

Holistic Dam Operations Assessment for Southeast Queensland

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Many large dams are built as multi-purpose structures, providing both flood mitigation and bulk water storage, but requiring a trade-off in functionality between those purposes. In response to the Millennium Drought (2001 to 2009) closely followed by devastating floods in 2011, the State of Queensland initiated a comprehensive review of the operation of its flood mitigation dams. Part of this study involved development of an Integrated Assessment Methodology to provide an informed and unbiased assessment of the competing factors affecting dam operations. The methodology assessed the primary variables of flood damage and other impacts, future bulk water infrastructure and water security requirements in the form of a net present cost/benefit. The study concluded that modification of the dam flood release strategy to reduce flood damage during large events would come at the expense of increased frequency of minor flooding, or vice versa, with minimal net benefit. Similarly, reducing bulk water storage to increase flood mitigation would increase water supply costs by a similar magnitude to the flood damage prevented.

Keywords: *Flood damage, water supply, water security, net present cost, joint assessment*

Introduction

Flood mitigation or water supply?

Many of Australia's larger dams have been built as multi-purpose structures, providing some degree of flood mitigation together with bulk water storage. Completed in 1985, Wivenhoe Dam on the Brisbane River is a multi-functional dam that is used for the storage and supply of water, for flood mitigation and also as the lower pumping pool for a hydro-electric generation scheme. The policy behind the operation of Wivenhoe Dam involves the balancing of its functions, namely securing water supply and providing flood mitigation for the communities located downstream along the Brisbane River. Wivenhoe Dam is equipped with five radial gates that increase the water storage capacity and which can also be used to release water at set times during flood events, as well as fuse-plug spillways for emergency release of water during extreme flood events.

Southeast Queensland experienced severe and prolonged drought conditions during the period from 2001 to 2009. The Millennium drought, as it became known, was the most severe drought to impact the region in 125 years of record, eclipsing the previous record Federation drought (1900-1903). Wivenhoe Dam levels dropped to 17% capacity by August 2007, during which time severe water restrictions were imposed throughout the regulated supply areas and consumption fell to below 170 L/person/day. The State government implemented several drought contingency measures including the construction of a \$1.8billion desalination plant at Tugun on the Gold Coast (GCDP) and the \$2.1billion Western Corridor Recycled Water Scheme (WCRWS), involving the conveyance of treated wastewater from five existing treatment plants in Brisbane to advanced treatment plants to enable this water to either be used by industrial users such as Swanbank and Tarong power stations or utilised in an indirect potable reuse scheme involving Wivenhoe Dam. The Millennium drought was officially declared over once the combined capacity of Somerset and Wivenhoe Dams reached 60%, which occurred in May 2009 when Somerset dam spilled for the first time since early 2001.

Public and political opinion has a tendency to vary in response to the prevailing circumstance. During a flood event in October 2010, the State opposition called for the floodwaters that were being released from Wivenhoe Dam to be retained and the water storage capacity of Wivenhoe Dam increased by raising the full supply level by 2m. However, all this changed as a result of the 2010-2011 wet-season when six significant rainfall events led to unprecedented flood conditions throughout Queensland. Some 78% of the state was declared a disaster zone and record releases from dams in all regions of the State occurred, especially in Southeast Queensland. The January 2011 flood event led to significant impacts in the cities of Brisbane and Ipswich, with damages estimated to be between \$3.5 and 4.5billion. Following these floods, several parties called for the Wivenhoe full supply level to be lowered from its current capacity to provide additional free volume for flood mitigation.

Making an informed response

The conflicting objectives of water supply and flood mitigation require a balanced assessment in order to make an informed decision rather than a knee-jerk reaction to the latest water crisis. Responding to the devastating floods in January 2011 and subsequent recommendations of the Queensland Floods Commission of Inquiry, the State of Queensland initiated a detailed review of the operation of the flood mitigation dams in southeast Queensland as part of the Wivenhoe and Somerset Dam Optimisation Study (WSDOS) and North Pine Dam Optimisation Study (NPDOS). Seqwater developed a dam operations model to perform stochastic simulations of the Wivenhoe Dam flood operations for thousands of synthetic flood events in order to examine the complex interaction between dam operations, flood release and downstream tributary flows. Additionally, the Integrated Assessment Methodology (IAM) was developed to assess and compare the relative costs and benefits of dam operation or other strategies affecting the southeast Queensland flood mitigation and water supply systems. The primary focus of the project has been the trade-off between flood mitigation and water supply.

Assessment of flood damage is based upon the complex relationship between dam releases, river flow, flood heights, flood frequency and resultant damage sustained in terms of property and infrastructure affected and financial loss. These must be weighed against issues such as potential changes to water supply, drought risk, as well as present and future infrastructure costs. The objective of the integrated assessment was to quantify, compare and report on various operational options for mitigating flood damage to identify preferred options and assist in making trade-offs between the multiple influences on dam operations.

To allow different scenarios to be compared, it is necessary to translate these impacts into a consistent and measureable format. The simplest comparable format is that of a Net Present Cost (NPC), although there are limitations with this approach. For phenomena that are both discrete and random, such as floods, NPC must be presented in the form of average or expected value. The actual cost may however vary significantly depending upon the magnitude of floods that then occur (if any). NPC is only one indicator of the relative benefit of a particular option. Other criteria that may be considered to be important can be identified, but cannot be directly compared unless they can be converted into an equivalent cost.

The total expected Net Present Cost is the accumulated costs that can be directly attributed to, or modified by the scenario or operating strategy. For this study, scenarios were assessed based on their effect on a combination of:

- Flood damage – spatially distributed property damage directly related to inundation during a flood (or water release) event
- Flood impact – impacts associated with loss or disruption of a service due to a flood event
- Serviceability and supply impacts (e.g. water security) – costs directly or indirectly resulting from changes to a flood mitigation or water supply strategy
- Direct infrastructure and other capital costs associated with implementation of a strategy

Since flood damage assessments are always to some degree controversial, this paper focusses on the methodology rather than absolute numbers or specific outcomes. The reader is referred to DEWS (2014) and Aurecon (2014) for more information.

