capacity. Using the definition of Wang *et al* (2005) it will discuss the occurrence probability that the system external load is greater than its carrying capacity. It was proven that risk increases along the decrease of the reservoir's capacity due to sedimentation; the risk also ameliorate whenever the calculated flood designs are used in the routing process.

New flood risk strategies are required, based on extending floodplains and designating certain downstream areas as flood prone areas upon dam breaks, implementation of new critical water levels in the reservoir impounding, and construction of increasing the crest height to maintain the flood control volume within the reservoir.

Keywords: *flood routing, climate change, risk assessment*

1. INTRODUCTION

1.1 Background

Floods are the most frequent and devastating natural disaster in the Asia region, and like disasters in general, have grown impacts in spite of our improved ability to monitor and describe it. [1] For the past thirty years the number of flood disasters has increased com-

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pared to other forms of disaster. China and India are the most frequently affected and followed by Indonesia, the Philippines, Bangladesh, Iran, Thailand, Sri Lanka, Vietnam and Pakistan. [2]

Climate change compounds the existing challenges of managing floods. Even less certain – as Manuta & Lebel (2005) had described – climate change increases the frequency or intensity of extreme precipitation events and therefore exacerbate risks of disastrous flooding both in upland watersheds where such events can trigger landslides. [3] However, in Asia most upland areas are water granaries where huge reservoirs are built.

Reservoirs were mainly designed and constructed in the upstream of each watershed to change the hydrologic characteristics of the basin and decrease the maximum flood discharge. As a popular choice to improve supply in a hierarchical approach to water resources management reservoirs were widely constructed in the world. [4] In the while, application of technology overtime had improved reservoir construction and maintenance, thus ameliorating operational safety and service security. However, environmental risks are also looming, like sedimentation and climate change. The latter is a recognized problem.

As most reservoirs were designed hydraulically be able to handle designated floods, the issues of flood risk and flood recovery have moved up the political and scientific agendas in recent years following increased frequency and severity in flood incidents and the increased likelihood that this trend will continue as a consequence of climate change. [5] Due to the global climate change, hydrological adversities are drivers to further risk in managing these reservoirs. [6]

Reservoirs are basically designed to allow a certain volume of water – design flood as it was named – to enter the impounding and to be released through the water outlet without harming the dam construction. Various standards are applied hereto, either to designate the incoming flood as well as the method to handle the flood from a hydraulic viewpoint.

Reservoir routing methods are used in the design and operation of storage facilities at high flow conditions. Traditionally, deterministic approaches have been used for reservoir flood routing computations, which do not account for possible variations in governing parameters. However, when enough empirical data is at hand, hydrologic variables uncertainties (such as inflow, stage, and outflow) may naturally be eliminated.

1.2 Objective of the Paper

In the climate-sensitive regions like the monsoon affected South-east Asia, it is foreseen that global climate change will be perceived in various mezzo to micro scale of adversities, like change in rainfall patterns that may results into prolonging drought periods as well as intensified rainfalls during the wet season.

The hydrology of Java's major rivers can be recognized from the seasonal river discharge data that strongly influenced by the biophysical characteristics of the river basins. [7] However, if these intensified rainfalls happen in form of successive storms in the upper watershed of reservoirs, this phenomenon may be an ultimate threat to the reservoir's safety. Even most reservoirs' impounding are designed to control a certain incoming flow and the water outlet (spillway) are calculated to hydraulically handle large floods, other hindrance must be considered.

One combined problem is that reservoir capacity shall decrease along the reservoir's age and when the inflow pattern changes dynamically, there will always be a latent problem of dam failure due to overtopping. This paper wants to explore the combined problem that emerges from these successive storms in relationship to the reservoirs impounding change.

Based from a hydraulic analysis on this problem, a risk performance analysis is conducted to decipher further possibilities of a dam failure phenomenon due to over-topping of the impounding.

1.3 Location of the Research

Four reservoirs are considered in this paper, namely: Karangkates (Sutami), Selorejo, Bening and Wonorejo. All are yearly-operated reservoirs, managed by the Jasa Tirta I Public Corporation – an Indonesian state owned corporation responsible for rendering water services and conduct operation-maintenance of related water infrastructures.

These reservoirs were constructed in the Brantas River Basin, are important water storage for the densely populated basin.

