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Flood immunity for a road or bridge: what benefits it can bring to road users, road authority and broad community?

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Abstract

Many road sections and bridges in Australia are subject to flooding. The road has to be closed in the event of flooding causing significant delays, disruptions and negative impacts to local economy and community. Typical flood immunity design is to raise a road section or a bridge to a certain height that is immune to a flood in 1 in 10, 20, 50 or 100 year flood intensity. Raising a road section in a floodplain or a bridge over a river is costly as volume of earthwork for embankment may increase exponentially and a higher bridge usually requires larger piers and stronger structure. While cost is high, the benefit is not well understood. There are a number of drawbacks in practical economic evaluations of flood immunity projects. A review of existing evaluations indicates that some evaluations had relied on over-simplified assumptions (e.g. all vehicles were delayed for 2 hours in the event of flooding). In other evaluations, driver behavioural response to a road closure (diversion, waiting or not-travelling) was not analysed. Some evaluations only included diversion costs but omitted the costs incurred by voluntarily and involuntarily trip cancellations. Furthermore, diversion routes for light and heavy vehicles were not appropriately identified for many project evaluations. The key objective of this paper is to provide a practical economic evaluation framework of flood immunity projects that fully accounts for road user costs, road agency costs and local economic impacts. A worked example is provided to demonstrate how the proposed methodology can be used in the economic evaluation of flood immunity options.

1. Introduction

In Australia and NSW, a significant proportion of road sections are subject to flooding. Although flooding is a relatively rare event, its consequences can be severe or sometimes catastrophic in terms of transport outcomes and devastation to the local economy in the short term.

Flood immunity projects aim to eliminate or reduce the duration of road closure caused by flood events. They range from raising bridges, raising road surfaces to improving drainage. Flood immunity projects can be packaged with other engineering options to achieve improved access across the transport network.

In the current practice, economic appraisal of flood immunity initiatives tends to include the net savings of travel time and vehicle operating cost of diverted trips. In most cases, road user costs of voluntarily or forced trip cancellations have not been appropriated assessed. A review of recent economic appraisals of flood immunity projects uncovered a number of methodological drawbacks:

- Road user costs were estimated for those motorists that have chosen a diversion route or waiting. The user costs incurred by not-travelling were ignored.

- Over simplified assumption that resulted in unrealistic estimation. For example, in some economic appraisals, a flat delay was assumed for all vehicles crossing the screen line, regardless a driver diverted, waited or not travelled.
- The diversion routes were not clearly identified and it was often assumed that diversion routes for light and heavy vehicles were the same, ignored heavy vehicle restrictions.
- Historical flooding and road closure data were not collected and used for the analysis.
- Drivers behavioral response when facing a road/bridge closure (i.e. diversion, waiting and not-travelling) has been rarely undertaken in actual project evaluations.

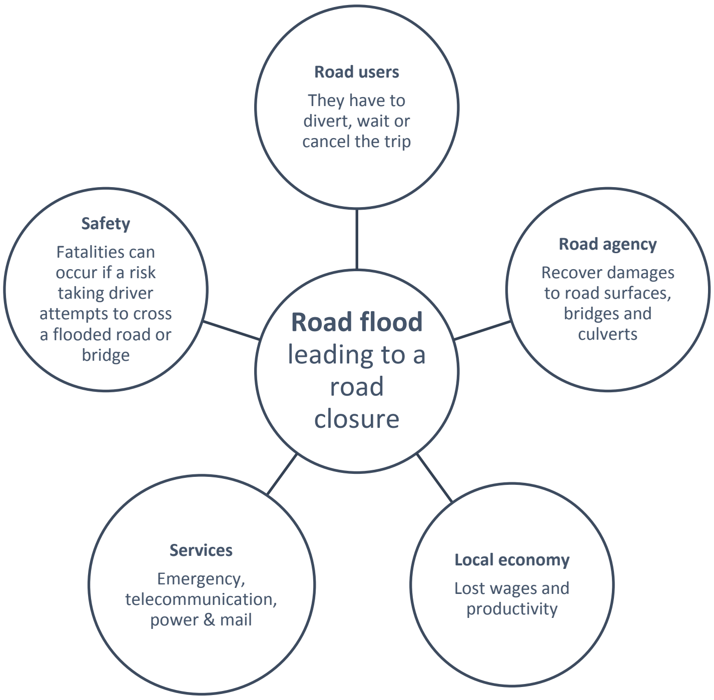
There is a lack of official guidance of the flood immunity evaluations in Australian jurisdictions. The Queensland Transport Guidelines (Queensland TMR 2011) are the only transport CBA guidelines that provide some guidance on flood immunity evaluations.

This paper aims to overcome these drawbacks by providing a framework of economic assessments of flood immunity projects. It provides a method for estimating driver behavioral decisions (diversion, waiting or cancelling the trip) during road closure and estimating associated road user costs. It discusses an Input Output Analysis for quantifying local economic impacts caused by road closure during flood events.

2. Impacts of a flood-oriented road closure

A road closure caused by flooding would affect road users, road agency, emergency services, local economy and safety as illustrated in Figure 1.

Figure 1: Impacts of road flood



Road users:

When a road is closed due to flooding, drivers can have the following choices:

- Divert to alternative routes if alternative routes do exist
- Wait at the closed road section
- Not travel: turn back, cancel the trip or wait at their points of origin

Each option will involve a cost that needs to be estimated in the economic appraisal of flood immunity projects.

Local economy:

Local economy would be affected due to flooding and road closure. General consequences are:

- Lost wages and productivity if people cannot get to work and businesses are encumbered by flooded roads
- Loss of perishable goods in short term
- Loss of economic growth in long term
- Large inventories prepared by households for flooding days

Road agency:

Flooding events can cause a variety of damage to existing infrastructure ranging from washing away of road surfaces to collapsing of bridges. Flood waters may wash away infrastructure such as pavements, culverts, and timber bridges. Rushing water can also undermine foundations of bridges and embankments. Infrastructure repairs would require resource inputs (money and manpower). Repairs to the road could prolong the duration of road closures beyond the time the road was submerged. Flood immunity by upgrading infrastructure that is stronger or is raised above likely flood levels can reduce these costs.

Pavements are particularly susceptible to damage by heavy vehicles after the inundation when insufficient dry-back period has been observed. Potholing and rutting may occur after flooding, requiring urgent repairs to avoid further damage. Drains may need to be cleared. Roadside furniture (signs, guardrails) may have been damaged or washed away. Earth and rocks may need to be moved from roads.

Emergency services:

Road flooding can cut off essential services that result in unavailability of surface evacuation routes. In a project evaluation, it is unlikely sufficient data will exist to determine the probability of an event requiring an evacuation. Air transport could be a possible alternative to diversion, waiting, and not-travelling. However, the use of air transport is likely to be limited and may only be used in the case of emergency evacuations or to deliver essential supplies if stocks have run out. Air evacuations are more costly and less timely than road. Historical data is used to determine the duration of closure that typically requires the delivery of supplies. A flood immunity project would save the costs for emergent evacuations and supply deliveries by air transport.

Drowning fatalities:

Flooding could result in drowning fatalities when a driver attempted to drive cross a flooding road section. Floodwaters can inundate vehicles or even wash them away. A 30 cm of floodwater can be enough for a small passenger vehicle to float (Shand et al. 2011). Moreover, motorists may be unable to judge what lies beneath flooded roadways.

Haynes et al. (2016) used a flood database known as PeriAUS[1] and analysed 2,487 flood events in Australia from 1900 to 2016. Among it, 1,959 flood events had no fatalities while 528 flood events resulted in 1,859 fatalities. On average, each flood caused 0.74 fatalities. Among those 1,859 flood fatalities, 787 people died in attempting to cross bridge, causeway, road or watercourse. The average number of drowning fatalities per flood oriented road closure cannot be directly derived from their study, as the database has no information of road closure. The estimate is also complicated by the possibility that one flood event could

[1] PeriAUS is a flood database which contains historical data on the incidence (magnitude, affected locations, etc.) and consequences (property damage and fatalities, etc.) of natural hazard events in Australia.

result in road closures for several road sections. A rough estimate indicates that the drowning fatality rate was around 0.3 fatalities per flood.

