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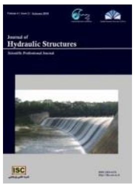

Dam failure, management and outlook in the light of climate change: a review in case study of the Wivenhoe Dam, Brisbane

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Abstract

Research on multi-dimensional aspect of dam engineering is gaining momentum because of massive flood destructions in lives, ecosystem and development including Wivenhoe dam flood in 2011, Oroville dam's spillway incident 2017 and the Europe's widespread flooding in 2021. The aim of this study is to capture and review research activities in dam science since 1980. A case study of the Wivenhoe dam Brisbane Australia, focusing on its design, catchment, water storage and flood mitigation capacity, management procedure, climate change and historical rainfall pattern has been carried out to conclude why such a catastrophic flood event happened in Brisbane in January 2011. The methodology applied in the study includes related literature review followed by documentation and analysis of reports and data of Queensland Water, Wivenhoe Alliance and Flood Commission. Reviewed literatures indicated that dam failures are primarily associated with improper design, inadequate monitoring in construction period and poor management (operational) practices. In the case of the Wivenhoe dam flood, the report of the Flood Commission of Inquiry Australia was that the dam was operated so that its flood mitigation was near optimal. Whilst the operators were found to be at fault for not following the Operation Manual, it was found that the manual was confusing and difficult to follow, and therefore, they were cleared of all liability. Hence, it is difficult to conclude what would have actually happened if the Wivenhoe dam operators had released more water earlier, author's reasoned outlook about the flood mitigation measures used at the time is to ask the question "was reasonable discretion" used during the flood. In the light of the warnings that the dam operators were given even as far back as December 2010 about the strong La Nina, it would seem that operators made sub-optimal decision about water releases and hence "reasonable discretion" wasn't applied properly. Hence, it can be said that the Brisbane Flood 2011 was a dam release type flood basically related to poor management.

Keywords: Brisbane flood; dam failure; flood management; flood mitigation measures; Wivenhoe dam.

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1. Introduction

Climate change as a product of complicated dynamic system including rapid industrialization, population expansion and technological improvements with less priority to environment has been considered a main factor responsible to natural disasters [1, 2]. Water, its quantitative availability and quality are the main pressures on and issues for nature-positive economic development under climate change [3, 4]. Climate change is one of the greatest challenges of current generation and is in the center of the global debate among policy makers, scientists and practitioners [5, 6]. Due to the climate change and new pattern of rains and snowfall, there is a greater frequency of extreme climatic events, such as prolonged drought and high intensity rainfall causing devastating floods and landslides [7, 8].

Dams are large and costlier hydraulic structures built across stream or river to satisfy water requirements of various end-users including hydropower, agriculture, municipality water, flood control and industry [9, 10]. The dam science has a written history of at least 5000 years while the first modern dam of the world as a major engineering project was constructed on the Nile River in 1902 [11]. Based on the literatures published, dams throughout world are generally classified into seven categories including rock-fill dam, earthen dam, hollow-masonry gravity dam, solid-masonry gravity dam, timber dam, steel dam, and arch dam. Arora [12] recommended some key features to be considered while selecting the particular dam type includes: foundation, valley, x-sectional shape, capital and maintenance cost, lifespan, kind of labor, facility of inspection, subsequent raising and resistance against temperature changes. Based on the report of International Commission on Large Dams (ICOLD), nearly 58,000 large dams are currently effective in use [10].

Dam has substantial contribution in water storage, particularly in water-limiting conditions and areas where precipitation follows uneven distribution. Dam projects differ based on level of development, for example: the major focus on new dam in developing nations lies on the design parameters whereas the safety and qualitative extensions of already existing dams are the primary concerns in developed world [13]. In this context, dam engineers have contributing differently and their contribution has changed over recent decades with the advancement of new technologies and design software [14]. Instead of engineering aspect, the sustainability of dams are integrated with factors such as population increment, water security, urbanization, and changing climatic pattern [9, 15]. Dam failures are mainly caused by improper design, lack of thorough investigations, inadequate care in construction time and poor management practices [12]). Findings of studies in dam engineering indicate that three types of major failure occur in dam: a) hydraulic failure, b) seepage failure, and c) structural failure. Garg [11] reported that hydraulic, seepage and structural failures represent 35%, 38% and 20% respectively whereas rest of the 7% are linked with other miscellaneous causes.

Systematic studies on dam science, particularly dam failure and different aspects of failure statistics and probability have been conducted throughout the world [16-20]. For dam safety and its longer life, it is important to include all forces, pressure and loads acting on dam in planning and designing stage. The major forces any type of dam have to withstand include: a) weight of the dam, b) seismic forces, and c) pressure created due to different components like water, wave, silt, ice, wind and uplift [11]. In the study of [17], Proske, comparison of observed failure frequencies and the failure probabilities of large dams is carried out. In their study related to probabilistic identification of seismic response mechanism, [13] compared seismic performance of two identical arch dams based on linearity. Hariri-Ardebili [21] claimed that less attention has been paid by designers for seismic load analysis in dam engineering which might become one of the reasons for failure in future. One of the challenges while designing concrete dam is to determine the maximum safe dynamic load [19]. In their study, [22] developed a model for characterizing a concrete gravity dam and recommended a technique to assess the seismic fragility analysis.

