ARTICLE IN PRESS

Cities xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Cities

journal homepage: www.elsevier.com/locate/cities

# Flexible adaptation planning for water sensitive cities

Mohanasundar Radhakrishnan*, Assela Pathirana, Richard M. Ashley, Berry Gersonius, Chris Zevenbergen

*IHE Delft Institute for Water Education, 2611, AX, Delft, The Netherlands*
*CRC for Water Sensitive Cities, Clayton, Melbourne, Australia*

A R T I C L E I N F O

*Keywords:*
Floods & floodworks
Infrastructure planning
Municipal & public service engineering
Sustainability
Urban regeneration

A B S T R A C T

Cities have started adapting to uncertain climate drivers such as temperature and sea level rise, and some cities are also transitioning towards concepts such as Water Sensitivity. In adaptation planning, flexibility is considered as an important characteristic to respond to changing circumstances. This paper develops a novel approach to identify where flexibility can best be embedded in urban flood risk management systems. The identification of a flexible water sensitive adaptation response is based on change propagation; i.e. the response's ability to minimise negative or maximise positive *impacts* in urban *systems*. The Flexible adaptation planning process (WSCapp), comprising change propagation – especially how positive and negative impacts propagate in an urban environment, can be used by those concerned with urban planning and urban adaptation to identify "*where*" the flexible adaptation responses can be implemented. WSCapp can be used to decide the type of adaptation response such as changes to streetscape, place making or architectural forms that can best contribute towards the objectives of a water sensitive city.

## 1. Introduction

Adaptive approaches in planning, design and implementation can help to minimise the hazardous effects of climate change and explicitly allow for the uncertainties associated with these in urban areas (Revi et al., 2014). Policy makers, planners and others managing urban areas have recognised the likely effects of climate change and have initiated strategic adaptation actions that are aligned usually according to a particular vision used by a particular sectoral or service provision (Chu, Anguelovski, & Roberts, 2017; Jabareen, 2013). There are also signs of a breakaway from a sectoral vision, in which urban adaptation planning is compartmentalised, with moves towards multi-sector and multi-disciplinary planning approaches to better bring about sustainable development (Malekpour, Brown, & de Haan, 2015). However, decision making related to adaptation faces uncertainties, which necessitate a flexible approach that can adapt to the changes. Flexibility is important for this and is here defined as the attribute of a system which enables the system to respond in an efficient way in terms of performance, cost and time, when the system is confronted with uncertainties, negative consequences and opportunities (Anvarifara, Zevenbergen, Thissen, & Islam, 2016).

Flexibility is increasingly seen as a desirable feature that enhances system capabilities and functionality in the face of uncertainty (Schulz, Fricke, and Igenbergs (2000). Gersonius et al. (2016) recommend flexibility in combining different types of strategies "retain, resist, relieve, retreat, accommodate and prepare" (4RAP) to increase resilience towards flooding in designing and planning systems for water sensitivity (Fig. 1). For example, the City of Melbourne's resilience strategy considers flexibility as an important characteristic to respond to changing circumstances when using a mix of strategies such as adapt, survive, thrive and embed (City of Melbourne, 2016). Flexibility is also a property which counters the effects of maladaptation throughout the entire life cycle by allowing system change (Gersonius, Ashley, Pathirana, & Zevenbergen, 2013).

A "water sensitive city" (WSC) vision (Brown, Keath, & Wong, 2009) considers urban water management from a perspective of intergenerational equity and resilience to climate change and hence is more than just Water Sensitive Urban Design (Ashley et al., 2013). The WSC approach recommends an urban design that reinforces 'water sensitive' behaviours. This is evident in the adaptation plans and actions taken by cities such as Rotterdam, Copenhagen, Dresden and Melbourne (City of Melbourne, 2016; EEA, 2016) and is an aspiration for London (HM Government, 2016). The adaptation measures in these cities are termed as 'transformational adaptation measures' (EEA, 2016). They use behaviour and technology to change the performance of urban systems fundamentally. In addition, transition or strategic planning for sustainable development requires a proactive planning culture in order to create conditions for change to deal with future issues (Malekpour

* Corresponding author at: IHE Delft Institute for Water Education, 2611, AX, Delft, The Netherlands.
*E-mail address:* m.radhakrishnan@un-ihe.org (M. Radhakrishnan).

https://doi.org/10.1016/j.cities.2018.01.022
Received 8 March 2017; Received in revised form 29 September 2017; Accepted 31 January 2018
0264-2751/ © 2018 Published by Elsevier Ltd.

