A framework for considering externalities in urban water asset management
David Marlow, Leonie Pearson, Darla Hatton MacDonald, Stuart Whitten and Stewart Burn

ABSTRACT
Urban communities rely on a complex network of infrastructure assets to connect them to water resources. There is considerable capital investment required to maintain, upgrade and extend this infrastructure. As the remit of a water utility is broader than just financial considerations, infrastructure investment decisions must be made in light of environmental and societal issues. One way of facilitating this is to integrate consideration of externalities into decision making processes. This paper considers the concept of externalities from an asset management perspective. A case study is provided to show the practical implications to a water utility and asset managers. A framework for the inclusion of externalities in asset management decision making is also presented. The potential for application of the framework is highlighted through a brief consideration of its key elements.

Key words | externalities, risk assessment, sustainability, utility management

INTRODUCTION
Urban communities rely on a complex network of assets to connect them to water resources. Traditionally, provision of this infrastructure has been dominated by a focus on water quality and supply (Erbe et al. 2002). More recently, water has been treated as a scarce resource that requires management of both supply and demand issues (Rauch et al. 2005). While such approaches are important from the perspective of broader sustainability goals (Pearson et al. 2010), their development is often taking place against a historical backdrop of underinvestment. For example, in the USA it has been estimated that there is a potential 20-year funding gap for drinking water capital, operations and maintenance ranging from US$45 billion to US$267 billion, depending on spending levels and revenue growth (EPA 2002). Recent infrastructure studies have confirmed that there is widespread deterioration of water and wastewater systems (ASCE 2009).

Underinvestment in infrastructure is important from a societal perspective because, by definition, it must eventually lead to increases in asset and/or service failures, especially under extreme operating conditions caused by weather events like storms, drought or severe winters. This last circumstance was evidenced in December 2010, when c. 40,000 people in Northern Ireland were without water for as long as 11 days due to widespread pipe failures following a severe freeze-thaw event (BBC 2010). In general terms, widespread or frequent failures result in a decrease in the quality, quantity or reliability of water and wastewater services provided at various scales, and corresponding increases in social and commercial disruption and health and/or environmental impacts. Environmental impacts can be direct, such as in the case of pollution incidents, or indirect, such as increased demand due to excessive system leakage.

In the parlance of economics, asset and related service failures impose welfare costs that are both unconsented and uncompensated. Such costs are referred to as ‘externalities’. Externalities are created when a legitimate action taken by economic agents creates impacts on third parties, and the cost (or benefits) of these impacts are not factored into the decisions of the those directly involved in the transactions (Gardner et al. 2006; Hatton MacDonald et al. 2010). Externalities can be either positive (e.g. improved biodiversity, recreation opportunities and visual amenity) or negative (e.g. environmental impacts and social disruption). The benchmark for defining what is negative or positive...
depends upon definitions of rights and expectations (Young 2000). Often the status quo is chosen, so positive externalities can, for example, include curtailment of polluting activities.

As a fugitive resource, any use of water generates a range of externalities (Rogers et al. 1998), so the literature generally focuses on issues from the perspective of extraction of water and disposal of wastewater (e.g. Hatton MacDonald & Proctor 2008). Less attention has been given to the role externalities play in asset management, though there are relevant insights to be gleaned from the literature relating to cost-benefit analysis (e.g. Ofwat 2007; Hanley & Barbier 2009; UKWIR 2010). Examples of work that has considered externalities specifically in relation to asset management include the treatment of strategic analysis of investment within the privatized sector of England and Wales (Skipworth et al. 2002; Kapelan et al. 2010). Asset management frameworks are, however, influenced by governance regimes, political constraints and ownership models, and to some extent thus vary from country to country. Furthermore, while strategic analysis is important, there is still a need to consider the justification of specific investment decisions. Further consideration of this subject area is thus warranted.

As part of broader research to link asset management principles and sustainability concepts (Marlow et al. 2010a), this paper addresses externalities from an asset management perspective, showing how a utility can consider externalities by undertaking risk–cost–benefit analysis. Specific focus is given to investment decisions relating to individual assets, and a case study of a pipe replacement is presented to highlight the challenges involved. In particular, it is shown that, even when utilities attempt to integrate explicit consideration of externalities into investment decisions, a lack of rigor presents conceptual and practical issues. As such, a framework for considering externalities is proposed, along with insights into aspects of its application.