Malm *et al.* [23] predicted the major failures (displacements and cracking type) in arch dams because of variation in season which was based on the results of the ICOLD Benchmark Workshop. They highlighted three important aspects needed to be considered for optimum result: "(1) the importance of performing transient thermal analyses using robin boundary conditions (i.e., based on convective heat transfer boundaries); (2) the impact of dam-foundation contact formulation; and (3) adapting a realistic nonlinear material model". In their study on monitoring of large type earthen dam, [24] measured three main parameters including water level, internal stress ratios and pore water pressure based on designed performance indicators for longer time to check the stability. However, [21] urged that empirical models can indicate the dam behavior in general, they cannot represent the changes happened in dams because of abruptly changing climatic behaviors.

Table 1: A summary statistics of dam failures based on dam category and the context [10]

Dam type	% of failed dam to total	Failure context	% of failed context to total
Arch	0.08	Hostile human action	0.05
Buttress	0.23	Other extreme natural event	0.02
Multi-Arch	0.29	Extreme earthquake	0.03
Gravity	0.09	Extreme flood	0.17
Earth-fill	0.14	Unusual flood	0.21
Rock-fill	0.16	Flood (unknown magnitude)	0.13
Barrage	0.01	Unknown source	0.39

Research on multi-dimensional aspects of dam science and management is gaining momentum because of flood destructions in lives, ecosystem and development throughout the world including Wivenhoe dam flood in 2011, the 2017 Oroville Dam's spillway incident, and massive urban floods in London, New York and Xhenghou [17, 20]. The widespread flooding in Europe in July 2021 initiated an overdue conversation about the preparedness of governments and institutions to respond to such large and devastating events [20]. Hence, systematic researches on the hydrologic history, current status, and its impact on future are important for the sustainability of dam science. In this context, this study has solicited past literatures, research findings and authorized reports of government agencies to review the design, management, and overall analysis of the Wivenhoe dam, Brisbane Australia. In the light of water-driven disasters, this study provides a platform to critically review the dam science primarily focusing on Wivenhoe dam for improving preparedness and to identify the challenges in dam engineering to build flood-resilient futures.

2. A case study of the Wivenhoe dam

2.1. Brisbane flood 2011

In the second week of January 2011, the Brisbane city (27°30' S, 153°1' E) of Australia encountered a massive flood of record because of the Wivenhoe dam (The catchment of the Brisbane River and Wivenhoe dam is presented in Figure 1-a and 1-b). This flood not only destructed in the suburbs there, but also showed fingers towards the dam owners because a total of 24 people were drowned and 90 towns, over 0.2 million residents and 18,000 properties were affected with an economic damage of $2.55 billion [25]. In addition, an eroded boulders of maximum weight around 1200 ton were deposited at the downstream of the spillway. Major floods occurred at the site in 13 January 2011 which was less frequent than the 1 in 2000-year Annual Exceedance Probability (AEP). The maximum discharge during the flood event from the spillway was above 7,000 m^3/s, which was significantly higher compared to design discharge for the safety and sustainability of the Wivenhoe dam [26].

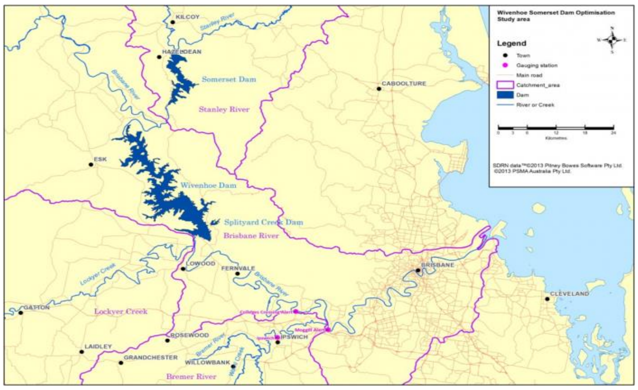

Figure 1(a). Brisbane River Basin with dam location

Figure 1(b). Wivenhoe Dam

The following sections describe about dam's design, catchments, water storage capacity, flood mitigation capacity, climate change and management procedure of the Wivenhoe dam.