Flood damage and impacts

Types of flood damage

Flood damage is a broad term covering damage and associated impacts to buildings, infrastructure, environment and the community. Tangible damages are those that are materially real and measureable. This may include both direct, physical damages caused by the flood water, and indirect impacts related to the flood event such as emergency response, clean-up, community support and disruption to employment, commerce, tourism or other services. There may also be intangible damages, such as environmental or social impacts, which are much more difficult to quantify and to place a monetary value on.

Damage assessment

When conducting flood damage assessments, greatest focus is generally placed on direct tangible damages as these are the most obvious and easiest to attribute a direct cost relationship. This cost relationship was a key focus, and therefore also a fundamental limitation of the IAM. The IAM reviewed available data, but opportunity for otherwise independent derivation or modification of damage-cost relationships was limited. Primary focus of the assessment was therefore direct tangible damages to buildings (residential and non-residential) and infrastructure (roads, bridges and rail) and indirect tangible damage to roads and bridges, related to clean-up, road closure and repair/reconstruction.

Residential property damage

Residential flood damage is dependent on numerous factors including flood depth, velocity and duration of inundation. However, due to the limited data available most current estimates of property damage are based on peak flood levels, with the other factors assumed to have relatively minor influence on building damages.

A number of Australian studies have developed residential stage-damage functions. One of the consistently referenced works is ANUFLOOD (Greenaway and Smith, 1983). The ANUFLOOD stage-damage curves are only appropriate in gently flowing waters (velocity less than 1 m/s). Dale et al (2004) developed stage-damage functions including velocity, but these have not been widely adopted so far. The Queensland Department of Natural Resources and Mines, in its publication '*Guidance on the Assessment of Tangible Flood Damages*' (DNRM 2002), presented stage-damage based on ANUFLOOD functions for three house sizes. WRM (2006) developed stage-damage functions for Maroochy Shire Council. These were subdivided into three types of damage; external damage (vehicles, fences, sheds etc.), internal damage (contents of main building) and structure damage. These functions were adopted and updated by KBR (2011) for use by Ipswich City Council. For the same council, O2 (2012) recommended a hybrid function between the ANUFLOOD approach and that developed by the NSW Department of Environment, Climate Change and Water (DECCW), which serves as one of the guideline documents for Floodplain Risk Management.

Based on review of the existing damage assessment approaches, the O2 (2012) methodology was adopted for the IAM. Amongst other benefits, the O2 study assessed structural damages based on reconstruction and reparation costs, which leads to higher damage estimates but is considered to provide more reliable results than other available approaches. Like the WRM (2006) approach, the O2 methodology distinguishes external, internal and structural damages. Damage functions were derived for five different housing types:

- Fully detached, single storey (FDSS)
- Fully detached, double (and more) storey (FDDS)
- Fully detached, high set (FDHS)
- Multi-unit, single storey (MUSS)
- Multi-unit, double (and more) storey (MUDS)

Figure 1 shows example stage damage functions for FDHS properties. Note that internal and structural damages are based on depth above floor level whereas external damages are depth above ground level.

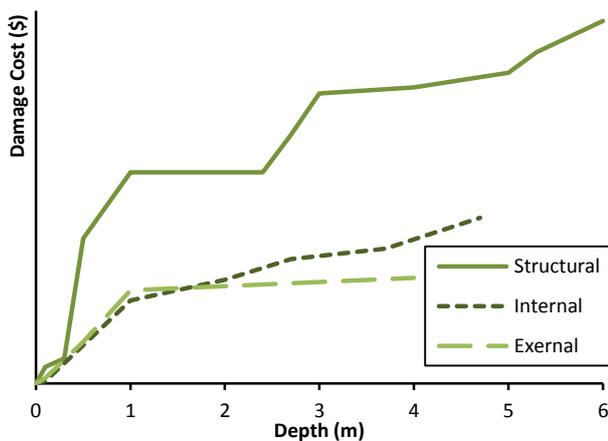


Figure 1 Residential stage-damage functions

Non-residential property damage

The ANUFLOOD study (Greenaway and Smith, 1983) methodology for non-residential properties characterises properties by two aspects - their size and a 'value class'. While the size can be easily assessed by the buildings footprint in GIS, the value of the property is estimated by its main use within five categories ranging from very low to very high value. As opposed to residential buildings, for non-residential properties the assessment does not distinguish between structural, internal and external damages. Instead, the overall damage is directly expressed in the damage function.

The methodology for non-residential building damage developed in the ANUFLOOD (1983) study has subsequently been applied in several flood damage studies, including DNRM (2002), WRM (2006), KBR (2011) and O2 (2012), without major improvements. Due to the absence of other assessment approaches, the ANUFLOOD methodology for non-residential buildings was also adopted for the IAM study. However, the limitations of this methodology are noted both in the IAM and in this paper, and further research into the assessment of non-residential damages is recommended to enable implementation of a state-of-the-art assessment.

Transportation infrastructure damage

Damages to transportation infrastructure such as roads and railway lines can lead to significant consequences not only in the flooded area, but in the whole region or country. The reconstruction and reparation of transportation routes can also take a very long time, especially after major flood events. Consequences of flooding can be direct or indirect, depending on whether or not the damage is caused directly as a result of inundation. Indirect damages are of major interest, as the flooding of roads, railway lines or even airports may lead to considerable economic impact outside the flooded area.

DNRM (2002) identified that the repair of roads and bridges is commonly the largest component of damages to public assets. The amount of damage is a result of flood-related factors and the ability of the road to withstand

flood conditions, and needs to consider both the initial repair costs and the possibility of a significant reduction in the overall life of the road surface. The DNRM method provides typical damage rates per kilometre of road inundated based on studies completed following floods in Victoria, and includes initial repairs and subsequent accelerated deterioration of roads (i.e. reduced pavement life) and initial repairs and subsequent additional maintenance required by bridges.