Selorejo is situated in the upper part of the Konto River Basin, a tributary in the Brantas River Basin; it has an initial gross storage of 62.3 million cubic-meters and was completed in 1972 with a catchment area of 236 square km. [8] Karangkates is situated in the upper part of the Brantas River Basin, it was completed in 1972 with an initial storage of 343 million cubic-meters with 2.050 square km. [9] Bening is situated at the Widas tributary of Brantas, with a storage of 58.9 million and a catchment area of 89 square km. [10] Wonorejo is situated in the upper part of the Song tributary, has a storage of 122 million cubic-meters was completed in 2000 with a catchment area of 126.3 square km. [11]

2. DATA ANALYSIS

2.1 Analysis Methodology

Kuo *et.al* (2007) conducted a risk analysis for overtopping event of a reservoir. In this study, they stated that there were many uncertain factors that could affect dam overtopping risk. [12] They also pointed out that various uncertainty analysis methods were available to propagate the associated uncertainties into resulting risk and reliability values. However, uncertainty analysis was omitted in this paper, and the author relies completely on the historical data sets to provide insight on the reservoirs' response to incoming floods.

The analysis sequence is as follows:

- Step 1: obtain storage curve function of the specified reservoirs, based on recent hydrographic surveys.
- Step 2: based on historical floods create an empirical hydrograph to describe the upper watershed response to distinctive storms.
- Step 3: conduct flood routing routine through the reservoir using the combined empirical hydrograph with designated or historical flood records.
- Step 4: assess the dam's failure probability by comparing storage change to the evolving risk of overtopping.
- Step 5: describe certain strategies to manage the evident risk overtime.

2.2 Change of Storage Function

Change in storage function is directly related to sedimentation process in a reservoir. Inflow to a reservoir normally transports sediments in three forms: wash load, suspended load and bed-transport. Most of the suspended load and bed-transport are silted in the reservoir's storage, in the so-named «dead storage».

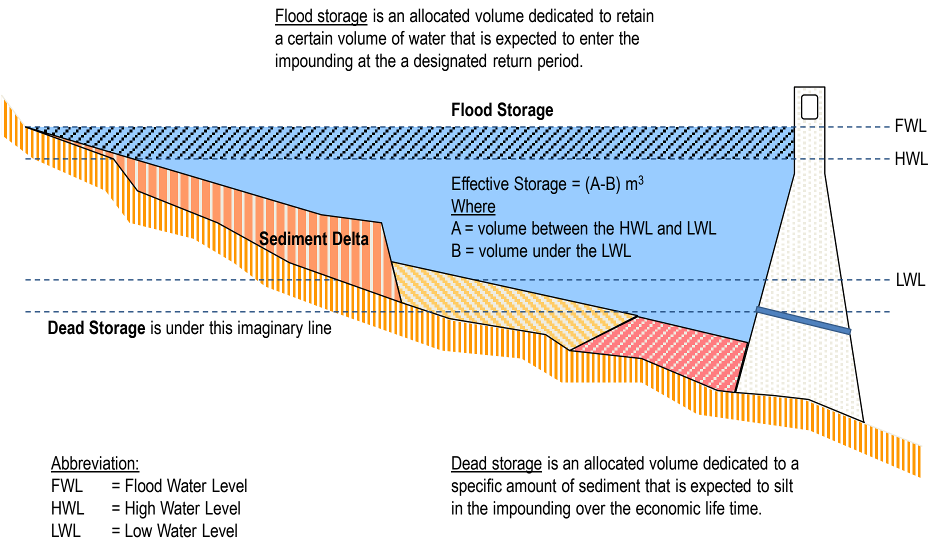

Figure 1 Sedimentation process in a reservoir [13]

The sedimentation process is generically described as deciphered in Figure . However it can be seen that a sedimentation process will affect the effective storage as well, even a certain «dead storage» is allocated to host the siltation volume. More over as it can be deducted, the flood control volume may also be affected, as sedimentation in a reservoir is normally distributed in a delta shape.

Most economic functions of the reservoirs in the world are depleted due to sedimentation. As far as 2007, Indonesia has 122 large dams, where like most Asian countries endures sedimentation at a significant rate. White (2000) estimated that close to 0.3% of man-made storage is annually lost annually in Asia. [14] This threatens not only the economic use of a reservoir but as well its flood control capacity.

2.3 Hydrograph Derivation

In a reservoir routing process, the inflow hydrograph is an important aspect of the analysis. Inflow hydrograph for a reservoir can be calculated from the relationship between the observed water level fluctuation in the reservoir and the released outflow.