2.2. Wivenhoe dam design

The Wivenhoe dam is predominantly a central core rock fill type gated dam and is a multi-purpose dream project, owned by South East Queensland Water [27]. The dam was designed by the Water Resources Commission and constructed (1977- 1984) by a consortium of companies including Thiess Brothers to protect Brisbane from floods in response to the worst flooding in 1974 [28]. The length and height of dam are 2.30 kilometers and 59 m respectively with a concrete spillway section [29]. Construction of the dam involved the placement of around four million m^3 of earth and rock fill, and around 140,000 m^3 of concrete in the spillway section which required excavation of 2 million m^3 of earth and rock [29]. The dam spillway capacity is based on a probable maximum flood inflow of about 15,000 m^3/s and 48-hr duration probable maximum precipitation of 480 mm leaving a freeboard of 2.90 m before the embankment is overtopped [28]. Lesleighter *et al.* [26] indicated overtopping as the major threat to the security of the Wivenhoe dam although it was designed on overtopping by an event with a 1 in 100,000 AEP.

Russo [29] added that the adoption of an intake located in a slot in the left hand spillway abutment helped achieving an economic efficiency in the dam construction but scarifies some hydraulic performance. It means the intake structure of the dam is chosen for overall economy rather than hydraulic efficiency. The dam site lays on the Helodon sandstone also known as the Wivenhoe sandstone of lower Jurassic age [29]. Two embankment types are incorporated in the design. The main embankment across the riverbed consists of a rock fill section with a central core whereas the embankment to the left of the spillway has a sloping core section [26]. Overall, it can be said that the adoption of a large capacity diversion channel in the sandstone of the right abutment combined with a spillway diversion gap proves a safe and economical design of the Wivenhoe dam.

2.3. Wivenhoe dam catchment

The catchment has significant role while designing any hydraulic project because its contribution and activities are always associated with success or failure of that project. The quantity and location of precipitation within the selected catchment are two important factors for evaluating the effectiveness of dam in flood control initiative [25]. The size, shape and slope of the catchment, the nature of the surface area and soil categories within the catchment have profound influence in the runoff contribution [30] and hence these parameters should be closely evaluated during the design of any water infrastructures.

The Wivenhoe dam has comparatively a larger catchment area approximately equals to 7020 km^2, primarily containing grazing land, forestry and metropolitan as well as small towns [27]. Nearly 50% Brisbane river catchment (i.e. 15000 km^2) is covered by the Wivenhoe dam. Honert and McAneney [25] reported that the average catchment rainfall in excess of 200 – 300 mm in 48 hours might result the possibility of moderate to major flooding. Substantial development including construction of dams along the Brisbane river banks and increasing human settlements have changed the physical characteristics of the Wivenhoe dam catchment [25].

2.4. Water storage capacity of the Wivenhoe dam

The primary objective of the Wivenhoe Dam is to store sufficient amount of water for providing quality drinking water to the South-East Queensland region. The storage behavior of the dam was simulated for the 96-year rainfall data record of Wivenhoe catchment [29]. The dam has two sections for water storage: potable water storage and flood water storage compartment. The total storage capacity of the dam is about 3.15 million ML with surface area nearly 110 km^2 [27]. The provision of additional space also known as dam's flood storage compartment is there with primary objective to hold back the flood water, i.e. storing flood water and subsequently releasing as a controlled flow to protect the downstream parts of the dam [28]. The Wivenhoe Alliance also reports that continuous heavy rainfall of less than three days can fill the dam's flood storage compartment which demands the sound strategic management of dam levels, otherwise significant adverse effects might be created on the dam safety.

2.5. Flood mitigation capacity of the Wivenhoe dam

The major objective of incorporating flood mitigation measures into the Wivenhoe dam was to decrease flood hazards in the urban areas of flood plains below the dam [29]. To incorporate this objective, the dam was designed to hold back around two million mega liters of water. The SEQWater [27] agrees that using mitigation facilities within the dam, flood level reduces downstream by an estimated amount of 2m during a large flood event. The flood mitigation capacity of the Wivenhoe dam is a function of the magnitude of the incoming flood event and the volume of flood storage available [31]. This clearly indicates that the larger the flood and closer the storage to full supply level, the less capability there remains to mitigate the flood effects. According to [27], overtopping of the Wivenhoe dam is possible but such an event requires several days of intense rainfall. Due to the nature of central core rock fill type, Wivenhoe dam is not able to resist overtopping phenomena. It is therefore, necessary that the dam should be kept ready for flood operations at all times. Failure to maintain this state of readiness could endanger the integrity of the dam and its ability to control downstream flood releases [30].

2.6. Management procedure of the Wivenhoe dam

Management depends on interdisciplinary science which demands the coordinated approach of all the elements (hardware as well as software) within the system and hence construction and management should go side by side for success of the project [32] i.e. without good management procedure and practices; any excellent construction schemes can lose their performance. The

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overall goal in the Wivenhoe dam management is to provide maximum protection in urbanized areas, minimum disruption to rural industries and minimum impacts to flora and fauna from probable flood water hazards.