Research indicates that people drown in their vehicle as a result of the vehicle being inundated, being swept away, trying to escape a vehicle by attempting to swim or walk to safety or being thrown from a vehicle (Kellar and Schmidlin 2012). Vehicles could either be willingly driven into floodwaters, entered floodwater without warning, or parked and suddenly surrounded by floodwater (Haynes et al. 2016). Motorists had willingly entered floodwater to reach a destination, to rescue someone, recover something or to evacuate. Reasons for motorist deliberately entering floodwater include: not taking warnings seriously, not understanding the dangers, underestimating the risk, being impatient and thinking that they are invincible. Drivers may develop a false sense of security whilst inside a vehicle and it is possible that motorists may not fully appreciate flood conditions such as the depth and speed of floodwaters, and the influence such conditions may have on safety. The road network flood immunity would reduce the number of drowning fatalities.

3. Road user costs of flooding oriented closure

When a road is closed due to flooding, a driver could face three broad options: diversion, waiting or not-travelling. The estimate of the proportion of behavioral choice is the most difficult part of flood immunity evaluations as there is usually no good data to make a deterministic forecast. The possible behavioral response is presented in Section 3.4.

Once the behavioral response is determined, it is relatively straightforward to estimate the road user costs involved in diversion, waiting or not-travelling.

3.1 Cost of diversion

Appropriate estimation of road user costs of diversion will require the information of distance, road surface condition (e.g. roughness, gradient and curvature), and crash rate of direct and alternative routes for cars and heavy vehicles. Costs of diversion typically include:

- Additional travel time on the longer diversion route, which can be estimated from the diversion route distance and average speed. Value of travel time can be estimated from travel speed, travel time and the standard value of time (VOT) parameters.
- Additional vehicle operating cost (VOC) due to a longer distance. A diversion route would generally be longer and in a lower standard than the direct route. To appropriately assess the additional VOC, information of road condition is needed for both direct and diversion routes. Variables inputting to VOC calculation would include road gradient, curvature, roughness and travel speed. The VOC per kilometer would also increase when travelling on a steeper or a curvier road section. Road roughness in the VOC estimate is defined by the International Roughness Index (Index), which could be used to classify the surface condition to five categories (very poor, poor, fair, good and very good). A poor surface condition would incur a higher VOC on per kilometer basis.
- Potential more road crashes due to longer route or a poorer road condition on diversion road. This would require an estimate of crash rates of the direct and diversion routes, either based on historical crash data, or based on typical crash rates by road stereotypes.
- A higher road externality cost due to longer diversion route or lower fuel efficiency on the diversion route.

Road diversion could happen only if alternative routes were available and drivers were informed with the road closure and alternative diversion routes. The availability of alternative routes is subject to the severity of the flooding and the extent of flooding impacts on the network. Diversion routes may differ depending on the vehicle size due to heavy vehicle restriction on routes and dry-back period. Heavy vehicles have a limited choice due to restrictions on load, height and vehicle size. When a road section is initially closed, information regarding which routes are still viable may not be immediately available causing some delays in travel. These routes may have undergone less safety treatments and may have slower speed limits.

3.2 Cost of waiting

The estimate of road user costs of waiting involves a forecast of number of vehicles choosing the waiting option (Section 3.4) and the average waiting time. Waiting time is dependent on closure time. For cars, only daylight hours should be counted because relatively fewer cars travel at night. For freight vehicles, waiting time may include night hours due to freight operation characteristics. Waiting time generally does not increase proportionately with closure times, as road users may choose the not-travelling option, or utilise the closure time for other personal or productive activities. Waiting time can be estimated from traffic arrival rates and expected closure time.

Most motorists may experience some delays or waiting if they receive the flooding warning prior to their trip. When motorists reached a flooding road and learned the road was closed, they would gather information of likely closure duration and alternative routes. They would then decide their options of waiting for road reopening, diversion or turning back. These drivers may involve an even longer diversion distance as they have to turn back to get onto the diversion route. If the driver received an early warning, waiting time and diversion distance can be reduced.

The value of waiting time can be estimated using the standard values of time (VOT) multiplied by waiting time. Many studies had shown people strongly dislike waiting time, implying that waiting time could be valued higher. For example, waiting time for public transport is usually valued 50% higher than in-vehicle time in public transport project evaluations (TfNSW 2016). For a long hour waiting due to flooding-oriented road closure, a higher VOT may overstate the disutility associated with a waiting time which is not recommended. Value of time of freight vehicle includes the value for crew as well as freight. For perishable freight and livestock, information should be collected on the value of freight and the consequences of a delay time for example loss of value and costs incurred to preserve the freight. In addition, overnight waiting may involve an accommodation cost, which can be added to the perceived waiting cost.

3.3 Cost of not-travelling

A decision of choosing not-travelling option also imposes costs but tend to be omitted in the project evaluation. Cost of not-travelling cannot be directly estimated. An approximate method is proposed using the mid-point of road user costs of travelling on the direct and diversion routes. If there was no flood, all existing trips would occur, suggesting the utility of the trip would be at least equal to or greater than the travel cost on the direct route. The individual has decided not to travel on the diversion route because of additional travel time and costs, suggesting that the utility of the trip is less than the travel cost on the diversion route. A practical approach is to assume a linear distribution of travel costs of the direct and diversion routes. The mid-point is taken to represent the average cost of not-travelling. If the user cost of waiting option has been estimated, the cost of not-travelling can be the midpoint of user costs of the direct route and costs of the waiting option. If both values are available, the lower value should be used for conservative benefit estimation (referring to Section 5.3 for example.) It is acknowledged that the estimation method for non-travelling is an under-developed areas thus further research is needed.

3.4 Driver behavioural choice

One of key inputs to evaluating flood immunity initiatives is the proportion of diversion, waiting or not-travelling when the direct route is closed due to flooding. Behavioral choice model offers a solution in that it is assumed that travellers are rational decision makers and they choose an option that incurs the least cost. Thus, the estimation of the probability of travel behaviour choice will require an understanding of the perceived cost of diversion, waiting and not-travelling. Road users may not have an accurate perception of the costs of diverting and these costs will differ for each road user. Factors affecting the decision making include:

- Availability of a diversion route.
- Road condition of the diversion route: distance, speed limit, surface roughness, gradient, curvature, crash rate and heavy vehicle restrictions.
- Perceived relative costs of diversion, waiting or not-travelling. The perceived costs are different to the resource costs. For waiting option, drivers may perceive the consequence of late arrival, disutility of waiting time and accommodation costs. For diversion option, drivers may perceive additional fuel cost and travel time due to a longer route.
- Flood warning and information of reopening. Roadside warning may affect driver's decision on diversion. Earlier warning can affect driver's decision of postponing the trip. The expected number of days of road closure will also affect the decision.
- Type of commodities of freight vehicles. Perishable goods are more time sensitive and vehicles transporting these goods are more likely to divert.
- Urgency of the trip. Urgent trips are more likely to divert.
- Availability of modal shift. Some freight can be shifted to rail. Passenger travel can be shifted to air. Tourists can change their destination.