RESEARCH CONTEXT: ASSET MANAGEMENT DECISION MAKING

Urban water infrastructure delivers a range of services to communities and the environment that have societal value and are paid for through water bills and/or taxes. Changes in the structure, type, function and management of this infrastructure influence both the cost of service provision and the value generated. Investment in infrastructure should ideally be assessed in this context, which requires analysis of cost and benefits at various spatial and temporal scales, including at the strategic and tactical level. If social or environmental externality costs are not considered in this analysis, then investment decisions may not be efficient when considered from the perspective of the community (Burn et al. 2007). Consideration of externalities can change the type of service provision strategy (e.g. decentralised solutions), the management strategy adopted (e.g. level of maintenance), the type of intervention selected (e.g. renovation or replacement) or the type of incentive to stimulate a response (e.g. pricing mechanisms). The overarching asset management policy of a utility is thus dependent on how externalities are treated.

Linking externalities with risk concepts

Some externalities associated with urban water are controlled through regulatory mechanisms; i.e. by setting required service levels or discharge consents, underpinned by systems of regulatory fines. Within asset management, utilities can also consider such issues from the perspective of risk. Risk is defined as the product of failure probability and consequence (WERF 2009). From a theoretical perspective, risk, \( R(x, t) \), probability, \( P(x, t) \) and consequence of failure \( C(x, t) \) are all random variables that vary both in space \( (x) \) and time \( (t) \). Conceptually then, risk is defined as:

\[
R(x, t) = P(x, t) \cdot C(x, t)
\]

Externalities are relevant to the consideration of failure consequences, which vary depending upon the specific operational context of assets (e.g. Val & Stewart 2005).

In practice, utilities take a more pragmatic view than is implied by (1), and often attempt to characterise risk by considering the potential magnitude of some abstract failure event that represents a ‘worse-realistic case’ (WERF 2009). This approach allows a utility to manage risk across a broad range of assets, by indicating where a proactive management strategy should be adopted (Burn et al. 2007). The policy of identifying and proactively managing ‘critical assets’ is a standard practice in many utilities. As assets age, however, there is a need to determine the timing of replacement, which is an aspect of tactical analysis. Ideally, a utility will then assess the economic time for asset replacement with appropriate consideration being given to uncertainty and risk. To illustrate the issues involved, it is useful to consider a specific example, so the next section
presents a case study of analysis relating to a large diameter (≥300 mm) pressure pipe.

**TACTICAL ANALYSIS: A CASE STUDY**

Management of large diameter pressure pipes is challenging because their failure can result in significant impacts (Gaewski & Blaha 2007). Furthermore, the rate of deterioration varies along each pipeline and across the system, which means that age alone is a poor predictor of asset structural condition. Assessing pipe condition is expensive given the assets are buried and the general uncertainty with respect to deterioration. With these challenges in mind, related management approaches applied in Australia have been investigated using a case study approach (Marlow et al. 2010b). One case study considered the replacement of approximately 2.5 km of 250 mm/300 mm diameter cast iron pipe, which was thought to be in poor structural condition. The pipe ran along a busy street, passing through an iconic shopping area, which meant that a catastrophic failure of the asset had the potential for imposing significant externalities associated with social disruption. These circumstances led the utility to commission analysis to predict the remaining economic life of the pipe. This analysis involved the development of a physical probabilistic model that considered deterioration, structural capacity and imposed loads (Moglia et al. 2008), which was then used to develop an economic model (Davis & Marlow 2008), as described below.

**Economic modelling approach**

The benefits associated with the service provision capacity of both the old and new pipe were assumed to be the same and thus not considered in the economic analysis. However, pipe replacement was considered to accrue additional benefits associated with the avoidance of future failures. This is illustrated in Figure 1, which shows a timeline from the current time (t) to some future time (TMAX) when the asset would be considered derelict and have to be replaced (i.e. end of physical life is reached at TMAX). At any time between these extremes, the asset could be replaced through a scheduled intervention.

As shown in Figure 1, replacing an asset at any time later than t implies that the cost associated with potential failures (the star shapes in Figure 1, which represent probabilistic rather than actual failures) would be incurred up until the time of replacement (time t). In contrast, replacing the asset earlier than TMAX means that costs associated with potential failures occurring after the replacement will be avoided. Within this framework, the optimum time to replace the pipe was taken as the time at which the Net Present Value (NPV) was a maximum. Other economic criteria could, however, be used if required, including minimizing investment costs subject to constraints or maximizing benefits subject to cost or other constraints (Jeuland 2010). In application, future monetary flows were discounted by factor \((1 + d)^{-t}\) where \(t\) is the time (in years) from the present, and the net present value (NPV) of intervention calculated as:

\[
NPV = NPV_{\text{Benefit}} - NPV_{\text{Cost}}
\]  