Direct damage is only one component of transportation infrastructure impact. Rolfe et al. (2011) conducted a comprehensive study on indirect consequences of flooding of transportation infrastructure, identifying that indirect damage may have a significant share of the overall flood damage due to traffic interruption since the flooding can lead to considerable impacts outside the flooded area. Numerous bridges cross the Brisbane River downstream of Wivenhoe Dam. A number of these have relatively low immunity and therefore influence dam operations, with the 'rural' dam operating strategy currently in place to control minor flood releases to minimise disruption to rural life where possible.

Specific flood impacts were assessed for seven low level road bridge crossings of the Brisbane River. These impacts included costs associated with physical closure, cleaning/repair and re-opening of the infrastructure as well as an impact on productivity in the form of a delay cost per vehicle. The impact cost for a flood event is calculated by estimating the number of vehicles impacted by the closure, the average lost time per vehicle due to diversion via alternate routes, and the cost per vehicle hour of delay. Closure times are a function of the flood duration above the bridge deck level, and the time required to close, clean, repair and reopen the bridge prior to and after the flood. Values adopted for the assessment were based on information provided by the Queensland Department of Transport and Main Roads (DTMR), which included experience from the Brisbane River floods of 2011 and 2013.

It is noted that the study only assessed the impact of flooding on the bridges with relatively low immunity. Major bridges in the CBD and suburbs of Brisbane City provide critical infrastructure links across the Brisbane River. These bridges have a high immunity, but closure and even failure may potentially occur during extreme flood events. Consequences of their failure are regional and lie well beyond simply the number of impacted vehicles, however there is currently no available information to predict either when failure may be expected or the regional impacts that such failure may have. Flood impacts related to these bridges were omitted, but considered likely to have minimal relative impact on the study conclusions on the basis that:

- Minor impacts (e.g. bridge closure) are rare, short-term and not significant compared to the other flood damages that would occur during the same event
- Major impacts (e.g. bridge failure) would only be expected during extreme flood events, occurring outside the range where Wivenhoe operations are focussed on flood mitigation rather than dam safety, and thus outside the focus of the WSDOS assessment.

Other flood damage costs and impacts

Residential, non-residential and transport infrastructure represent the three common damage types for which generic flood damage costs studies are available. Damage and impacts were also estimated for infrastructure items specific to the Brisbane River, including ferry services (damage to ferry terminals and disruption to service) and reinstatement of Wivenhoe Dam fuse-plug spillways if triggered by extreme flood events (based on Seqwater cost estimates).

Review of damages attributed to the 2011 and 2013 Brisbane River floods identified a range of other damage costs, including utilities, public assets and infrastructure, clean-up and rehabilitation. A single flood event does not realistically provide sufficient data for a full assessment, so in the absence of other comparable data, these costs were assumed to have a consistent relationship to one of the three common costs to allow the costs to be scaled to events of other magnitude.

Damage assessment methodology

Flood damage, and hence direct costs associated with the flood, is dependent on the severity of a particular flood event. Floods are random events and, while they may satisfy a particular probabilistic distribution, the severity and occurrence of any particular future flood event or events cannot be predicted with any certainty. A simple method for producing a weighted measurement of flood impact (damage, time of closure of a bridge, etc.) is average annual impact, which is the integral of the impact-frequency curve:

$$A = \int_0^1 I(P)P dP \quad (1)$$

where A is the average annual impact and $I(P)$ is the impact of a flood of probability P . Average annual damage can then be converted to a net present cost:

$$NPC = \sum_{i=1}^Y \frac{A}{(1+R)^i} \quad (2)$$

where R is a cash flow discount rate and Y is a financial forecast period. Just as the actual flood damage in a given year may vary significantly from the average, dependent on the flood (if any) that occurs in that year, so too the actual net future cost will depend on the timing and severity of flooding that occurs within the forecast period. The flood damage cost is therefore referred to as an average or Expected NPC.

Calculation of ENPC associated with flooding involves a multi-step process to estimate the damage costs resulting from the full range of flood events from very likely/minor damage to very unlikely/maximum damage, culminating in a probabilistic economic assessment:

STEP 1 Hydrologic assessment to determine flood characteristics (e.g. discharge, duration, tide level) at key points in the system for the complete range of flood events

STEP 2 Hydraulic assessment using the flood characteristics to calculate flood attributes (e.g. water level, velocity, duration of inundation)

STEP 3 Flood damage assessment to quantify the damage and other impacts caused by each flood event

STEP 4 Probabilistic and economic assessments to calculate the AAD and expected NPC

This procedure is straightforward to implement for a small or simple system and can be conducted using design-event type procedures, conducting an independent hydraulic and damage assessment for each flood event. A complex dam-influenced system like the Brisbane River experiences rainfall events with significant variation in spatial and temporal distribution, creating different magnitude and timing of multiple inflows upstream and downstream of the dam that then become interrelated with dam operations. The procedure for calculating NPC is then much more complicated.

WSDOS and the Seqwater Dam Operations model were developed to perform stochastic hydrologic and dam operations modelling to assess the interrelated nature of the Brisbane River tributaries and operation of Wivenhoe and Somerset Dams. To extend this stochastic assessment through Steps 2 and 3, the ENPC calculation would involve the hydraulic simulation and damage assessment of literally thousands of flood events. Although potentially possible for simple (e.g. one-dimensional) models, stochastic simulation of large or complicated hydraulic models is impractical due to the time and storage space required to process such a large number of floods. The process can be simplified by assuming that:

- Flood attributes required for calculating damage (e.g. flood depth or time of inundation) within a defined area can be directly related to one or two key flood attributes (e.g. peak discharge and/or peak or coincident level at a defined point)
- Costs can be directly related to these attributes, and
- The key flood characteristics can be provided directly from the hydrologic model

These assumptions allow Steps 2 and 3 to be conducted independently from the stochastic simulation. The hydraulic and flood damage assessments can thus be conducted for a range of flood events and used to generate rating curves linking the flood characteristic to the resulting damage. Once the flood characteristics for any given flood event are known from the hydrologic modelling, flood impact and damage can be determined directly from the rating curve.