Traffic modelling can play a role in determining the proportion of diversion, waiting and not-travelling. In some specific cases, a "dry day" and a "wet day" operational modelling can be developed for simulating route choices when certain road sections are "switched off" in the road network. Traffic modelling is not suitable for estimating "not-travelling" and it has limitations in estimating the likelihood of waiting option and waiting time. Table 1 provides some typical decision making criteria of diversion, waiting or not-travelling. Behavioural choice for "not-travelling" will need based on thoretcical choice model informed by assumed costs of diversion, waiting and not-travel

Table 1: Travel behaviour when facing a flooding oriented road closure and decision factors

	Divert	Wait	Not travel
Private car	If perceived cost is less Perceived cost = Value of private time + perceived VOC	If perceived cost is less Perceived cost = Value of private time + accommodation and other incidental costs	If waiting time > a pre-determined threshold If travel cost on diversion route > a pre-determined threshold
Business car	If perceived cost is less Perceived cost = Value of business time + perceived VOC	If perceived cost is less Perceived cost = Value of business time + accommodation and other incidental costs	If waiting time > a pre-determined threshold
Heavy vehicle	If perceived cost is less Perceived cost = Value of time for crew + value of freight time + perceived VOC	If perceived cost is less Perceived cost = Value of time for crew + value of freight time (in particular perishable goods) + accommodation and other incidental costs	If travel cost on diversion route > a pre-determined threshold

4. Economic analysis of flood immunity initiatives

4.1 Flood data and indicators

The flood immunity evaluation would typically require a flood data of at least 20 years. The data should provide details of the year of road flooding, number of days of road closure, and a broad description of local / regional impacts (if available). An analysis of the flood data is then undertaken to derive the following indicators:

Closure Time

The historical closure data is used to forecast the road closure time in the event of flooding. Total closure time can be observed aftermath however the closure time would be unknown for those waiting motorists. Closure times can be longer for heavy vehicles. Restrictions may be placed on heavy vehicles until the surface has sufficiently dried and the strength of the surface has returned which is known as the dry-back period (QLD TMR 2011).

Average Annual Time of Closure (AATOC)

The AATOC is the average number of hours that a road is closed per year. The AATOC represents the proportion of the year that the given road is closed to traffic. The average is based on the range of time series flood data used. An appropriate number of observations should be obtained in the sample to represent accurate closure averages.

$$AATOC = \frac{(\sum Hours\ Closed)_i}{Years_i}$$

Where,
AATOC – Average Annual Time of Closure
Hours $Closed_i$ = Number of hours closed per flooding event
$Years_i$ = Number of years of flood data evaluated

Using the flood data in the case study (Section 5, Table 4), the road has been closed due to flooding for 960 hours over the last 20 years, which equates to an annual average closure time of 48 hours per year.

Average Duration of Closure (ADC)

The annual duration of closure is calculated as follows:

$$ADC = \frac{(\sum Hours\ Closed)_i}{(\sum No\ of\ Floods)_i}$$

ADC = Average duration of closure
No of Floods = Total number of flood events over evaluation period

The ADC represents the average duration of each flood-oriented road closure. This indicator is useful in deriving the proportion of road users choosing diversion, waiting or not-travelling, and costs incurred by the road users who opted to wait or not travel. Based on the flood data in the case study (Table 4), the road is closed for an average of 160 hours per flooding event.

Average recurrence interval (ARI) and annual exceedance probability (AEP)

The annual recurrence interval (ARI) is the average, or expected, value of the periods between exceedances of a given rainfall total accumulated over a given duration. The annual exceedance probability (AEP) is the probability that a given rainfall total accumulated over a given duration will be exceeded in any one year. AEP is calculated using the following formula.

AEP = 1 - exp(-1/ARI)

Road infrastructure is built to a certain level of flood immunity. For example, a 1 in 10 year flood immunity bridge is expected to be submerged during flood events that are equivalent or more intense than 1 in 10 year flood events. Table 2 gives the different flood intensities, related ARI, AEP, expected days of Bridge closure and the bridge height requirements for flood immunity of the case study described in Section 5.

Table 2: Flood intensity, road closure and immunity requirement

Bridge design standards	ARI	AEP	Days of Bridge Closure in flooding	Bridge height required for flood immunity (m)
Flood intensity - 1 out of 10 years	10	9.5%	3	259.0
Flood intensity - 1 out of 20 years	20	4.9%	7	261.0
Flood intensity - 1 out of 50 years	50	2.0%	14	263.0
Flood intensity - 1 out of 100 years	100	1.0%	20	264.5

Note: Numbers in the table are for illustration purpose only. In particular, the bridge height must be analysed on case by case basis.

4.2 Transport benefits

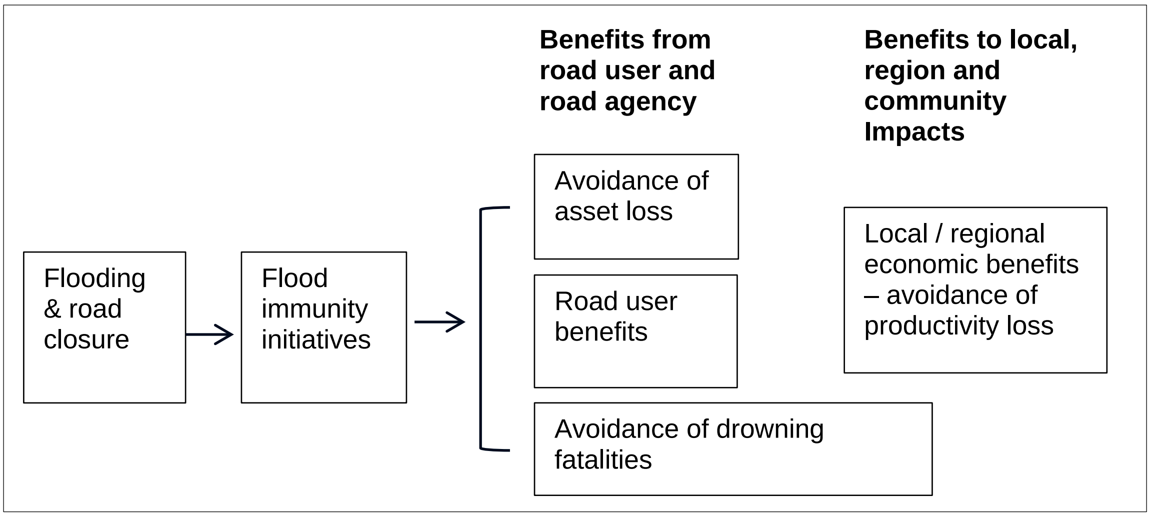
Cost benefit analysis provides an appealing tool for identifying the optimal level of disaster mitigation, resilience and recovery. It compares the mitigation costs and the expected benefits of avoided or reduced natural disaster costs on the probability of event occurrences.

Transport benefits of flood immunity projects include road user benefits and road agency cost savings (in avoidance of asset damage). Flood immunity initiatives aim to reduce the duration of closure caused by flooding events for road section. The following flood immunity design options are available that subject to cost benefit analysis:

- No flood immunity (usually the base case scenario)
- Flood immunity for 1 in 10 year flood
- Flood immunity for 1 in 20 year flood
- Flood immunity for 1 in 50 year flood
- Flood immunity for 1 in 100 year flood

The broad economic benefits of flood immunity initiatives are illustrated in Figure 2. The benefits are generated from road users, road and emergency service agencies and broad communities. The road user and agency benefits are assessed in the Cost Benefit Analysis (CBA) framework, while the local / regional economic impacts are assessed in the Economic Impact Analysis (EIA) framework presented in Section 4.3.

Figure 2: Framework of economic benefit assessment for flood immunity projects



The road user benefits would include:

- Value of Travel Time Savings (VTTS): Travel time savings refer to the difference between the vehicle hours in longer diversion route and the shorter and direct route. The diversion route may have a lower speed limit than the direct route which may

result in additional travel time. The diversion route may get congested when more vehicles are diverted leading to a slower speed.
- Vehicle Operating Cost (VOC) savings: The unit VOC values per vehicle kilometer by light and heavy vehicles should be estimated for the direct route and the diversion route. The estimation should be based on surface roughness, curvature, gradient and estimated travel speed.
- Road safety benefit: The road crash rate should be estimated as the number of crashes per 100 Million Vehicle Kilometre Travelled (MVKT). The longer diversion route and more VKTs would result in, in statistical sense, more road crashes. In addition, crash rate on diversion route may be higher than the direct route. In an economic appraisal, the crash rates should be estimated for the direct and diversion routes from historical crash data over 5 years.
- Environmental externalities: They can be estimated from the VKT and standard externality cost per VKT.
- Waiting time savings: The benefit of avoidance of waiting time is estimated and applied to the standard value of travel time.
- Avoidance of opportunity cost of “not-travelling”: The option of “not-travelling” incurs a cost which should be included as the benefit if avoided in the project case.
- Avoidance of drowning fatalities caused by road flooding.