In order to apply equation (2), the costs and benefits of intervention needed to be estimated. The total costs associated with the intervention were considered to be the sum of two components: the costs of pipe failure \((C^F)\) up to intervention at time \(t\) and the cost of intervention \((C^I)\) at time \(t\). As pipe failure is a stochastic process, the expected failure cost (or risk cost) EFC was estimated by:

\[
EFC(t) = nh(t)C^F(t)
\]  

where \(h(t)\) is the hazard function (on a yearly time scale) and \(n\) is the number of individual pipe segments along the pipeline (Davis & Marlow 2008). The hazard function \(h(t)\) was derived through the application of the physical probabilistic model and represents the probability of imminent pipe failure at time \(t\). The failure costs \(C^F\) included the direct costs born by the utility in reacting to the failure, and indirect and externality costs such as customer disruption and social disruption. With these assumptions, the costs associated with an intervention at time \(t\) were...
expressed as:

\[
\text{NPV}_{\text{Costs}} = \sum_{t=0}^{T-1} [nh(\tau_0 + t)C^F(\tau_0 + t)(1 + d)^{-t}] + C^I(\tau_0 + T)(1 + d)^{-T} \quad (4)
\]

The first term in (4) represents the discounted failure costs summed between the current age of the pipe (\(\tau_0\)) and the scheduled intervention time \(T\). The second term represents the discounted cost of intervention at time \(T\). Similarly, the benefits of intervention are given by:

\[
\text{NPV}_{\text{Benefits}} = \sum_{t=T}^{T_{\text{MAX}}-\tau_0} [nh(\tau_0 + t)C^F(\tau_0 + t)(1 + d)^{-t}] \quad (5)
\]

where \(T_{\text{MAX}}\) is the upper limit on the physical lifetime of the pipe. As this model involves imposed and avoided social costs, it reflects consideration of both positive and negative externalities.

As the benefits of asset replacement are associated with avoided failures, the analysis is highly sensitive to how failure consequences are estimated. In particular, inclusion of any significant negative externalities in the analysis brings the time of the intervention forward. In this case, the utility determined that disruption to transport and related social disruption were the key externalities, and based the calculation of externality costs using the figures shown in Table 1. With these assumptions, the externality costs per burst were estimated at US$121,620 for bursts occurring on or near an intersection. These figures justified immediate replacement of the pipe. For reference, the cost of pipe replacement was around US$4,000 per metre, so the overall replacement cost \(C^I\) was approximately US$10 million.

While the values shown in Table 1 are those used in the business case, sensitivity analysis carried out as part of this research showed that, depending on the monetary value placed on externalities, the timing ranged from ‘replace now’ to ‘replace in 57 years’. The later was the replacement time if only internal costs born by the utility (e.g. reactive maintenance costs) were considered; i.e. assuming externalities had no value.

### Understanding the decision making process

To investigate the decision further, semi-structured interviews were undertaken with 11 individuals involved in the decision to replace the pipe, three of whom developed the business case (Marlow et al. 2010c). These individuals indicated that the values used to represent externality costs (shown in Table 1) were selected somewhat arbitrarily and in light of their perception of risk. This perception was informed by knowledge of pipeline management issues, along with their assessment of the potential for community outrage and impacts on the utility’s reputation in the event of a catastrophic failure. Through the interview process, it was clear that the values placed against externalities were, to some extent at least, selected to justify immediate replacement. However, it was also noted that if rigorous and defensible analysis had shown that the appropriate management decision was ‘deferral’ this decision might have been taken.

While it may appear that in the case of such like-for-like replacements the issue is merely a matter of timing, in reality the time value of money generates opportunity costs, i.e. the use of the money and resources precludes the possibility of employing them elsewhere, which implies the community must sacrifice some other goods or services. Such issues can be significant. Consider, for example, if the pipeline was replaced 15 years earlier than its true economic replacement time. Assuming a discount rate of 7% (the rate applied by the case study utility), then the NPV of \(C^I\) at 15 years would be 36% of the present day cost.

### Implications

The case study highlights that decision makers can value externalities solely within the context of business drivers, interpreted with respect to their own perception of and attitude to risk. Under such conditions, decision makers may be willing to pay more to avoid generating a given externality
than would be justified from a societal perspective. As the cost of avoiding externalities is funded by communities, and the expenditure represents an opportunity cost, their value should ideally be assessed from the perspective of society, which requires the application of more rigorous economic assessments. More usually, externalities are not considered or considered only implicitly in the pragmatic risk-based approaches used to determine management strategy, as described previously. In either case, stronger guidance on how to consider externalities in decision making would facilitate ‘risk appropriate’ decisions to be made. With this in mind, a framework for considering externalities in asset management decisions was developed. The key driver for implementing such a framework is that either under or over emphasis on externalities generates either welfare or opportunity costs that have societal significance.