Calculation of damage ratings

In keeping with these assumptions, the Brisbane River floodplain area was divided into sixteen zones controlled by regions of hydraulic influence (e.g. downstream, at, and upstream of each major confluence) and Local Government Authority (for ease of reporting). Individual ratings were developed for each of the zones to allow for different flow conditions occurring within the catchment for any particular event. Spatially distributed flood damages (residential buildings, non-residential buildings and transportation infrastructure) were assessed using an array-based GIS integrated spatial modelling concept utilising a combination of Excel based spreadsheet model input/output and Python based modules. Python is an open source programming language offering scripting

interfaces to various programs such as Microsoft Excel and ArcGIS. It incorporates numerous packages for specific aspects such as the NumPy package for comprehensive analysis of multi-dimensional arrays. The GIS assessment combined spatial information for buildings, roads, railways and other assets (such as size, building type, ground and floor levels) with flood level mapping and the stage damage functions discussed above to determine flood damages for a wide range of flood events, thus generating ratings providing a direct relationship between flood magnitude and damage cost.

Typical damage ratings for a relatively urbanised zone are shown in Figure 2. Transport infrastructure damages tend to initiate earlier than residential and non-residential property damages, but increase at a slower rate. This is consistent with current design standards that typically afford properties a higher immunity than roads, and property damage being a function of inundation area and depth (i.e. event magnitude) while transport infrastructure is proportional to inundated length only. Property damage increases rapidly once that immunity threshold is breached.

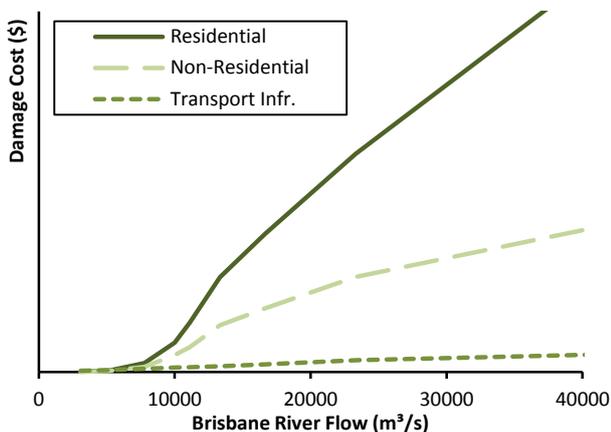


Figure 2 Flow-damage ratings

Flood modelling for the study was based on flood level surfaces from 2009 BCC flood modelling for Brisbane River discharges ranging from 3,000 to 38,000 m³/s. These surfaces were developed using a two-dimensional TUFLOW model but have a limitation that each flood surface produced by the modelling is from a single event linked to a characteristic flow at Brisbane Port Office. While inflows from major tributaries such as Lockyer Creek and Bremer River are included, they cannot be varied independent of the Brisbane River flow. The study therefore identifies changes in areas dominated by Brisbane River flood levels, but may over or underestimate levels in the tributary floodplain depending on the contribution of the tributary relative to the main river. Updated flood modelling will shortly be undertaken as part of the Brisbane River Catchment Flood Study, which is being coordinated by the Department of State Development, Infrastructure and Planning (DSDIP). With sufficient variability in the tributary/river combinations, a multi-dependent damage rating could theoretically be developed to determine a flood surface, and hence damage, resulting from two (or more) characteristic flows or other attributes.

Impact ratings were also determined for each of the seven low-immunity bridges. The impact cost for a flood event is a function of the time of closure and the diversion time, dependent on the availability of alternate routes. As illustrated in Figure 3, this can lead to a multi-stage rating as the likely amount of damage increases while alternate diversion routes also become increasingly affected. Closure times are a function of the flood duration above the bridge deck level, and the time required to close, clean, repair and reopen the bridge prior to and after the flood, making the impact a multi-variate function dependent on both the flood duration above a threshold (time above deck level) and peak flow (damage caused by the event).

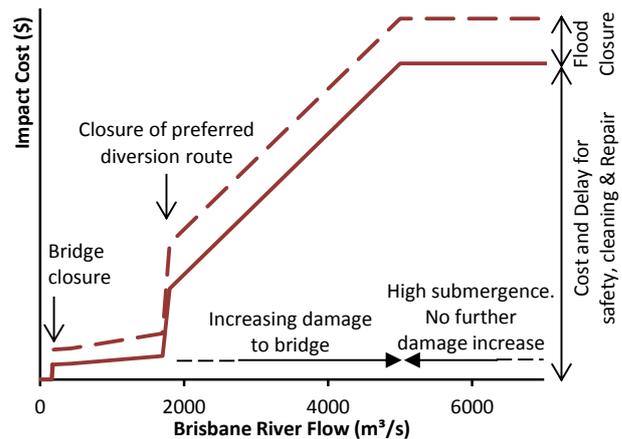


Figure 3 Bridge closure flow-impact ratings

Brisbane River flows and damages

The Integrated Assessment of the Wivenhoe and Somerset Dam operations used flows extracted from the GoldSim-based WSDOS project Dam Optimisation Model developed by Seqwater so as to represent the variability inherent in the Brisbane River catchment and influence of the dam operations. This model was set up to simulate 48 historical rainfall events from the URBS hydrologic model calibration, up to 80 conventional design rainfall events and around 5000 synthetic stochastic rainfall events with rainfall intensity ranging from 2 year to 100,000 year ARI.

The stochastic events were based on analysis of radar imaging of 8 historic Brisbane River catchment floods, reinterpreted to provide 600 different synthetic rainfall event distributions. These synthetic events were developed by the Bureau of Meteorology and SKM and were used to 'stress test' Wivenhoe Dam operations for a wide variability of spatial and temporal distributions and the resulting combinations of dam release with tributary inflow in the river downstream of the dam. Due to this variability, the rainfall probability does not directly correlate to flood discharge probability. Results for each event were accumulated and analysed using the Total Probability Theorem (Nathan & Weinmann 2013) to determine expected probability estimates for the flood frequency curve, and subsequently for the damage frequency curves used to estimate average annual damages.