Agency benefits would include:

- Avoidance of infrastructure damage cost: Historical flood damage data is collected to forecast the road damage cost of future flood events.
- Avoidance of emergency service costs: A flood event may trigger emergency management or evacuation in some extreme circumstances. Air transport may be used for the delivery of supplies if stocks have run out. Emergency services cost can be derived from historical data.

A number of input data sources are required to assess above benefits.

- The minimal 20 year flood data including number of flood events, intensity of flood (one in 10, 20, 50 or 100 year flood), days of road closure, any emergency evacuation, and emergency services delayed by the road closure.
- Drowning fatalities in the road section over 20 years.
- Local and through traffic passing the road section with appropriate breakdown on vehicle type. It is preferable to collecting data on trip purpose, origin and destination, commodity type (in particular time sensitive commodity and perishable goods) of heavy vehicles but normally these details are hard to get. These datasets would be helpful in analysing modal shift, diversion and freight benefits.
- Diversion routes for light and heavy vehicles, in particular any heavy vehicle restrictions.
- Design standards that give information of either 1 in 20, 50 or 100 year flood immunity.
- Infrastructure damage costs of past flood events.
- Flood immunity objectives of the road section, corridor or local network. Specifically, whether the road section requires a 1 in 20, 50 or 100 year flood immunity.

With the appropriate input data, the flood immunity benefit can be estimated in following steps:

- A flood data analysis to estimate the closure time, Average Annual Time of Closure (AATOC), Average Duration of Closure (ADC), number of days closed by the Average Recurrence Intervals (ARI).
- Network analysis to identify the diversion routes for light and heavy vehicles. For each identified diversion route, road Information (crash rate, speed limit, gradient, curvature and road length in KM) is collected.

- Estimate the proportion of diversion, waiting or not-travelling: Firstly, a cost analysis is needed to estimate perceived costs of diversion, waiting or not-travelling. The closure time should be analysed for different flood intensity (1 in 20, 50 and 100 year flood). The proportion of diversion, waiting or not-travelling is then analysed from estimated travel costs of options and closure time.
- Quantify the benefits of flood immunity design options (1 in 20, 50 and 100 year flood immunity standards.)

International evidence suggests that the mitigation measures can bring higher economic benefits than passive disaster recovery expenses. US Federal Emergency Management Agency (Rose et al. 2007) reviewed nearly 5,500 mitigation grants between 1993 and 2003 and found the BCR of mitigation grants ranged from 1.5 to 5.0 and averaged at 4.0 as shown Table 3:

Table 3: The expected Benefit Cost Ratio of Mitigation Grants from literature

Hazard type	Cost ($m)	Benefit ($m)	BCR
Earthquake	947	1,392	1.5
Wind	374	1,468	3.9
Flood	2,217	11,189	5.0
Total	3,538	14,049	4.0

Source: Rose et al. (2007) Benefit-cost analysis of FEMA hazard mitigation grants, Natural Hazards Review, November 2007

The London Office of the Environmental Resources Management cited the evidences from World Bank (Environmental Resources Management 2005). If $40 billion had been invested in physical or engineering type mitigation measures such as adequate design of buildings or bridges, then $280 billion of economic losses worldwide from natural disasters would have been avoided in the 1990s. Furthermore, it is estimated that, in China, the $3.15 billion spent on flood control over the past four decades of the 20th century actually averted losses of about $12 billion. The statistics again indicates the BCR ranging from 3.8 to 7.0.

4.3 Local economic impacts

Local economic benefits of the flood immunity projects are the avoided losses of the Gross Regional Products (GRP) in the affected towns or a region. When an access road was cut off, a town was isolated, and people could not get to work, business and economic activities would slow down or stop. Local economy is affected and the GRP diminished.

Local economic impacts can be assessed within the framework of the Economic Impact Analysis (EIA) which measures the Gross Regional Product (GRP), employment and household income changes due to an economic shock (the road closure due to flooding). Tools used in an EIA ranges from a complex Computable General Equilibrium (CGE) modelling to a simple Input Output (IO) Analysis. A flood immunity initiative generally involves moderate to low costs thus a full CGE model is not warranted. An IO analysis would offer an appropriate approach commensurate with the cost and benefit of flood immunity measures. The inputs to an IO analysis are economic indicators of the locality, namely Gross Regional Product (GRP) by industrial sector, number of road closure days. The IO multipliers that capture initial and flow-on effects can be used to estimate the GRP loss in a flood event of 1 in 20, 50 and 100 year intervals and the annual GRP loss can be estimated.

It is worth noting that economic appraisal of road investment typically considers direct road user and road agency benefits only. The GRP benefits from an IO analysis may not directly enter the Benefit Cost Ratio (BCR) calculation but can be used in sensitivity analyses.

4.4 Broad community impacts

Costs of flooding extend beyond just the road users and road authorities. Closures can result in the loss of access to communities. Prolonged loss of access can lead to shortages in essential provisions and perishables. These impacts have not been included in the proposed assessment framework which is generally referred to an “unquantifiable benefits”.

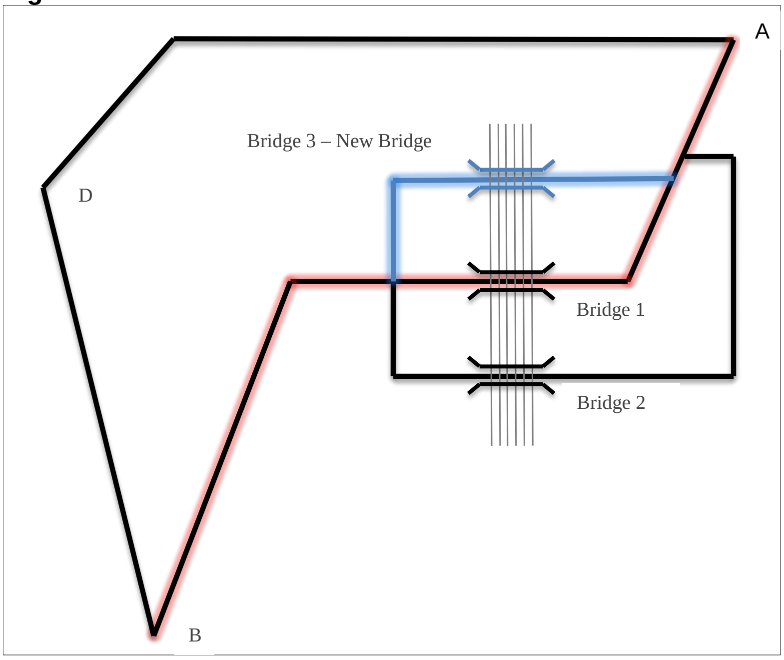
- **Lost value of perishable goods**
  Upgrading transport and road infrastructure aims to reduce indirect damage to perishable goods. Perishables such as fruits may only have a life of a few days. Even short road closures could result in large quantities of fruit not making to market before the expiration. Flooding can cause significant damage to perishable goods either directly by destroying them at farm lands or indirectly from delays in getting them to market. Even the fruit that make it to market maybe of diminished quality. Price adjustments will transfer part of the lost value to the consumer and broad consumer would also suffer. If data regarding the number of vehicles carrying perishables and the average loads of these vehicles are available, costs can be included in the freight component of road user costs. Besides fruit and vegetables, there are other goods that are very time sensitive for example newspapers.
- **Loss of economic growth in long term**
  Communities that are prone to flooding and frequent loss of access may not attract businesses if the closures are deemed a significant disruption to business activities. Loss of business to a community could have a significant flow on effect hindering the long-term growth of an area. Any loss in growth to the affected community is likely to have been passed onto another community. This cost is subjective but could potentially be quite high for a community. Flooding may also affect long-term tourism, property price and population growth.
- **Impact on emergency services**
  Even closures of a short period that result in loss of access could potentially prove to be costly in the event of an emergency. For example, emergency medical treatment may not reach a casualty, thus amplifying the seriousness of the casualty or resulting in fatality. Air evacuations are costly and less timely than access by road. The loss of essential services becomes more serious for long closures as the probability of an incident occurrence increases when the duration without the essential service is prolonged. Placing a monetary value on the loss of essential services is difficult given the low probability that such services will be required and lack of data around such events.
- **The size of inventories**
  Households and businesses in remote areas subject to periodic isolation due to flooding need to hold higher levels of stores of food, household supplies and inventories. A reduction in the frequencies and durations of periods of isolation will reduce the sizes of inventories that need to be held.