**A FRAMEWORK FOR CONSIDERING EXTERNALITIES**

The challenge for considering externalities in asset management is that the specific context of each decision or policy is important. Furthermore, the transaction costs of analysis must be considered in light of the relative magnitude of the externalities involved. A framework is thus needed that guides a utility to determine whether or not a sophisticated approach to externality assessment is required. The five step approach shown in Table 2 will facilitate this decision.

The first step is to set boundaries that constrain the extent of what is being considered. This is again context-specific and depends upon the focus and purpose of the analysis. For example, strategic analysis undertaken by utilities does not usually consider broader economic externalities such as the generation of jobs or flow-on cost and benefits to other sectors, as these are beyond the scope of a utility’s responsibilities. From a broader economic perspective, however, factors such as the impact of urban water on agricultural and industrial productivity and vice versa are important when setting overall policy, and may be considered in pricing of water services (e.g. Rogers et al. 2009).

Once the boundaries have been set, the process of identifying externalities is in many respects analogous to the

<table>
<thead>
<tr>
<th>Step</th>
<th>Critical Issues</th>
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</table>
| 1. Pragmatic scoping | Water utilities should first consider:  
• Which impacts to include?  
• Are these impacts really externalities?  
• Are they likely to have a negligible impact in the context of the decision?  
• Is there an economic/affordable option available that does not impose a specific and significant negative externality? |
| 2. Define externalities for consideration |  
• Clarify the link between the urban water asset and people, which in turn generates indirect impacts on ecosystem functions and human wellbeing  
• Identify who is affected in the transaction, i.e. the ‘others’  
• Identify if positive (i.e. provide a benefit to others) or negative (i.e. create a cost to others) externality  
• Identify what ‘value’ is appropriate for inclusion, i.e. financial, costs and benefits or welfare  
• Determine specific boundary conditions that relate to: people, environment, governance, time, space, measurement unit and event |
| 3. Quantifying impacts |  
• Identify the physical magnitude of each externality  
• Determine who is affected  
• Determine what magnitude of physical impact is expected  
• Determine what direction (positive or negative) of physical impact is expected |
| 4. Value externalities |  
• Determine the preferred and pragmatic method and data for value estimation, e.g. market price, surrogate markets, survey based and benefit transfer  
• Undertake analysis |
| 5. Evaluation |  
• Determine appropriateness of valuation to current decisions and context (socio-political, management and environmental); and  
• Undertake sensitivity analysis to assess the robustness of available and feasible interventions across a range of externality values |
identification of risks in a risk assessment. A decision has to be made as to what is significant, but no approach can guarantee all relevant issues are captured. Previous experience and knowledge are a useful starting point, and systematic techniques such as Delphi studies and focus panels can also help (Marlow & Burn 2009). The application of qualitative ranking approaches will facilitate assessments of whether more detailed studies are necessary. For example, Table 3 presents a summary of potential externalities that could be considered by utilities in their analysis, categorised in terms of the type of externality and the different components of the overall urban water system. An attempt has been made to indicate if the externality is likely to be significant.

Once significant externalities have been identified, there is then a need to quantify impacts, in other words to determine the magnitude of the externalities under consideration. From the perspective of existing assets, this is part of failure consequence analysis, which can be carried out at various levels of quantification (WERF 2009). At one extreme, analysis is based upon expert opinion alone. At the other, quantitative (cause-effect; dose-response type) models are used to predict the magnitude of the impacts.

The magnitude of externalities associated with infrastructure are generally related to the frequency and extent of failures, including the length of time over which service is lost, as well as the socio-economic and environmental characteristics of the area impacted. For example, the magnitude of traffic disruption associated with pipe failures is related to the length of time it takes the utility to undertake emergency repairs, the timing of the disruption and the number of vehicles affected, which in turn depends on the type of road (Speers et al. 2002). Similarly, the impact of effluent spills on a river depends on the length of time