2.4 Flood Routing Results

Reservoir routing is normally performed for both design and analysis purposes. When the inflow hydrograph is known, the outflow rate can be determined by using reservoir routing. In this paper, reservoir routing will be carried out using a numerical solution. The continuity equation is given below:

$$\frac{\partial S}{\partial t} = I(t) - Q(h) \quad (1)$$

Where: S is storage, t is time, $I(t)$ and $Q(h)$ are inflow and outflow, respectively.

Since S and $Q(h)$ are both unknown, another equation is needed to solve for the change in outflow with time. Differential storage in the reservoir ∂S can be expressed by $\partial S = A(h)\partial h$ where $A(h)$ is the surface area of the reservoir at an elevation of which is measured from the axis of bottom outlet and ∂h is the differential depth. Using elevation-area-volume relationship of the reservoir then $A(h)$ can be represented mathematically. On the other hand, the outflow can be expressed as a function of by using the appropriate equations for bottom outlet or overflow spillway, which are derived from the conservation of energy principle. Therefore, Equation (1) becomes:

$$\frac{\partial h}{\partial t} = \frac{I(t) - Q(h)}{A(h)} = f(h, t) \quad (2)$$

While $\partial h/\partial t$ is the rate of change of water surface elevation. When all the expressions forming Equation (2) are expressed mathematically, the temporal variation of the reservoir water level and hence the outflow can be obtained.

There is a variety of solution available for routing of floods through a reservoir. All of them use Equation (1) but in various rearranged manners. As horizontal water surface is assumed in the reservoir, the storage routing is also known as «level pool routing». [15] Commonly used methods are the semi-graphical method of Pul and Goodrich; otherwise a numerical solution with the standard fourth-order Runge-Kutta method provides a more efficient computation procedure.

2.5 Risk Analysis

If the relationship between the concept of system disabled and the system external load and its carrying capacity is made, then system risk is regarded as the probability of the occurrence that the system external load is greater than its carrying capacity, namely: [16]

$$P_f = P(L > R) \quad (3)$$

In practice, the above meaning can be expressed with the minus value of L and R, and then Equation (1) is as following:

$$P_f = P(Z < 0) \quad (4)$$

Random variable Z can be expressed with many influence factors as:

$$Z = h(z_1, z_2, z_3, \cdots, z_k) \quad (5)$$

Flood risk analysis enlarges the concept of probability, for the risk analysis not only deals with all kinds of inherent uncertainty of the natural process, for example, the stochastic characteristic, but also deals with a lot of subjective wind age or error brought by the lack or imperfect of data and information. [17]

3. DISCUSSION

3.1 Computation Result

Initially four reservoirs were considered in this paper: Karangkates (Sutami), Selorejo, Bening and Wonorejo; all situated in the Brantas River Basin, East Java. For each reservoir, capacity rule curve for distinctive years was computed based on bathymetry survey results. These capacity rule curves were used to provide the reservoir's storage function in the flood routing analysis.

The flood discharge in this analysis was taken from historical records of inflows at the assigned reservoirs. The flood routing uses the graphical approach (Pul method) whereas it is assumed that outflow from the reservoir is canalized only through the spillway (no release from the turbines or the hollow jet valve).

Analysis result of all reservoirs is summarized as follows. Firstly, it could be seen that sedimentation directly affects the storage function in handling floods.

Karangkates (Sutami) provides us an insight on how different two historical floods – with the latter altered than the first – provides completely different results in the ability of the reservoir to handle the incoming flow.

Table 1 Flood routing results for the Karangkates (Sutami) Reservoir

Karangkates (Sutami)		**Out Discharge from Spillway** cubic-meter/s	**Water Level at the Reservoir** m	**Notes**
Scenario 1: peak flood discharge		1,161		29 Jan-1 Feb 2002
Routing based on capacity of	1997	351	274.80	Safe
	2007	364	274.87	Safe
	2010	395	274.98	Safe
Scenario 2: peak flood discharge		2,057		25-29 Dec 2007
Routing based on capacity of	1997	655	276.00	Overtopping
	2007	655	276.00	Overtopping
	2010	655	276.00	Overtopping

Applying the historical flood of 29 Jan-1 Feb 2002, with a peak discharge 1,161 cubic-meter/second, the Karangkates water level will rise to 274.80 (based on the storage capacity of 1997), 274.87 (1999) and 274.98 (2010) respectively. The reservoir's outflow is discharged completely through the spillway as follows: 351 (1997); 364 (1999) and 395 cubic-meter/seconds (2010).