5 Worked example

5.1 Project background and problem statement

Road route A to B in Figure 3 is a major arterial road that carries a heavy volume of passenger and freight vehicles. It crosses a large river via Bridge 1 which is subject to flooding. The Bridge 1, which has 4 traffic lanes (in both direction), is submerged in 1 in 10 year flood level and must be closed for a 1 in 10-year or more intense flood. When the Bridge 1 is closed, some traffic is diverted to Bridge 2, which has two lanes. The Bridge 2 is restricted for the PBS 3A vehicles, which must be diverted to a longer route (e.g. route ADB).

Figure 3: Road flood and diversion routes



A new Bridge 3 has been proposed. The objectives of the new Bridge 3 are:

- Improve travel efficiency for local and regional road users through catering for the corridor's mix of vehicles.
- Minimise disruption to road users from road closures, recognising the particular needs of isolated communities and those sections of the route with no alternative access.
- Maintain adequate access for emergency services during major flooding events and natural disasters, supporting the local Emergency Management Plans (EMP).

Broadly speaking, the new Bridge 3 aims to alleviate traffic on existing bridge (travel time, accessibility and congestion reduction) and flood immunity (reduce road closure and emergency vehicle access). The economic appraisal is required to support the Bridge investment decision. The base case of the analysis is the current road network continued. The project case is to construct a new Bridge 3 in one of the following 4 Options:

- Option 1: Flood immunity of 1 in 10 year flood
- Option 2: Flood immunity of 1 in 20 year flood
- Option 3: Flood immunity of 1 in 50 year flood
- Option 4: Flood immunity of 1 in 100 year flood

Table 4: Diversion routes and flood immunity design options

Route	Distance	Heavy vehicle restrictions	Flood immunity standards
AB – Bridge 1 (direct route)	4.5		1 in 5 year flood
AB – Bridge 2 (light vehicle & small truck diversion route)	13	PBS 3A restriction	1 in 50 year flood
ADB (representative PBS 3A diversion routes)	35		1 in 50 year flood
AB – New Bridge 3			
Option 1	4.5		1 in 10 year flood
Option 2	4.5		1 in 20 year flood
Option 3	4.5		1 in 50 year flood
Option 4	4.5		1 in 100 year flood

5.2 Bridge flood historical data and infrastructure cost

In a 20 year period from 1990 to 2010, there were 6 flood events resulting in the closure of the Bridge 1 (see Table 5). In the period of 20 years, the Bridge had been closed for 40 days. Among it, 14 days are attributed to a major flood in 1990 and 13 days are attributed to a major flood in 2010.

Table 5: Bridge closure statistics

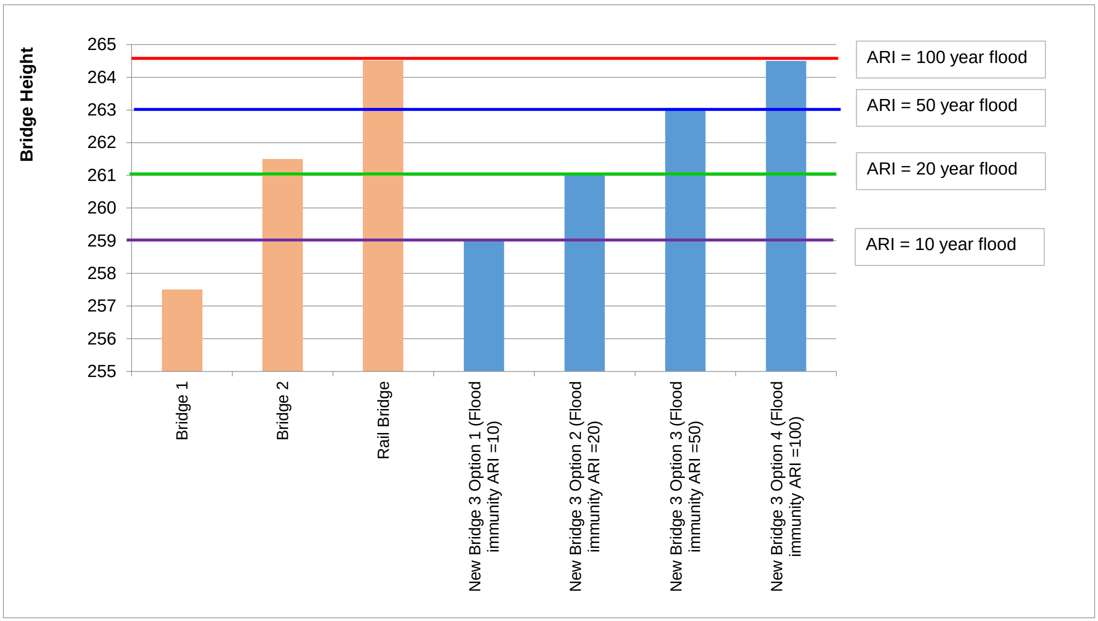
Years	Bridge closure time (days)	Bridge closure time (hours)
1990	4	96
1990	3	72
1990	14	336
1998	2	48
2000	4	96
2010	13	312
Total (20 year period)	40	960

The above flood data enables the calculation of Average Annual Time of Closure (AATOC) and Average Duration of Closure (ADC):

AATOC = 2 days
ADC = 6.7 days

Figure 4 shows the bridge height referring to the Australian Height Datum (AHD). It also shows the flood level at 1 in 10, 20, 50 and 100 year flood intensity. The Bridge 1 would be topped at any 1 in 10, 20, 50 and 100 year flood. Bridge 2 would stand for a 1 in 20 year flood but would also be submerged in a 1 in 50 year flood.

Figure 4: Bridge height and flood immunity design



The proposed Bridge 3 can be raised to a height that would stand for either 1 in 10, 20, 50 or 100 year flood. Typically a higher design standard would mean a higher capital cost.

The capital cost by flood immunity design standards is presented in Table 6. The cost for a higher flood immunity standard is higher. The annual maintenance cost is for the new Bridge which is unchanged by the flood immunity design standards.

Historical data shows there was insignificant infrastructure damage cost to the Bridge 1 due to flood. A small cost of $200k per flood event has been estimated for each flood accounting for minor repairs and for cleaning up after the flood. This is equivalent of $60k per annum. Flood damage cost on Bridge 1 is the same in the base case and the project case. This cost is unavoidable by the construction of the new Bridge 3.

Table 6: Cost and bridge closure by bridge design options

Flood immunity design standards	Capital cost for the new Bridge 3 ($m)	Annual maintenance cost for Bridge 3 ($m)	Annual flood damage cost on Bridge 1 ($m)	Average Annual Time of Closure (AATOC, hours, base case)	Average Annual Time of Closure (AATOC, hours, project case)
No flood immunity (base case)	$200	$0.2	$0.06	48.0	48.0
1 in 10 year flood	$210	$0.2	$0.06	48.0	33.6
1 in 20 year flood	$220	$0.2	$0.06	48.0	19.4
1 in 50 year flood	$230	$0.2	$0.06	48.0	5.0
1 in 100 year flood	$240	$0.2	$0.06	48.0	0

The costs in this table are for illustration only

In the base case, the average expected bridge closure is 48 hours per year, which is reduced to 33.6 hours for 1 in 10 year flood immunity design. This is reduced to 19.4 hours for 1 in 20 year flood immunity design and further reduced to 5 hours in 1 in 50 year flood immunity design. No bridge closure is assumed for 1 in 100 year flood immunity design. The flood immunity benefit is derived from the reduced AATOC resulted from raised bridge height.