Basically, three organizations namely: The Australian Bureau of Meteorology (BOM), SEQWater and local councils play major role in managing the operational procedure of the Wivenhoe dam [33] where an anytime ready 24-hr Flood Operation Centre (FOC) is activated before the flood storage compartment begins to be filled its designed level. The actions to be taken by the FOC is guided in the Flood Mitigation Manual 2009. All the related stakeholders including local councils, provincial government, and emergency services are consulted and communities are notified and warned to apply necessary precautions. On the basis of BOM’s weather forecast and SEQWater’s decision about water releasing from the dam, local councils then coordinate with residents [28]. Thus, it can be seen that the operation of the Wivenhoe dam is managed by multi-sector in a coordinated approach.

2.7. Comparison of rainfall data

Queensland experienced months of wide spread rainfall for months and saw the wettest December on record for 2010 [31]. The tropical cyclone Tasha activated severe monsoon activity in Queensland and led to significant floods in the history of Queensland. The AEP for Wivenhoe Dam average catchment rainfall were between 1 in 100 and 1 in 200 range for duration between 72 hours and 120 hours, derived by reading 72hour and 120 hour maps in conjunction with the skewness map [34]. The rainfall data for the corresponding months of December 2010 and January 2011 is detailed in the Figure 2, based on The Australian BOM (2011).

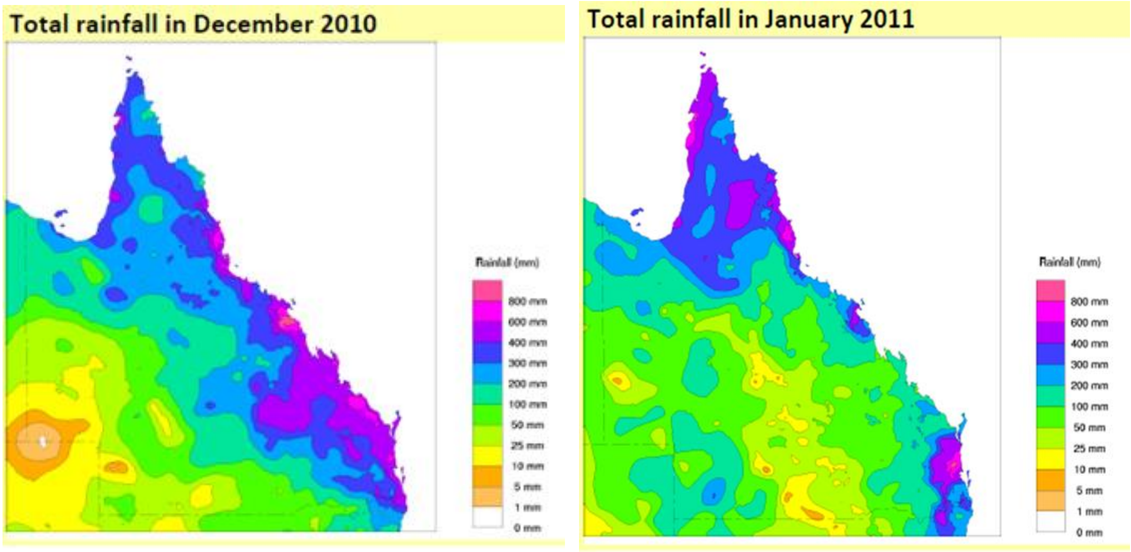

Figure 2. Total rainfall (mm) in Queensland in December 2010 and January 2011

The historical rainfall data for months of December and January was obtained from BOM and is graphically represented below in the Figure 3. Comparing the current rainfall data with the historic data, it could be evaluated that the average monthly rainfall for January 2011 followed the average pattern whereas the average monthly rainfall in December 2010 showed the pattern of a rare rainfall event (223.14 mm) as it exceeds the highest value of 200 mm in 1975.

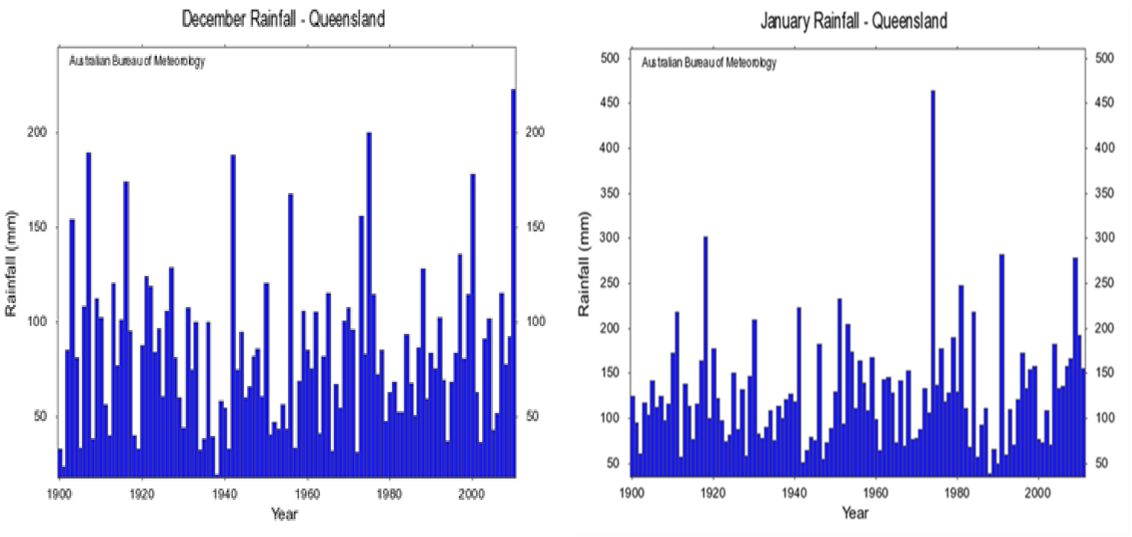

Figure 3. Historical rainfall data for Queensland for the month of December and January