However, applying another historical flood with an altered magnitude as recorded on 25-29 Dec 2007, grim results was found. Relying only on the maximum spillway capacity (655 cubic-meter/seconds) overtopping occurred for all storage capacities exercised herewith (1997, 1999 and 2010).

However this disaster was not evident on 25-29 Dec 2007 due to the reason that: (a) the reservoir water level was lower in reality and routing analysis assumed it to be as high as the crest of the spillway; and (b) water is released not only from the spillway but through the turbines as well, adding another 160 cubic-meter/s.

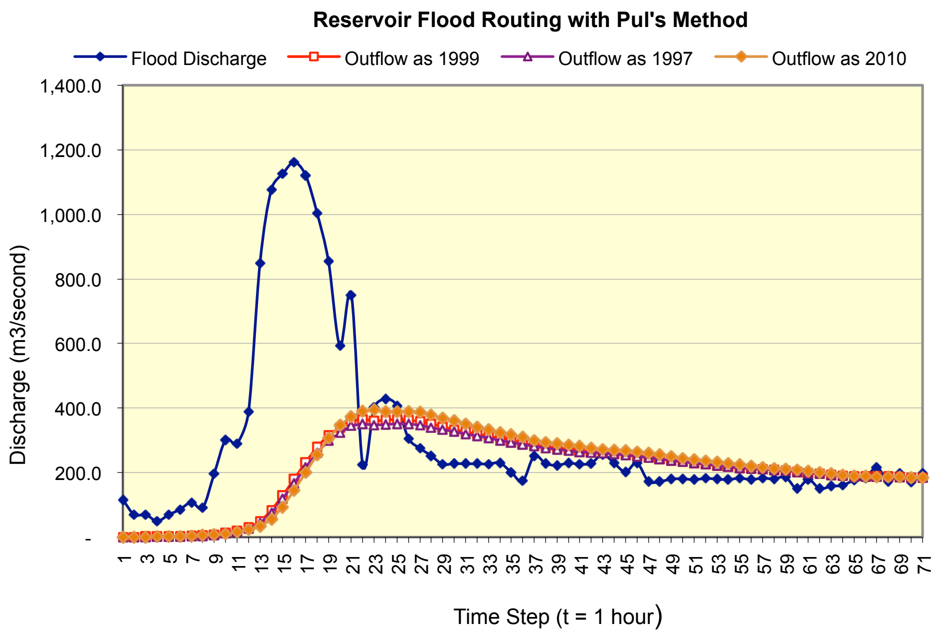

Figure 2 Flood routing through the Karangkates (Sutami) Reservoir using the 29 Jan-3 Feb 2002 hydrograph

Second, it was proven that for reservoirs with small catchment areas and lower sedimentation rate, the risk of the dam's failure is lower due to the altered flood remains within the hydraulic threshold of the reservoir. This is exemplified by the Selorejo Reservoir, and was noticed in the initial flood exercise for Bening and Wonorejo.

Table 2 Flood routing results for the Selorejo Reservoir

Selorejo		Out Discharge from Spillway cubic-meter/s	Water Level at the Reservoir m	Notes
Scenario 1: peak flood discharge		380		3-5 Jan 1960
Routing based on capacity of	2003	208	621.63	Safe
	2007	204	621.61	Safe
Scenario 2: peak flood discharge		179		26-29 Apr 2010
Routing based on capacity of	2003	84	620.89	Safe
	2007	83	620.88	Safe

Selorejo Reservoir itself has undergone a steady sedimentation rate, but as the siltation occurs under the high water level, less risk is perceived for the flood storage level, thus maintaining safe performance for the reservoir's under high-inflows.

Another interesting case is the Selorejo Reservoir. As it can be seen in Table 2, the reservoir responded well to the inflow and released the flood over the spillway as expected. The reservoir was exercised both for the historical flood of 3-5 January 1960 and 26-29 April 2010 and shows how the storage functions well, for both the 2003 and 2007 capacity curves. Refer to Table 2.