5.3 Estimate road user costs

When the Bridge 1 is closed, all users would be affected and would incur a cost regardless their choice for diversion, wait or not travel.

The assessment of user costs on the direct route or on a diversion route is based on route distance, travel speed, road conditions (urbanisation, gradient, curvature and surface roughness) and the expected road crash rates, as summarised in Table 7.

Table 7: Road condition data for assessing road user costs on direct and diversion routes

	Distance (km)	Speed in normal condition	Speed in wet condition or in diversion(km/h)	Travel time (hours)	Road condition	Casualty crash rate (Crashes / 100 MVKT)
Direct route(dry weather) (all vehicles)	4.5	90	70	0.05	Urban	24
Divert for Car and small trucks	13.0	60	40	0.33	Urban	24
Diversion for PBS 3A	105	90	70	1.50	Rural Gradient: 3-4% Curvature: 250 °/km Roughness: IRI = 3-4 (good surface condition)	28

Notes (1) PBS 3A vehicles have vehicle total length between 30 and 36.5 metres; (2) IRI is the International Roughness Index describing road surface condition

Road user costs on direct and diversion routes can be estimated using the standard approach for road project evaluation which covers the following cost items:

- Value of Travel Time Savings (VTTS)
- Vehicle Operating Cost (VOC) savings
- Road crash cost (this should also include any drowning fatalities caused by road flood)
- Road externalities

The estimated road user costs on direct and diversion routes are presented in Table 8. The user costs include VOT, VOC, expected crash costs and environmental externalities. The estimates have been made for the direct route, and the Bridge closure period on a diversion route. The estimates have been made for car, small truck (up to PBS 2B with the vehicle length less than 26m) and PBS 3A vehicles. It shows that the user costs on diversion are significantly higher, due to longer distance and congestion on the diversion road.

Table 8: Estimated road user costs on direct and diversion routes

	Direct route			Wet day on diversion route		
	Car	**Small truck**	**PBS 3A**	**Car**	**Small truck**	**PBS 3A**
VOT	$1.44	$2.65	$3.00	$9.36	$17.23	$30.00
VOC	$1.58	$5.40	$6.75	$5.92	$20.28	$68.25
Crash	$0.37	$0.37	$0.37	$1.08	$1.08	$3.38
Externality	$0.55	$3.03	$3.03	$1.59	$8.75	$12.59
Total	**$3.94**	**$11.45**	**$13.15**	**$17.94**	**$47.33**	**$114.22**

Source: Author's estimate, based on the flood immunity benefit model developed in this study

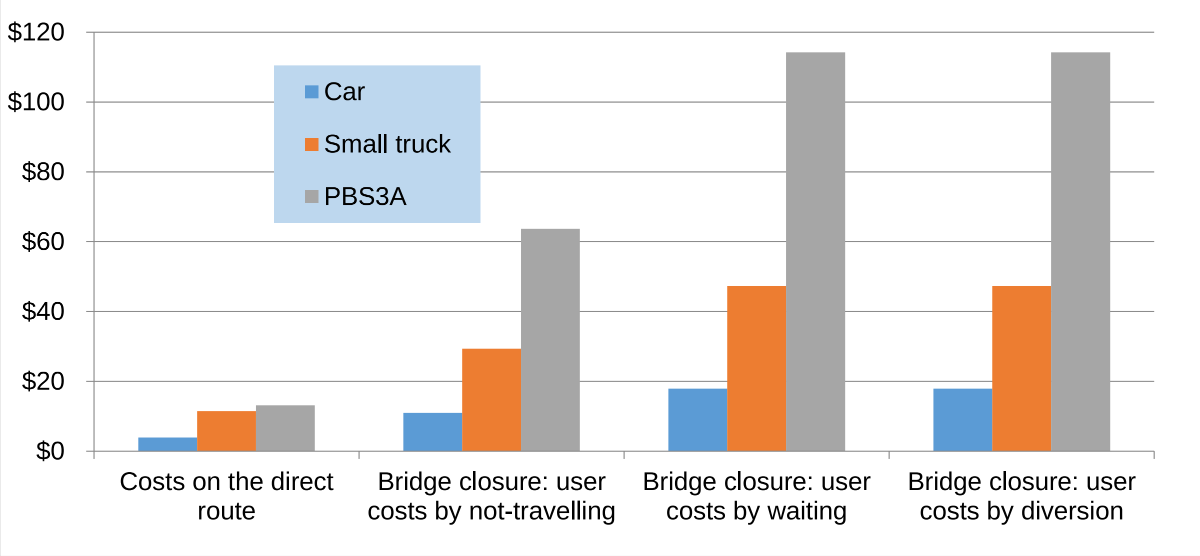
The road user costs for those drivers choosing the waiting option is calculated from the expected waiting time and the Value of Travel Time (VOT). The user costs for drivers choosing not-travelling option can be approximately estimated from user costs on the direct route and the expected costs on the diversion route or costs of waiting:

$$User\ costs\ for\ not\text{–}travelling\ option$$

$$= min\left[\frac{Costs\ on\ direct\ route + Costs\ on\ diversion\ route}{2}, \frac{Costs\ of direct\ route + Costs\ of\ waiting}{2}\right]$$

On a normal day, road users are willing to pay for the travel cost on the direct route, indicating the utility of making the trip is at least at the travel costs on the direct route. When the Bridge 1 is closed, those drivers opt for not-traveling, instead of diversion or waiting, indicating the utility of the trip is less than the travel costs on the diversion route or the cost of waiting. The user costs of not-travelling is estimated at the lower value of the mid-points between the costs of the direct route, costs of the diversion route and costs of waiting. While individual drivers would choose the least cost option, collectively for all drivers, the cost of diversion and waiting can be close.

Figure 5: Road user costs



5.4 Model driver behaviour in the event of flood

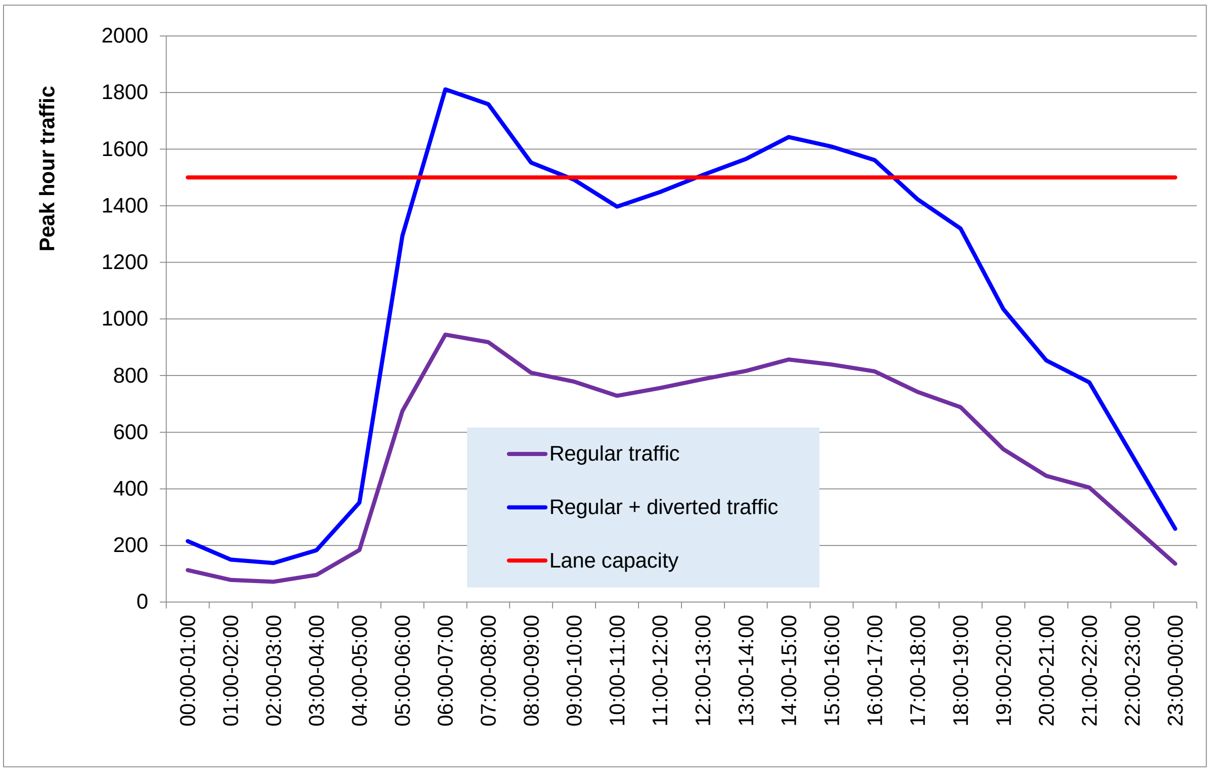
Each day, 39,100 vehicles cross the river screen line. Among it, 53% use Bridge 1, while 47% use Bridge 2. Majority heavy vehicles (74%) use Bridge 1, as Bridge 2 is restricted for up to PBS 2B (less than 26m). The heavy vehicle accounts for 11% of all traffic on Bridge 1, while it only accounts for 4% on Bridge 2. All crossing traffic can be potentially affected by the Bridge 1 closure in an event of flooding.