Notably, the use of the stochastic rainfall events in the hydrologic modelling had not previously been reconciled to other analysis methods. Comparison of the TPT results with current estimates of the flood frequency curve obtained from statistical analysis of historical gauge data identified a discrepancy. For the purposes of this study, this was reconciled by adjusting the probability increments used in the TPT assessment to make the discharge (and consequently damage) consistent with the stream gauge frequency analysis. It is acknowledged that this is an approximation, and usage of the stochastic events and stream gauge flood frequency estimates are both currently being assessed as part of the Brisbane River Catchment Flood Study. Using the simplified damage methodology, flows output from the Seqwater Dam Operations Model at key locations were combined with the damage ratings to calculate damages within each zone for each of the stochastic events. Total Probability Theorem was then used to estimate the damage-frequency curve, which could then be integrated to calculate the average annual damage cost and subsequently the expected net present cost. Figure 4 shows an indicative calculation of residential flood damage, highlighting the significant variation in damage costs possible for different rainfall events of any theoretical magnitude.

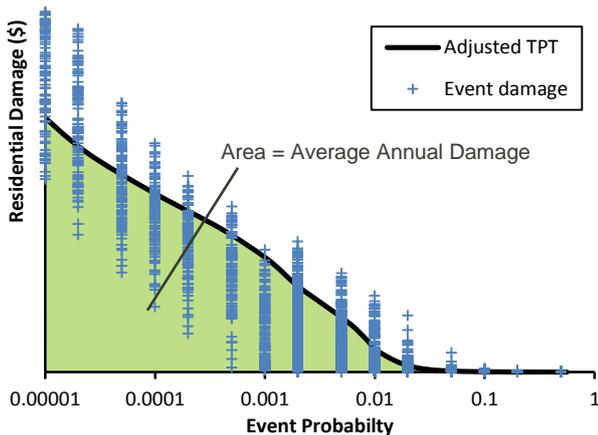


Figure 4 TPT assessment of flood damage

Bulk water supply

Water supply in southeast Queensland is provided by a number of reservoirs, of which the largest are Wivenhoe (1165GL), Somerset (380GL) and North Pine (214GL). Water allocation from the Central Brisbane River Water Supply Scheme including Wivenhoe and Somerset dams is around 279,000 ML/a. Water supply strategy requires the provision of a certain level of service, the ability of the bulk water system to provide water supply and meet community needs, while also having the ability to withstand drought conditions in order to satisfy this criteria with a probability of failure that is acceptably small. Any change to the supply capacity for south-east Queensland therefore affects:

- Bulk water infrastructure – planned infrastructure requirements to provide the required level of service into the future.
- Water security – the robustness of the system to maintain water supply during times of drought.

Bulk Water infrastructure

At the time that the IAM investigation was conducted, southeast Queensland’s bulk water supply strategy was based on a two-stage augmentation of the existing water supply infrastructure with desalination plants rather than construction of additional dams. Costs associated with each augmentation stage include initial construction and ongoing operational costs. These projected costs, illustrated in Figure 5, can be discounted for the decreased current value of future expenditure and accumulated to give a present cost of the proposed future works.

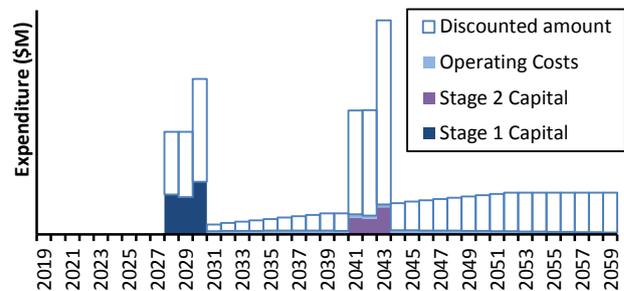


Figure 5 Projected augmentation costs

Changes to the bulk water supply infrastructure affect the water supply capacity, having a flow-on effect on the timing of the proposed augmentation stages. Due to the discount rate applied to future cash flow, short-term works have much greater present value than long-term works, and bring-forward of works increases the effective present cost. The net cost (or benefit) of proposed changes is the difference between the present costs of the modified works and the original base-case strategy. The timing of augmentation stages was assessed by Seqwater for a range of combinations of Wivenhoe and North Pine reservoir levels, resulting in revised augmentation dates for each of the options, which were then used to calculate the net present cost. As shown in Figure 6, moderate reductions in Wivenhoe’s supply volume would result in an approximately linear increase in cost, however reductions greater than 20% begin to have a much more significant impact.

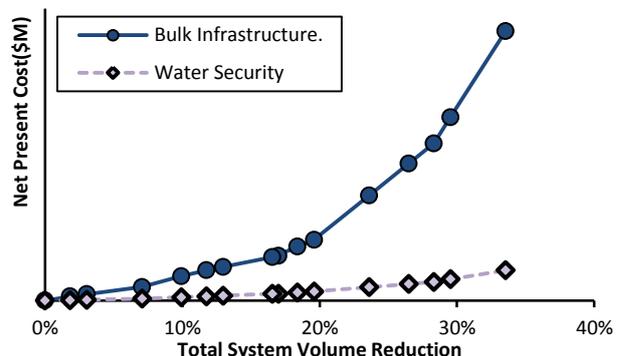


Figure 6 Water infrastructure and security costs

Water Security

The southeast Queensland region depends on bulk water storage, augmented by some manufactured water, to provide water for residential, industrial and agricultural use. A number of water storage thresholds have been identified to ensure reliability of supply, each

accompanied by a triggered response to augment the available water supply. Current strategy is based around three augmentation trigger thresholds (60%, 40% and 30% capacity) that sequentially trigger operation of the Gold Coast Desalination Plant (GCDP) at full capacity, operation of the Western Corridor Recycled Water Scheme (WCRWS) at full capacity, and immediate commencement of construction of drought response infrastructure, assumed to be a new desalination plant

Water security costs were considered to consist of production costs for the drought response manufactured water and any associated infrastructure capital costs. Production costs were based on annual operating costs for the infrastructure provided by Seqwater and assumed that the plant would remain active for two months longer than the average duration that the water level remains below the threshold. New drought response infrastructure is to be constructed when combined capacity falls below 30%. Effective cost of infrastructure is the bring-forward cost of the next planned augmentation (i.e. the difference in present cost between the triggered drought-response construction and the planned construction).