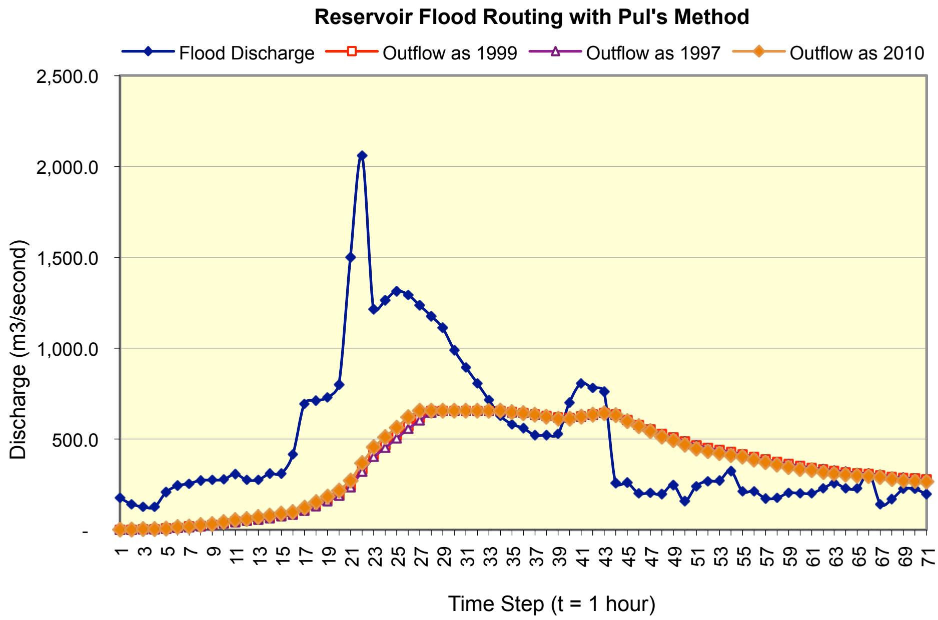

Figure 3 Flood routing through the Karangkates (Sutami) Reservoir using the 25-29 Dec 2007 hydrograph

Flood routing for Bening and Wonorejo prove that the historical flood hydrograph do not alter the risk of overtopping due to the lower rate of sedimentation for both reservoirs. Bathymetry survey for Bening and Wonorejo indicates that both lost less than 12% of their effective storage since their commissioning.

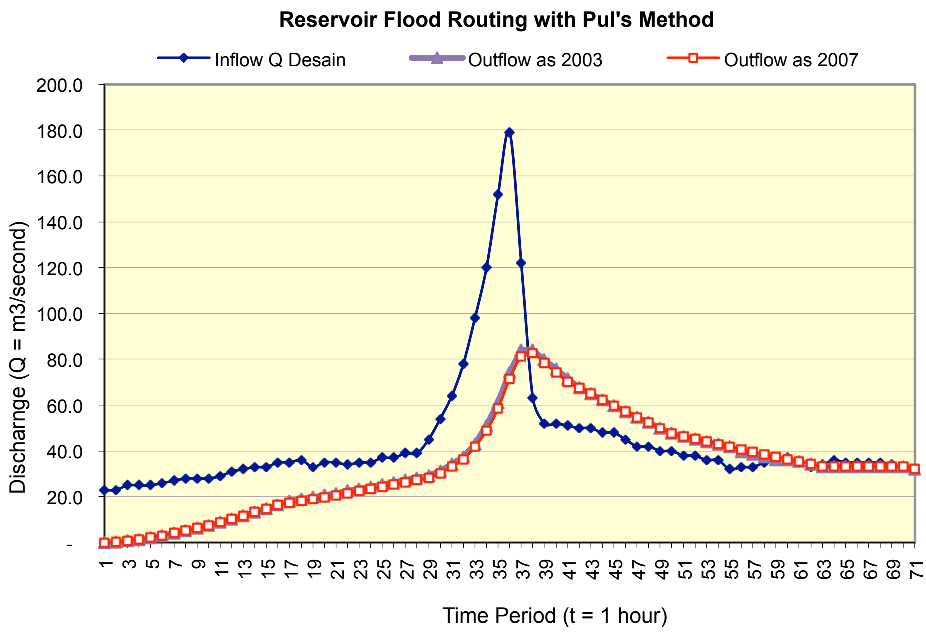

Figure 4 Flood routing through the Selorejo Reservoir using the 26-29 April 2010 hydrograph

The historical hydrographs applied in this paper to asses flood control of the Selorejo, Bening and Wonorejo reservoirs does not alter the dam’s failure risk – as the hydrograph is lower than the floods that were applied for the hydraulic design of these reservoirs.