The rainfall intensities varied significantly in the catchment areas above the dam, the AEP of short duration rainfall may be classified as extreme. The Wivenhoe catchment received record highest summer rainfall during 2010-2011 season. The state average rainfall total for this year was 510 mm which was significantly higher the seasonal average of 325 mm. This ranked sixth highest state average seasonal rainfall total on record. The decile rank of total rainfall is represented in the Figure 4.

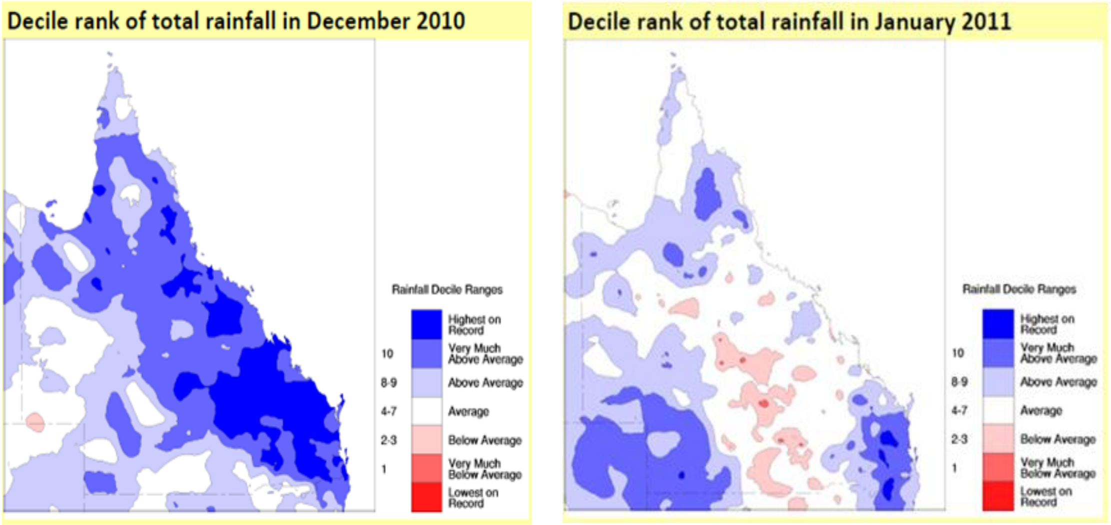

Figure 4. Decile rank of total rainfall in Queensland on December 2010 January 2011

Figure 5 [33] presents a stage hydrograph of the January 2011 flood event showing the relative reduction in downstream flooding depths. From the above statistics it could be clearly stated that during the month of December 2010, almost the entire catchment area of Wivenhoe dam had a rainfall decile range of substantially above average (10) to highest on record especially in the Brisbane river catchment area whereas in January 2011, the rainfall decile ranged between above average (8-9) to very much above average (10) and a small percentage of the catchment got a rare incident rainfall.

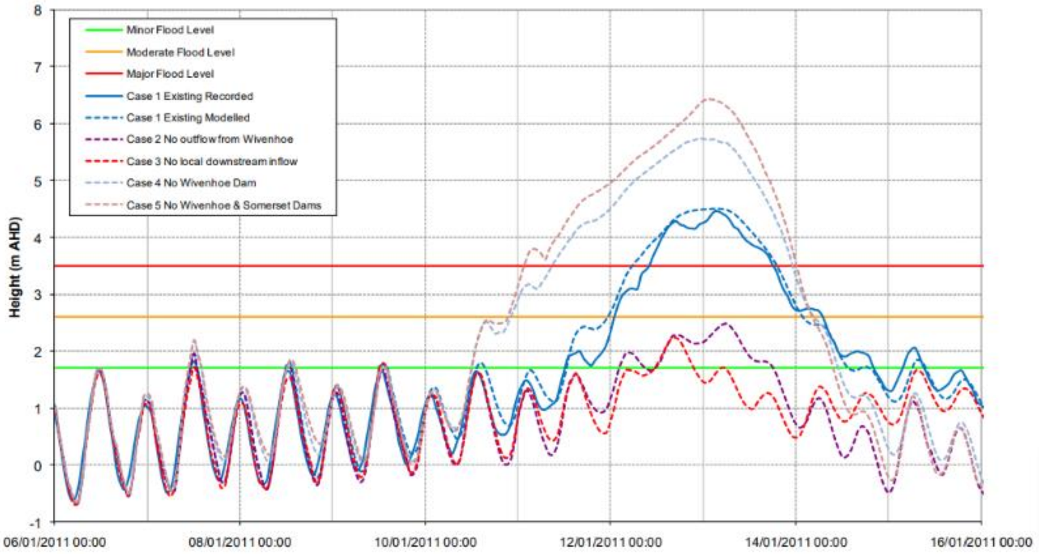

Figure 5. Stage hydrograph of the January 2011 flood event [33]