The drought response plan includes imposition of water restrictions when supply levels fall below a trigger threshold, currently set at 40% combined capacity of key water grid storages. There is little available information on the actual costs to the community, industry and government of the imposition of water restrictions as many of these are indirect and potentially intangible, including decreased production, inconvenience and loss of amenity, compliance and enforcement. Studies have indicated that water consumers are willing to pay relatively little to avoid low-level restrictions, but much greater amounts to ensure high-level restrictions are not imposed or are imposed very rarely. It should be noted that willingness-to-pay values are based on public perception of cost and probabilities rather than a technical assessment, and therefore do not necessarily correlate to an actual impact cost. Nevertheless, the public perception of restriction costs is approximately twice the operating costs of the WCRWS and desalination plant.

Water balance modelling was undertaken by Seqwater to determine the cumulative probability of reaching each threshold level. The probability of falling below a threshold (for the first time) was observed to be consistent with a standard Gamma (or Pearson III) distribution. Figure 7 shows the mean time to first falling below each trigger threshold, and demonstrates the significant impact of reducing the reservoir volume, particularly on the first (60%) trigger which falls from 25 years to less than 5 years with a 34% reduction in storage volume. Note that the relationship is not linear as volume reduction also affects the timing of infrastructure augmentation as discussed in the previous section.

The Gamma distribution relationship was used to estimate the probability of reaching a threshold (either for the first or subsequent times) in any year. Net present cost attributable to providing water security could then be calculated as the sum of the present cost of the consequences of reaching a threshold in each year multiplied by the probability of the threshold being

reached in that year. Figure 8 demonstrates the relative contribution of each of the trigger threshold components and the impact of reducing water storage volume. The 60% threshold incurs relatively minor costs (triggered operation GCDP) but is triggered most frequently, and therefore represents the largest single contribution, while the 30% threshold triggering of infrastructure construction is much rarer, but has significant cost implications. Overall however, the water security costs are an order of magnitude smaller than the impact on bulk water infrastructure, shown in Figure 6 above.

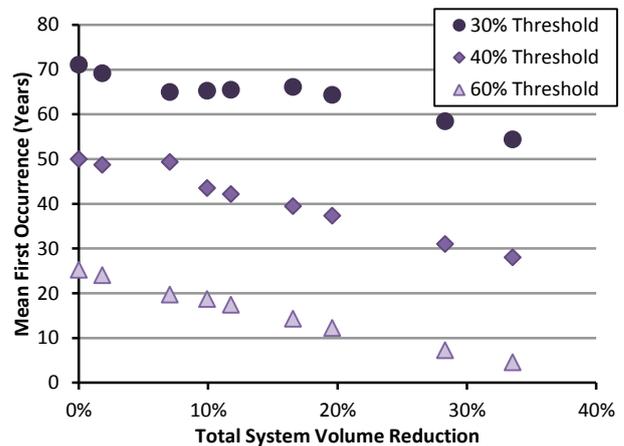


Figure 7 Mean time to fall below trigger threshold

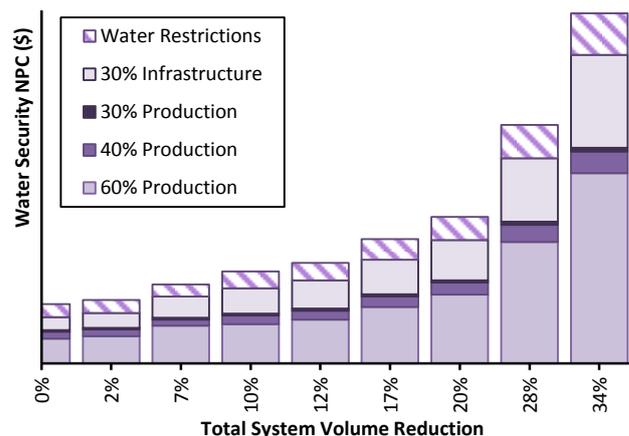


Figure 8 Water security costs

Integrated Assessment results

The integrated assessment combines the flood damages, impacts, bulk water infrastructure and water security costs to allow a balanced examination and comparison of the performance of different operating scenarios. Results for the Brisbane River floodplain downstream of Wivenhoe are shown in Figure 9 for a number of typical scenarios:

- 0 Current operating strategy and full supply volume
- A Alternate operating strategy, with earlier release to provide greater mitigation for larger floods
- 0+L Current operating strategy with moderate lowering of full supply volume
- A+L Alternate operating strategy with moderate lowering of full supply volume
- NP North Pine Dam current strategy (not to scale, shown for comparison only)

Note that these scenarios are provided for discussion purposes and are not intended to represent the final or preferred operating strategies.

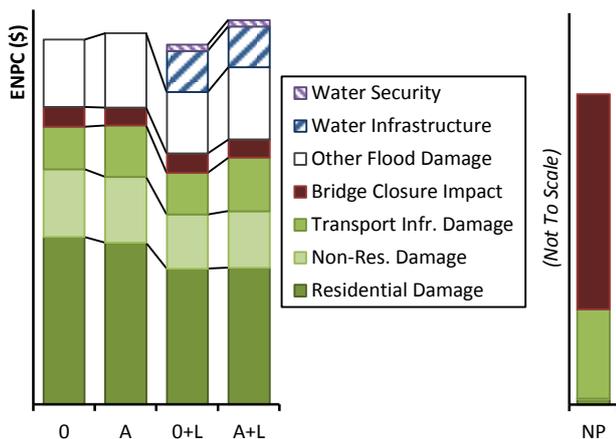


Figure 9 Typical integrated assessment results

Magnitude of cost contributions to total cost

The total expected net present cost is comprised of numerous contributing factors. For the Brisbane River floodplain, which affects the cities of Brisbane and Ipswich as well as a number of smaller rural communities, the largest single contributor is residential property damage. It is nevertheless worth noting that the higher frequency of transport infrastructure inundation still represents a significant contribution (25% to 40% of residential damage) despite having damage costs that are over an order of magnitude smaller during large floods as demonstrated back in Figure 2. Conversely, assessed bridge closure impacts are comparatively small despite having low immunity due to relatively light traffic volumes and availability of alternate routes.