3.2 Risk Analysis

Based on Equation (3), risk analysis was developed for the intended reservoirs. It was found that risk of a dam’s failure increase whenever the released flood discharge closes to the spillway’s designated capacity. Risk of a dam’s failure is a function of the flood probability to exceed the designated capacity.

From the risk analysis it can be found that the damage possibility is a probability function as well. The possibility to exceed a certain discharge is on the contrary a normal-distributed problem, while risk is an incremental function.

3.3 Risk Management

The hazard discourse focuses on the physical event that requires experts and bureaucracy to predict the occurrence and magnitude of flood hazard and thereby to control natural disaster. Flood disaster risk is seen as the probability of harm emanating from determinable physical causes.

This hazard led approach focuses more on relief and emergency after the disaster occurs and technical/ engineering measures to control and contain flood. The governance process is basically technocratic and state-centered; survivors of flood disaster are not involved in the decision-making process. [18] Most of disaster risk management institutions and arrangements across Asia have been anchored on this perspective.

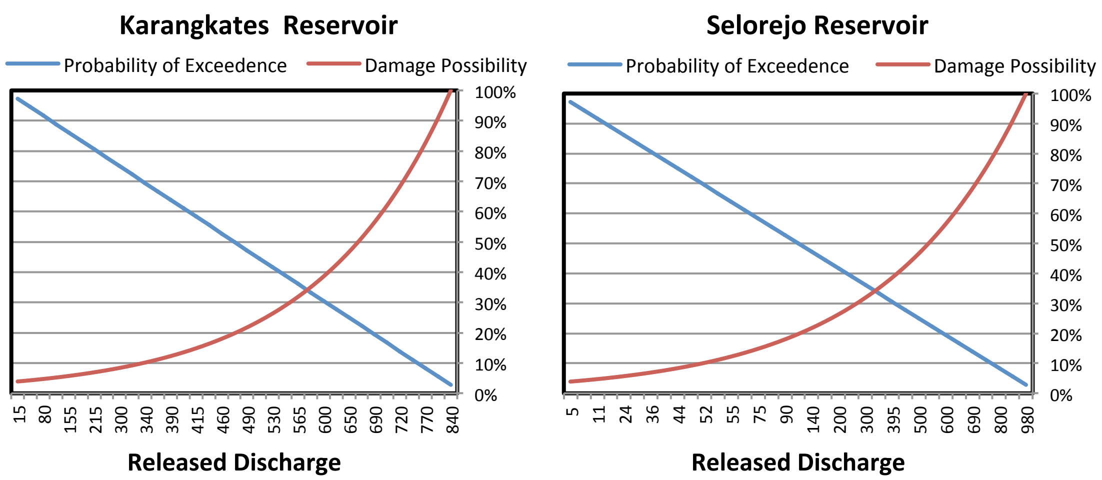

Figure 5 Risk analysis for two reservoirs taken into consideration

The jointly produced perspective, on the other hand, focuses on disaster risk management approaches that reduce peoples' vulnerability and enhance people's social resilience. Vulnerability refers to the condition of a person or a group in terms of their capacity to anticipate, copes with, resist and recover from the impact of a natural hazard.

In addition to relief and emergency measures an increasing attention is given on mitigation and preparedness measures which encompass efforts to address the political economy of vulnerability of individual, household and community. Institutions and systems of governance that structure political, social, cultural and economic relations and transactions in a society shape and determine peoples' vulnerability.

These socio-political and economic relations differentiate and influence resource allocation and people's access to resources, including capital, information and decision-making, which are crucial for survival and well-being.

There are two main discourses on flood disasters (see Table 3). The first, and dominant view, is that flood disasters are inherently a characteristic of natural hazards. Disasters arise inevitably when the magnitude of a hazard is high.

This contrasts with the second (alternative) discourse that sees flood disasters as being jointly produced by interaction of the physical hazard and social vulnerabilities. This alternative discourse brings into the fore social relations, structures, institutions and governance in understanding flood disaster. This view posits that flood disasters are not only the result of natural hazards, but also of socio-economic structures and political processes that make individual, families and communities vulnerable.