2.8. Climate change and Brisbane flood 2011

In 2007, Queensland government published the Intergovernmental Panel on Climate Change report to assess the vulnerability of cities locating at developed floodplains facing the threat of extreme rainfall events, particularly under climate change [35]. The report formulated a series of modeling scenarios of greenhouse gas emission as significant references to assist policy makers to set up optimal strategies which manage the adverse effects of climate change. In A1FI (high impact) emissions scenario, introduced by Queensland government to guide policy development, global mean temperature can be foreseen as indicated in the Table 2 during a future century period.

Table 2. Global warming best estimate (and representative ranges) relative to 1990 for selected years for the A1FI scenario

	2030		2050		2070		2100	
A1FI	Best estimate	Representative range	Best estimate	Representative range	Best estimate	Representative range	Best estimate	Representative range
	0.87°C	0.52-1.39°C	1.8°C	1.08-2.88°C	2.9°C	1.74-4.64°C	4.0°C	2.4-6.4°C

(Source: CSIRO`s climate change in Australia report)

According to these predictions, it is apparent that global temperature is increasing at an alarming rate which seems to cause larger weather disasters. Given the A1FI emissions scenario, the best estimate of projected change in annual mean temperatures in Queensland is predicted to rise up to 2.4 °C by 2050, and 3.6 °C by 2070. Furthermore, [36] pointed out that based on Clausius-Clapeyron theory, each 1°C increase in temperature is consistent with approximately 7% increase in water vapor concentration in air. It implies that a warming atmosphere leads to an increased water vapor content in the lower part of the atmosphere which consequently produce higher rainfall intensity. Simultaneously, it is analyzed that global mean perceptible water increases with global mean surface temperature at a rate of approximate 7.5%/K compared with only about 3%/K of global mean precipitation and evaporation increasing rate [37, 38]. The large amount of perceptible water entering surface water systems will contribute to expansion of runoffs and then trigger unpredicted flood event.

According to the records, a large area involving with most of the southeastern Queensland, central New South Wales between Canberra and Dubbo, and a broad region on both sides of the South Australia-Victoria border suffered a range of three to six times of their average rainfall in December [31]. This rainfall event resulted in total inflow of 2,650,000 ML into the Wivenhoe dam which is almost double (190%) the comparable volume of inflow from the massive January 1974 flood event. This unusual event of rainfall which stuck the south eastern Queensland could be attributed to the above climatologically evidences. Increased precipitation as a result of climate change can not only lead to the disaster in land, but also is associated with flooding from sea level rise [35].

2.9. Effectiveness of Wivenhoe dam for flood mitigation measure

The storage behavior of the Wivenhoe dam was modeled by the Works Department of Council based on 96 years of rainfall data for the dam catchment and the modeling determined that the rainfall preceding the 1974 flood was sufficient to fill the dam to spillway level [30]. The study of the council also revealed that the calculated 1 in 100-year design flood of 8,600 m^3/s produced a flood level about one to two m above the existing development control level in the Brisbane river corridor. Additionally, it was concluded that the existing development control levels do not represent the 1 in 100-year flood level. It is interesting in the light of the 2011 flood that the complacency is only related to residents heeding warnings and not to the possibility that the authorities had become complacent about the effectiveness the Wivenhoe dam's flood mitigation measures.

According to [31], no "reasonable discretion" was used to operate the Wivenhoe dam by any other procedure other than those set out in the Manual. Another reason for the improper flood management of the dam might be due to prime focus of the authorities on water storage due to recent long drought rather than flood mitigation. The report also stated that the dam releases which resulted in considerable flooding downstream were delayed as far as possible until the dam safety was at risk. It also described how there were two distinct flood events at the dam during the event, the dam successfully prevented downstream damage but the dam's flood storage compartment was filling quickly. The second flood resulted from an estimated rainfall intensity that could have exceeded an AEP of 1 in 2000. Such an extreme event on or near the dam reduced available flood mitigation options. From the flood mitigation procedures followed by the authorities during the 10th to 15th January 2011 period which corresponded to highest rainfalls in record, the dam to a great extend prevented the extent of damage that would have occurred if it had not been there. However, the question of why more water wasn't released earlier especially in the light of the information available about the strong La Nina and its impact on rainfall remains.