It must be cautioned that the relative contribution of these factors is highly dependent on the location, and the balance could be quite different if any one sub-area was investigated. As an extreme example, the area downstream of North Pine Dam has few flood prone houses but an active and highly flood prone causeway (Young's Crossing). Application of the integrated assessment methodology to the NPDOS project identified very minor property damage, moderate transport infrastructure damage and high traffic interruption costs (note that scale of North Pine results in Figure 9 is intended to highlight relative proportions of each cost component, not the comparative magnitude of North Pine and Wivenhoe costs).

Impact of modifying flood release operations

WSDOS and the IAM were used to investigate a range of alternative operating strategies for Wivenhoe Dam. These strategies control when and how the available flood storage volume is used. A number of the strategies, such as Strategy 'A' shown in Figure 9, modified the release triggers to discharge more flow earlier in a flood event to leave more volume available for later mitigation should the flood grow larger. Alternatively, a strategy could hold back early flood waters, thus potentially minimising the impact if the rain stops, but also consuming storage and thus reducing attenuation if the flood continues to grow.

The overall benefit of any strategy is therefore dependent on whether the potential benefits outweigh the potential costs. The IAM provides a means to conduct a balanced assessment of these costs and benefits. In the provided example, the IAM demonstrates that Strategy 'A' would accomplish the desired objective of reducing property damages (compared to the current operating strategy), which generally occur during moderate to major flood events. The consequence of this strategy, however, would be increased severity and frequency of minor 'rural' releases leading to increased inundation and damage to roads and bridges as well as other impacts (e.g. disruption to ferry services). The IAM indicates that these costs actually outweigh the benefit of reduced property damage, leading to this particular strategy having an overall net cost rather than a benefit.

Impact of modifying dam levels

Modifying dam full supply levels is a highly contentious option for many reasons, including a high degree of (often uninformed) public and political opinion, potential risk (discussed further in Limitations below) and requiring a comparison of elements that are not just dissimilar, but also actively compete against each other.

Lowering the dam level provides additional storage for mitigation without forcing a compromise between how and when flood flows are released. The compromise however comes between availability of mitigation during times of flood and of bulk water during times of drought. The IAM provides a means of weighting and assessing these conflicting issues. The example shown in Figure 9 demonstrates that, with current release strategy, a moderate reduction in Wivenhoe storage volume produces an evident reduction in all forms of flood damage (around 15% for the case shown). However, there is a corresponding increase in bulk infrastructure and security costs. In this case, the cost is of similar order of magnitude to benefit, such that the net benefit of the strategy is in fact less than 1.5%.

As identified in the sections above, the larger the reduction in supply volume, the more rapidly the bulk water costs increase. Therefore a larger reduction in water storage would produce a net cost rather than benefit. The cost reduction resulting from lowering supply volume is also dependent on the dam operating scenario. Operating Scenario 'A' demonstrates less benefit than the current operations for the same reduction in volume, to the point that storage reduction is actually counter-productive. This relationship was also observed for some operating scenarios that did initially reduce total flood damage costs (i.e. adopting the operating scenario would produce a net benefit, but that scenario plus volume reduction would produce a smaller benefit or even a net cost).

Limitations and future work

The Integrated Assessment Methodology has a number of significant limitations. The result is obviously dependent on the quality/reliability of the all the data (rainfall, hydrologic routing, flood modelling, GIS information, stage-damage relationships etc.) and the validity of the simplifying assumptions allowing use of damage ratings

(considered reasonable for much of the main river reaches but uncertain in co-dependent areas such as junctions). Another obvious limitation is that it can only assess and compare things to which a cost can be assigned. Direct tangible damages generally fit well into this category, but intangible damages are much harder to quantify. There are also still a wide range of tangible damages, direct or indirect, for which there are currently insufficient data or understanding to form the necessary defined relationships between flood, cause, impact and cost required for inclusion in cost assessment (e.g. bank slumping, erosion, and flora and fauna impacts).

The IAM is dependent on flows (and other characteristics) produced by the Seqwater WSDOS assessment. This assessment did not consider dam failure, whether as a result of dam overtopping or some other mechanism. The focus of the study was on dam storage and operation strategies affecting rural and urban flood mitigation. During extreme events, the dam operating strategy changes from flood mitigation to dam safety. For most scenarios this strategy remained relatively unchanged, and the probability and consequences of failure should therefore be virtually identical for most of the examined options and thus have little influence on the study conclusions. A limited number of the examined strategies considered raising the dam safety trigger threshold, and it is acknowledged in both the IAM and this paper that a full failure impact assessment would be required to assess the probability and consequences of such a change.

The methodology used for the IAM currently assesses flood damages and impacts for discrete flood events. Despite their rarity, flood events can (and do) occur in close succession. Two of the largest flood events in Brisbane's flood history occurred within 3 weeks of each other on 29 January and 15 February 1893. Although the probabilistic weighting theoretically accounts for this occurrence, the cumulative impacts of successive events are not considered, and costs may be underestimated (e.g. if Wivenhoe's fuse-plug spillways are failed by the first event, limiting the ability of the dam to mitigate even minor follow-up flooding) or overestimated (unrepaired damages would be double-counted). Additionally, the Seqwater stochastic WSDOS assessment (and hence the IAM) currently assumes that the dams are at full supply level for each of the events. This is not necessarily unrealistic, as major flood events are known to usually occur during wet periods and dams are more likely to be at or near full level, however minor events still contribute to the cumulative AAD and NPC. This could tend to overestimate flood damages, and hence the benefit of any flood reduction, thus making the scenario seem more favourable, or bias the damage estimates and perceived cost/benefit of scenarios that preferentially mitigate minor at the expense of major floods or vice versa. Pre-flood conditions such as starting reservoir level and fuse plug condition could be included as variables in the stochastic assessment. The Brisbane River Catchment Flood Study is currently investigating some of these relationships.

Ultimately, any change carries a risk, as whether the next 'crisis' will be flood or drought cannot be reliably predicted. The IAM, which works with averaged values, can identify strategies that should see a benefit on

average, but it cannot guarantee that any benefit will be realised. The cost/benefit analysis may recommend a reduction in dam volume only for the region to head into a prolonged period of drought, or vice versa. The IAM can be used to assess the odds, but not the outcome.