Table 3 Views on flood disaster and governing flood disaster risk

	Natural Hazard	**Hazard - Vulnerability**
Flood disaster	Hazard led; inherent characteristic of natural hazard;	Disaster is the result of the interaction of natural hazard and vulnerability
Disaster risk management	Focus on relief and control	Focus on mitigation and preparedness; mitigation measures address the political economy of vulnerability
Governance process	State-centered; technocratic and hierarchical	Pluralistic

In case of a dam's failure due to overtopping of the embankment, risks are large for the population that lived downstream. Even rare disasters are found in this case, most countries opted for reservoir management bodies to adopt a dam failure emergency response plan.

In Indonesia, the Ministry of Public Works had stipulated that every large dam in country has to obtain a risk management plan. This decree is widely accepted but enforcement and renewal on emergency plans requires necessary funding and technical adequacy. Thus it could be concluded, that the Indonesian Government has taken into account the vulnerability aspect and to a certain extent focus on mitigation and preparedness rather than relying on a «disaster driven» response system.

However it is evident, that in assessing hazard vulnerability, the role of the government remains important, more than other agencies, that is in the Indonesian case due to invested situation where almost all large dams are basically owned by the government.

3.4 Risk of Altered Flood Regimes

Climate change, especially when it interacts with other human interventions in watersheds and channels, could alter flood onset, duration, extents and frequencies. In our analysis we reduce this complexity to two generic kinds of changes (Table 4). We outline at the outset that the impacts of changes in flood regime may not necessarily be negative for all stakeholders, but rather produce both winners and losers even within the same basin.

Table 4 Impacts of altered flood regimes depend on livelihoods and lifestyle objectives [17]

		Flood regime change with climate change More intense, prolonged or frequent flooding.	**Less intense, shorter and rarer flooding** Less intense, shorter and rarer flooding
Livelihood and life-style relationship with floods	Depend on floods	Beneficial up to a threshold of adaptation; increased risks after the threshold.	“Lack of floods” disaster, higher productivity expected from disaster prone sectors.
	Avoid floods	Increased risks of disaster, altering every year.	Reduced risks of disaster, living with an adaptability..

Based on the computational results, as shown in section 3.2, four reservoirs in the Brantas River Basin are under increasing risk altered floods. Sedimentation has reduced the reservoir’s capacity and significantly altered the risk of non-compliance performance. However, the worst threatened reservoir is Karangkates (Sutami), where the analysis found out that upon applying a historical flood hydrograph, excluding the turbine and hollow jet valve function, the dam will endure overtopping.

It can be seen certain important measures must be taken in accordance to reduce the risk of overtopping due to the altered floods. Reservoirs must be equipped with **risk adaptation schemes** and flanked with (contingency) **risk-engineering efforts**.

Table 5 Examples of risk adaptation and risk engineering efforts for reservoir management under altered risks of flood

	Risk Adaptation	**Risk Engineering Efforts**
Flood disaster	Improving responsiveness and crisis management	Vulnerability assessment for downstream areas

	Risk Adaptation	Risk Engineering Efforts
Disaster risk management	Critical water level and update of reservoir operation level	Altering the spillway crest to increase flood storage capacity
Governance process	Awareness and cross-cutting issues on dam management	Emergency dam's failure plan and preparedness

4. CONCLUSION AND RECOMMENDATION

Four important reservoirs in the Brantas River Basin, East Java, were analyzed in this paper, in order to perceive the combined risk problem of reservoir capacity decrease and the altered flood that are excess of the global climate change.

Based on the computational results, all reservoirs are under increasing risk of altered floods; where the Karangkates (Sutami) is considered the most threatened one. Massive sedimentation has reduced the reservoir's capacity and significantly altered the risk of non-compliance performance, increasing further risk of the dam's failure due to overtopping.

Risk of a dam's failure increase whenever the released flood discharge closes to the spillway's designated capacity. Risk of a dam's failure is a function of the flood probability to exceed the designated capacity. It was found that climate change, especially when it interacts with other human interventions in watersheds and channels – that propagates sedimentation at reservoirs – could alter flood risks for the reservoir itself.

Finally, it can be recommended to take prompt measures to reduce the risk of overtopping due to the altered floods. Reservoirs must be well equipped with risk adaptation and flanked with soft-engineering aspects. Risk adaptation can be implemented by (among others) setting up new critical water levels in the reservoir; while soft engineering aspects can be exercised by developing emergency contingency plan for each reservoir.

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