Table 9: Daily traffic impacted by a Bridge closure

	Direction	Number of traffic lanes	Cars	Trucks	Total
Bridge 1	Eastbound	2	10,500	1,200	11,700
	Westbound	2	7,900	1,100	9,000
	Total		18,400	2,300	20,700
Bridge 2	Eastbound	1	8,000	400	8,400
	Westbound	1	9,600	400	10,000
	Total		17,600	800	18,400
Total river crossing	Eastbound	3	18,500	1,600	20,100
	Westbound	3	17,500	1,500	19,000
	Total		36,000	3,100	39,100

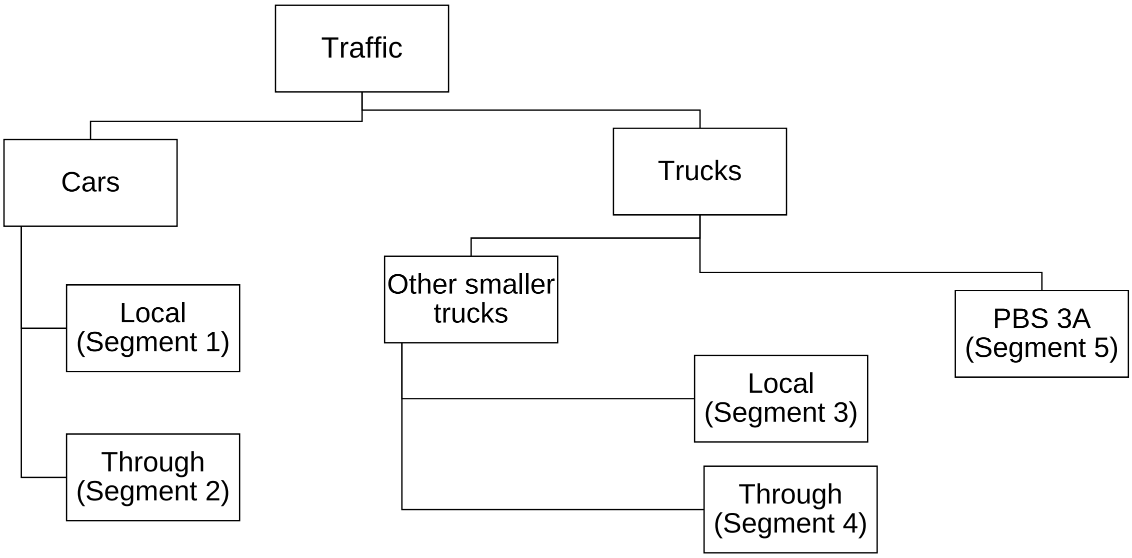
Traffic diversion would cause congestion on Bridge 2. Figure 6 shows that the Bridge 2 is operated under its road capacity in normal days. When the Bridge 1 is closed, and an estimated 44% traffic is diverted to the Bridge 2 (other 56% traffic is assumed being diverted to other longer routes or not travel), the Bridge 2 would be operated over its capacity for AM and PM peaks. The operating capacity is assumed at 1,500 vehicles per lane hour, however, in wet days, the capacity could be lower.

Figure 6: Traffic volume on Bridge 2 (Westbound, 2036)



Driver's behavioral choice of diversion, waiting and not-traveling will depend on many factors. To appropriately model the behavioral choices, we have classified the traffic into the following segments:

Figure 7: Segmentation analysis on driver behavioral choice



Separately estimating the benefits of local traffic and through traffic also provides transparency. When a flood occurred after a trip had already started, it is difficult to re-route or take other option such as "not-travelling". Local traffic tends to make short distance trips thus "not-travelling" option may be readily available. Local drivers are more likely aware of the Bridge closure and other travel alternatives. Through cars, once the trip has started, would more likely divert than turn back. Table 10 provides the estimated proportion of diversion, waiting and not-travelling. For local car, 37% drivers would divert, 60% not travel and the remaining small proportion would wait. For through cars, 59% drivers would divert, 39% not travel and the 3% remaining drivers would wait. The same choices have been estimated for small trucks (up to PBS 2B).

Table 10: Driver behavioral choice

	Local car (Seg 1)	Through car (Seg 2)	Total car	Small trucks (local, short diversion) (Seg 3)	Small trucks (through, re-route) (Seg 4)	PBS 3A, long re-route or diversion (Seg 5)	Total truck	All vehicles
Divert	37%	59%	41%	37%	59%	46%	48%	**42%**
Wait	3%	3%	3%	3%	3%	3%	3%	**3%**
Not travel	60%	39%	56%	60%	39%	51%	49%	**55%**
Daily traffic	14,720	3,680	18,400	345	690	1,265	2,300	**20,700**

Source: Author's estimate, based on the flood immunity benefit model developed in this study

PBS 3A vehicles have to take a longer diversion route but they are more likely to divert. Some freight vehicle may carry perishable goods that a diversion is only feasible option. The estimate of behavioural choice should be informed by traffic origin and destinations by commodity type, as shown in Table 11. Vehicles that carry foods and live animals are more likely to divert, while vehicles carrying less time sensitive goods are more likely to reschedule trips. However, all heavy vehicle trips are less likely to be cancelled entirely.

Table 11: Commodity breakdowns of long haul freight

Road freight	Proportion of commodity carried	Likelihood of divert instead of not make the trip
Food and live animals	13%	More likely
Beverages and tobacco	2%	More likely
Crude materials inedible, except fuels	29%	More likely
Mineral fuels, lubricants and related materials	6%	More likely
Animal and vegetable oils, fats and waxes	1%	More likely
Chemicals and related products, not elsewhere specified	2%	Less likely
Manufactured goods	15%	Less likely
Machinery, transport equipment	5%	Less likely
Miscellaneous manufactured articles	1%	Less likely
Tools of trade	5%	Less likely
Other commodities, not elsewhere specified	20%	Less likely
Unspecified	1%	Unknown

Early warning and a local Transport Management Plan (TMP) for road flooding can affect driver behavioral choices. The impact of delays arising from closure of the Bridge 1 due to flooding can be overestimated if the effects of warning are not appropriately considered. In some cases, several day warning being available prior to any closure being implemented. This would allow HPV vehicles easily re-routing to avoid the flooding bridge, and affected community to be prepared. Providing advance warning of road closure will also reduce vehicle kilometer travelled. Flooding warning can be disseminated via VMS, RMS website, real-time traffic information and directly sent to mobiles. This would allow drivers for re-routing to avoid turn back.