The Bureau of Meteorology publishes short-term rainfall predictions prior to and during storm events and long-term seasonal outlooks based on prevailing climactic conditions. These are highly qualified as estimates and are provided for risk awareness, but currently have no defined place in operational procedures. The use of seasonal outlooks in setting operational strategies (e.g. temporary lowering of supply levels) is intuitively valid but currently unquantified by systematic study. Similarly, a fixed flood release strategy does not achieve the best outcome for all floods, however tailoring of the operating strategy to specific events would require foreknowledge prior to and during the flood event. While short and long-term forecasts are available, in both these cases the uncertainty means that an improved outcome cannot be guaranteed and use could even result in a worse outcome, such as unnecessary downstream flooding, risk to water security, and risk of dam failure. Nevertheless, the use of seasonal outlooks and quantifiable precipitation forecasts for use in the strategic operation of the dams could potentially improve the odds. There is currently no documented evidence to either support or oppose the use of forecast information, although it is understood that this is currently being investigated by Seqwater in association with BoM. The Integrated Assessment Methodology would provide a consistent method for assessing the potential costs and benefits of such strategic operations.

Conclusions

Wivenhoe Dam on the Brisbane River was designed to serve several purposes including the storage and supply of water to southeast Queensland and flood mitigation to protect the cities of Brisbane and Ipswich. A limitation of multi-purpose dams is that they require trade-off between those purposes. In response to the Millennium Drought followed by devastating floods of 2011, the State of Queensland initiated a comprehensive review of the operation of the flood mitigation dams located in southeast Queensland. As part of this work, Aurecon was commissioned to develop an Integrated Assessment Methodology to provide a balanced assessment of various competing factors affecting dam operations in order to make an informed decision. The methodology assessed the primary variables of flood damage and other impacts, future bulk water infrastructure and water security requirements in the form of a net present cost or benefit.

Flood damages and impacts occur in many forms, often categorised into direct or indirect depending on whether the impact is caused directly by the flood water, and tangible or intangible depending on whether the impact is physically 'real'. Direct tangible damages are the easiest to quantify. The three most common types for which accepted generic flood damage relationships are available are residential and non-residential properties and transport infrastructure. Analysis of costs associated with the 2011 and 2013 Brisbane River floods provided limited data for other damage types.

Reduction in dam full supply volume is often suggested as a means for improving mitigation and reducing flood damage costs. The other side of the flood damage versus bulk water supply trade-off is represented by cost of water infrastructure requirements (to provide required level of service into the future) and water security (to withstand periods of drought), which are adversely impacted by reduction in water supply volume. The Integrated Assessment Methodology was used to test a range of scenarios affecting flood operations and supply volume of Wivenhoe Dam by assessing the net impact on these factors.

Changes to the dam flood operations strategy modify how and when flood inflow is released, potentially releasing flows earlier to improve later mitigation of larger floods or withholding flows to mitigate smaller events. In most cases, improving mitigation during larger floods reduces likely property damage, but at the expense of more frequent damage to transportation infrastructure which tends to have lower immunity and be affected by smaller floods (or vice versa). The overall benefit was usually marginal or even a slight cost. Greatest benefit was observed for strategies that increased the dam safety trigger levels (the level at which dam operations switch from flood mitigation to dam safety concerns), thereby reducing flood damage but at increased risk of breaching the fuse-plugs or even failing the dam. The IAM did not fully assess these risks and a full dam safety/failure assessment would be required to quantify the risks and consequences. Reduction in dam full supply volume reduces damage but increases future bulk water infrastructure and water security costs. Minor to moderate reduction could offer some benefit, but again the net benefit tends to be very marginal.

This paper presents a general methodology and possible outcomes rather than specific results. The reader is referred to DEWS (2014) for more specific details. Realistically, any decision to modify dam operating strategy or full supply volume is a gamble as to whether the next crisis will be a minor or major flood or a drought. The IAM provides a means to skew the odds of a successful decision in the decision maker's favour, but cannot guarantee a successful outcome. As an outcome of the WSDOS/IAM assessment, the Queensland government is currently investigating potential locations for new water supply reservoirs to allow Wivenhoe levels to be reduced without the impact on future water infrastructure and security. It is anticipated that a similar holistic approach will assist in the cost-benefit analysis of these options.

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References

- Aurecon Australasia 2014. WSDOS/NPDOS Integrated Assessment – WSDOS Assessment Results. *QLD Department of Energy and Water Supply*
- Dale, K.; Edwards, M.; Middelmann, M.; Zoppou, C. 2004 Structural flood vulnerability and the Australianisation of Black's curves. *Risk 2004 Conference Proceedings*, Risk Engineering Society, Melbourne
- Department of Energy and Water Supply (QLD) 2014 Wivenhoe and Somerset Dams Optimisation Study Report
- Department of Natural Resources and Mines (QLD) 2002. Guidance on the Assessment of Tangible Flood Damages
- Greenaway, M.A.; Smith, D.I. 1983. ANUFLOOD Field Guide. *Centre for Resource and Environmental Studies*, Australian National University, Canberra
- Kellogg Brown & Root 2011. Goodna & Booval Catchments Flood Risk Management Plans Estimation of Flooding Stage-Damage Relationships. *Ipswich City Council*
- Nathan, R.; Weinmann, E. 2013. Monte Carlo Simulation Techniques. Discussion Paper, *Australian Rainfall & Runoff*, Engineers Australia
- Rolfe, J.; Gowen, R.; Kinnear, S.; Flint, N.; Liu, W. 2011. Assessing the regional economic impacts of flood interruption to transport corridors in Rockhampton. *CQ University of Australia*
- O2 Environmental 2012. Rosewood Catchments Flood Study and Flood Risk Management Study, Draft Final Report. *Ipswich City Council*
- WRM Water & Environment 2006. Brisbane Valley Flood Damage minimisation Study – Brisbane City Flood Damage Assessment. *Brisbane City Council - City Design*