<table>
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<tr>
<th>Category</th>
<th>Externality</th>
<th>Abstraction</th>
<th>Water treatment</th>
<th>Water supply</th>
<th>Sewerage</th>
<th>Sewage treatment</th>
<th>Effluent disposal</th>
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<tbody>
<tr>
<td>Pollution</td>
<td>Air quality impact</td>
<td>x</td>
<td>m</td>
<td>x</td>
<td>m</td>
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<td></td>
<td>Land contamination</td>
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<td></td>
<td>Groundwater contamination</td>
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<td>Greenhouse gas emission</td>
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<td>River/stream water quality impact</td>
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<td>Sediment contamination</td>
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<td></td>
<td>Bathing beach impact</td>
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<tr>
<td>Environmental impacts</td>
<td>Habitat loss/generation</td>
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<td></td>
<td>Biodiversity impacts (terrestrial)</td>
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<td>Biodiversity impacts (riverine)</td>
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<td>Biodiversity impacts (estuarine)</td>
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<td>Biodiversity impacts (marine)</td>
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<td>Disruption to heritage sites</td>
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<td>Loss of archaeological value</td>
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<tr>
<td>Public Health and Safety</td>
<td>Health impacts</td>
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<td>Safety impact</td>
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<td>Social disruption</td>
<td>Road/pavement damage</td>
<td>x</td>
<td>x</td>
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<td></td>
<td>Domestic disruption</td>
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<td>x</td>
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<td>Noise nuisance</td>
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<td>Odour nuisance</td>
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<td></td>
<td>Congestion</td>
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<td>Rail/tram disruption</td>
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<td></td>
<td>Aesthetic/amenity impacts</td>
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<td>Recreational impacts</td>
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<tr>
<td>Noncompensated financial loss</td>
<td>Opportunity cost of water</td>
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<td>Opportunity cost of wastewater</td>
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<td>Opportunity cost of land</td>
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<td></td>
<td>Property damage</td>
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<td></td>
<td>Impact on property value</td>
<td>m</td>
<td>m</td>
<td>S</td>
<td>S</td>
<td>S</td>
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</tbody>
</table>

KEY: m: minor impact possible; short term, generally local spatial extent; S: significant impact possible; and x: externality not normally relevant.
over which the discharge occurs, the nature of the effluent, the physical characteristics of the flow (e.g. dilution) and the ecological status of the river.

Assessing the magnitude of impacts provides a measure of the extent of externalities. The remaining challenge is to place a value on the externalities under consideration. There is a range of economic techniques available, the application of which depends on whether the externality is tangible or intangible. In particular, four applied methods can be used: market price, surrogate market, survey-based and benefit transfer approaches, as described in Hanley & Barbier (2009). Of these approaches, benefit transfer is particularly attractive, as it involves the use of results from one or more applied studies in another valuation study, thus avoiding the need for primary research. Usually, this is undertaken by reviewing published studies to identify whether estimates can be applied to a different location. If conditions are suitable, then benefit transfer can be carried out using a variety of methods (Johnston et al. 2005). It should be noted, however, that benefit transfer can be subject to large error and thus its use is open to significant challenge.

CONCLUSIONS

Decisions relating to urban water asset management have direct and indirect impacts on water resources and communities, including imposition of opportunity costs and externalities, including imposition of opportunity costs and externalities. Through these mechanisms, poorly conceived replacement and renovation programs can impose significant welfare costs on society and lead to an economically inefficient use of resources. As such, it is important for utilities to target and time investment so as to minimise impacts and maximise the value delivered to communities and the environment. To this end, this paper has considered the role externalities play in such decisions. A framework for integrating consideration of externalities is presented. The key driver for using the framework is that under or over emphasis on externalities generates either welfare or opportunity costs of societal significance.

The case study presented highlights that the value placed on externalities can, in practice, reflect a utility’s ‘willingness to pay’ to avoid negative impacts on stakeholder relationships. From a community perspective, however, externalities are associated with welfare change (generally a loss) associated with the actions of a water utility. The value placed on an externality from this perspective is a true economic consideration; it is concerned with both the degree of change and the value placed on that change by society. This perspective assumes that there is a ‘social license to operate’ which establishes community expectations and requirements. The community then considers any deviation from these expectations to be an externality.

If analysis can be undertaken to represent externalities consistently, utilities will be able to provide economic justification to stakeholders that takes into account the broader impact of their activities. This situation could increase the level of investment made in renewals, and may be sufficient to shift investment to a different class of assets (for example, from end of pipe to decentralised sewage treatment). Consistency in the treatment of externalities can only be achieved if appropriate guidelines are set and used. The research detailed in this paper has been undertaken to help address this issue, but a great deal of further work is required, including the application of the framework to a range of investment decisions at different scales, the integration of concepts into management tools and the development of guidelines. Ideally, a database of values would also be built up that is of immediate relevance to urban water utilities. This will facilitate consistent consideration of externalities in decision making, and reduce the capacity for ‘back analysis’ of investment decisions in support of some preferred solution. Any primary studies undertaken should be structured such that results can be transferred across a range of investment decisions, so attention should be given to the information necessary to support a benefit transfer approach.

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