The Mid Brisbane River Irrigators Inc (MBRI) Submission questions if the dam operators did follow any of the manuals for flood operation strategies in the lead up to the major flood [39]. These strategies (W1 to W4) provide directions as to the action that should be taken as the dam level rises above full supply level. On 29th December, the dam was as high as 123% and rose to 188% on 12th January. The MBRI report also states that the worst inundations in the flood were for a period of 12 hours and while lower releases wouldn't have reduced properties being inundated but would have significantly reduced the number of properties affected. However, the

[39] report does present an alternative release strategy which they claim would have been within the upper limits of non-damaging floods downstream and would have avoided the need for the massive high energy and damaging releases that the dam operators were forced to allow to save the dam. A schematic comparing the Wivenhoe dam actual releases with the MBRI proposed alternate release strategy is shown in the Figure 6. Another schematic comparing the actual dam releases and levels with those reflecting the MBRI proposed alternate release strategy is shown in the Figure 7.

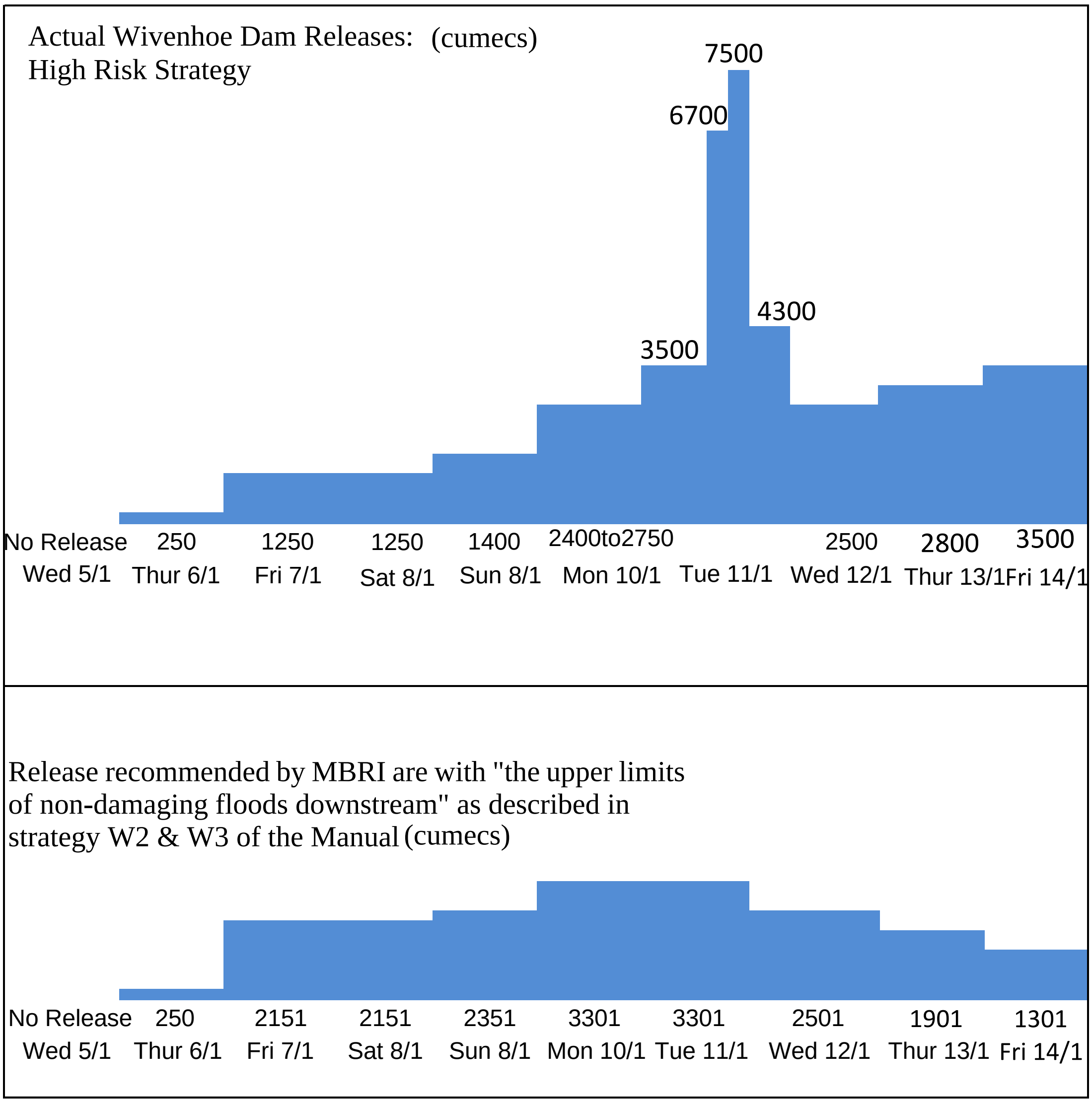

Figure 6. Comparison of the actual dam levels and the alternative releasing strategy (MBRI 2011)