5.5 Economic impact analysis

Road user benefits of flood immunity tend to be small as the Bridge is closed just around 2 days per year on average. However, local economy impact can be significant due to lost productivity during the Bridge closure period. An economic impact analysis (EIA) is used to inform the impacts on local Gross Regional Product (GRP) and provide additional justifications for flood immunity investment.

An input-output (IO) analysis is undertaken to provide a simplified estimate of the cost of flooding to industry operations in the region, should flood immunity improvements not be achieved. The economic impact analysis is a complementary tool to CBA that provides additional information not deliverable by CBA on the macroeconomic and socio-political effects of project implementation.

The IO analysis started from an analysis of local economic indicators. The Bridges 1 and 2 are serving the Town which is a major service centre being strategically located at the junction of a number of regional highways. Being a major regional centre, the Town provides a range of administrative, commercial, retail, health, industrial, entertainment and cultural facilities which service both the Town and the surrounding rural areas. Key sources of GRP and employments are from rental, hiring a real estate services, health care and social assistance and construction, as shown in Appendix 1. Existing population in the Town is 52,000 as at 2018. 23,000 people are employed which generate a Value Added (GRP) of 3.2b. Tourist output was $281k and tourism alone employed 1,500 people.

The direct productivity loss is estimated during the Bridge closure period for those un-made trips. The flow-on effects are estimated by the GRP multipliers[2]. The GRP effects have been modelled for 4 scenarios as shown in Table 12.

Table 12: GRP loss caused by flood events

Flood intensity	Days of the Bridge 1 closure	GRP loss ($m)
Flood event of 1 in 10 year flood intensity	3	$22.41
Flood event of 1 in 20 year flood intensity	7	$52.29
Flood event of 1 in 50 year flood intensity	14	$104.59
Flood event of 1 in 100 year flood intensity	20	$149.41

The economic benefits of implementing flood immunity designs from avoided GRP / productivity loss are presented in Appendix 1 in details.

6. Conclusions

Flood immunity projects generate benefits to road users, agencies, local economy and broad community. The road user and agency benefits can be assessed in the framework of Cost Benefit Analysis, while local economic impact can be assessed in the framework of Economic Impact Analysis. Impacts on broad community are difficult to measure which should be usually categorised as “unquantifiable benefits”.

Historical flood data is used to inform the closure time, asset damage, drowning fatalities (if any) and how these negative impacts could be avoided by flood immunity options and engineering designs. Higher flood immunity standards would incur a higher capital cost and a higher benefit. The economic analysis would inform the optimal level of investment by maximising the net benefit.

[2] The analysis included multipliers for direct and indirect effects (which is known as Type I multipliers) but excluded any induced effects (which is known as Type II multipliers)

Most important analysis in flood immunity evaluations is an assessment of driver behavioral choice of diversion, waiting and not-travelling. While a choice model based on rational decision-making assumption offers a solution, it is not likely that information is available for building such a model. Practical assessment is based on an assessment of perceived cost of each option, expected closure time, heavy vehicle restriction, availability of flood warning and feasibility of modal shift. A traffic modelling could assist the assessment.

The case study indicates that only a small amount of road user benefits can be realised for the proposed bridge flood immunity (Table 13). The additional capital costs for providing the required flood immunity standards would be much higher. For the proposed Bridge 3, additional road user benefits from no flood immunity to 1 in 50 year flood immunity standard over 30 year period is $8.2m only (present value using 7% discount rate).

Table 13: Road user benefits and avoided GRP loss by flood immunity options

Flood immunity standard	Flood immunity benefit - road user ($m, PV over 30 years using 7% discount rate)	Benefit - Local economic ($m, PV over 30 years using 7% discount rate)
1 in 10 year flood	$2.8	$27.8
1 in 20 year flood	$5.5	$60.3
1 in 50 year flood	$8.2	$86.2
1 in 100 year flood	$9.2	$104.8

This means the project would not likely be justifiable from road user benefits. However, a sizeable benefit of $86.2m (1 in 50 year flood immunity) for local economy in terms of avoidance of productivity loss can be realised. This benefit is conventionally not included in BCR calculation of road projects however it could be included in the sensitivity analysis.

Acknowledgement

The views expressed in this paper are those solely of the author and need not reflect the views of Roads and Maritime Services NSW.

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Appendix 1: Table Input output analysis

Industry sector	GRP ($m)	Proportion of not be able to make trip in the flood event	GRP Multiplier	GRP Loss of 1 in 10 year flood ($m)	GRP Loss of 1 in 20 year flood ($m)	GRP Loss of 1 in 50 year flood ($m)	GRP Loss of 1 in 100 year flood ($m)	Flood immunity benefit (1 in 10 year immunity design) ($m)	Flood immunity benefit (1 in 20 year immunity design) ($m)	Flood immunity benefit (1 in 50 year immunity design) ($m)	Flood immunity benefit (1 in 100 year immunity design) ($m)
Rental, Hiring & Real Estate Services	$465	55%	1.33	$2.80	$6.53	$13.07	$18.67	$0.28	$0.61	$0.87	$1.05
Health Care & Social Assistance	$350	55%	1.24	$1.95	$4.56	$9.12	$13.03	$0.20	$0.42	$0.61	$0.74
Construction	$330	55%	2.21	$3.30	$7.69	$15.38	$21.97	$0.33	$0.71	$1.02	$1.24
Public Administration & Safety	$230	55%	1.44	$1.49	$3.48	$6.96	$9.94	$0.15	$0.32	$0.46	$0.56
Education & Training	$225	55%	1.18	$1.20	$2.80	$5.60	$8.00	$0.12	$0.26	$0.37	$0.45
Manufacturing	$190	55%	2.03	$1.74	$4.07	$8.14	$11.63	$0.17	$0.38	$0.54	$0.66
Financial & Insurance Services	$190	55%	1.23	$1.06	$2.47	$4.94	$7.06	$0.11	$0.23	$0.33	$0.40
Retail Trade	$185	55%	1.41	$1.18	$2.75	$5.49	$7.84	$0.12	$0.25	$0.36	$0.44
Wholesale Trade	$145	55%	1.56	$1.02	$2.39	$4.77	$6.82	$0.10	$0.22	$0.32	$0.39
Agriculture, Forestry & Fishing	$140	55%	1.76	$1.12	$2.60	$5.21	$7.44	$0.11	$0.24	$0.35	$0.42
Electricity, Gas, Water & Waste Services	$140	55%	1.78	$1.12	$2.62	$5.25	$7.49	$0.11	$0.24	$0.35	$0.42
Professional, Scientific & Technical Services	$130	55%	1.64	$0.96	$2.25	$4.50	$6.43	$0.10	$0.21	$0.30	$0.36
Transport, Postal & Warehousing	$125	55%	1.66	$0.94	$2.18	$4.37	$6.24	$0.09	$0.20	$0.29	$0.35
Accommodation & Food Services	$115	55%	1.53	$0.80	$1.86	$3.72	$5.31	$0.08	$0.17	$0.25	$0.30
Administrative & Support Services	$85	55%	1.51	$0.58	$1.36	$2.71	$3.87	$0.06	$0.13	$0.18	$0.22
Other Services	$85	55%	1.43	$0.55	$1.28	$2.56	$3.66	$0.05	$0.12	$0.17	$0.21
Information Media & Telecommunications	$50	55%	1.49	$0.34	$0.78	$1.57	$2.24	$0.03	$0.07	$0.10	$0.13
Arts & Recreation Services	$25	55%	1.78	$0.20	$0.47	$0.94	$1.34	$0.02	$0.04	$0.06	$0.08
Mining	$10	55%	1.32	$0.06	$0.14	$0.28	$0.40	$0.01	$0.01	$0.02	$0.02
Total GRP effects	**$3,215**			**$22.41**	**$52.29**	**$104.59**	**$149.41**	**$2.24**	**$4.86**	**$6.95**	**$8.44**
GRP effects over 30 years (PV)								**$27.81**	**$60.26**	**$86.21**	**$104.76**