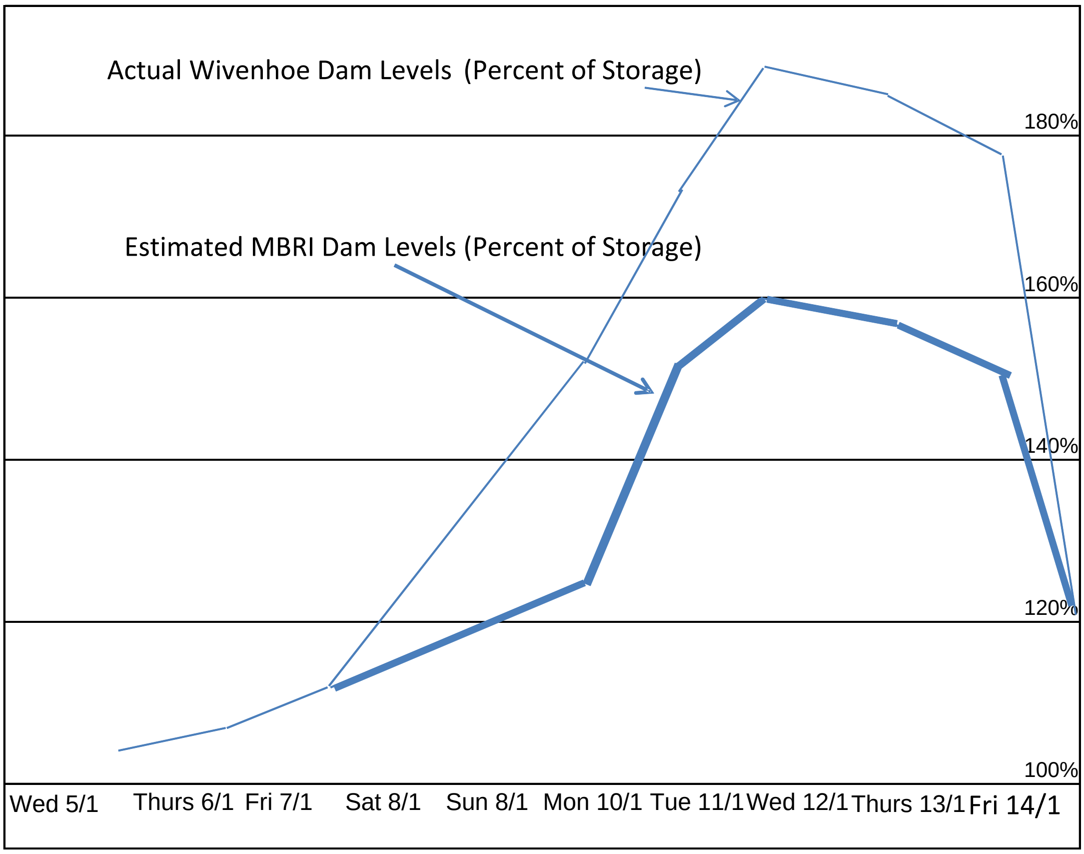

Figure 7. Comparison of the actual dam levels and the alternative releasing strategy (MBRI 2011)

However, a part from the flooding of Brisbane, the massive last minute releases to save the dam also caused environmental damage to the river and along with extensive damage to farms downstream. The MBRI submission claimed that residents along the river consistently reported the most telling comparison between the 1974 flood and 2011 was the velocity of the water. For instance, the fast flowing water of January 2011 wiped out large well-established gum trees that had grown there for many years and which had survived many natural flood events only to be now devastated by a flood in this section of the river created by the need to save a dam.

3. Conclusion

The Wivenhoe experience provides a valuable alert in dam engineering and management. This study reviewed dam failures mechanism and integrated components of the Wivenhoe dam. Based on the discussions in this study and related literatures, it can be concluded that if the implementation of flood mitigation measures developed for a dam built after the 1974 flood caused more damage to even just the large gum trees along the river than any previous floods, then the measures which include the Manual’s FSL are seriously questionable. Perhaps if the FSL was lowered, the Manual’s release strategies would be effective. However, the dam was primary built as a flood mitigation structure and yet more damage has occurred along the river in this flood compared to what is remembered by the locals. This raises a question, were the flood mitigation measures developed with the aim of trying to mimic a natural flood? Maybe they were, but in the end, the releases to save the dam had a greater impact than past floods. Perhaps the mitigation measures are only focused on how a flood impacts on Brisbane, however, if the velocity of the water released was a serious issue up stream, what was the effect of that on Brisbane compared to past floods? While it is difficult to conclude what would have actually happened if the dam operators had released more water earlier, author’s reasoned opinion about the flood mitigation measures used at the time is to ask the question was “reasonable discretion” used during the flood. In the light of the warnings that the dam operators were give even as far back as December 2010 about the strong La Nina, it would seem that operators made sub-optimal decision about water releases and hence “reasonable discretion” wasn’t applied properly. Hence, it can be said that the Brisbane Flood 2011 was a dam release type flood basically related to poor management.

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