Please cite this article as: Radhakrishnan, M., Cities (2018), https://doi.org/10.1016/j.cities.2018.01.022

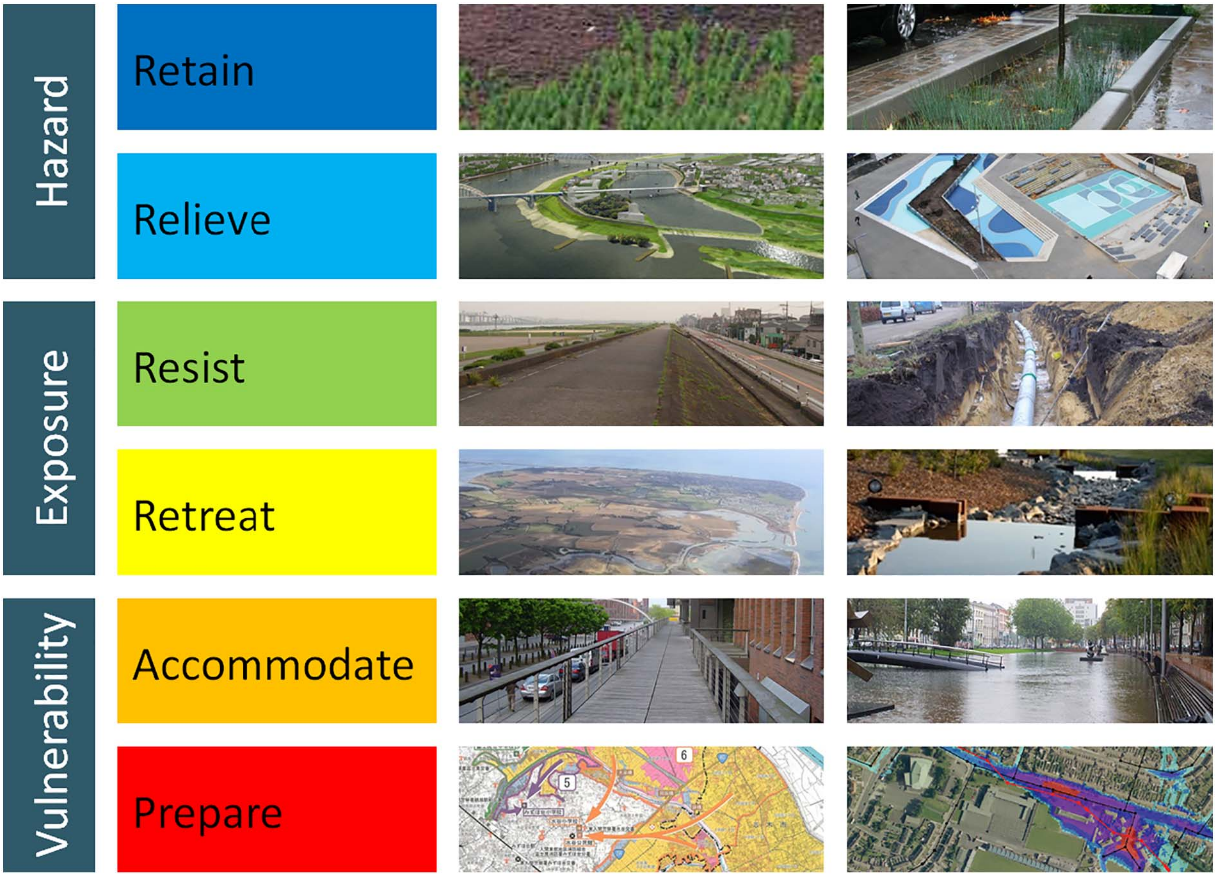


**Fig. 1.** 4-RAP model of available strategies – where the 4R's signify the retain, relieve, resist and retreat strategies; 'A' signifies accommodate strategy; and 'P' signifies prepare strategy - to enhance flood resilience.
(Adapted from Gersonius et al. (2016))

et al., 2015). For example, in Melbourne, water, wastewater and stormwater management was formerly aimed at the protection of waterway health, tackling water shortages during drought, ensuring water supply through alternative sources and protection against flooding (Ferguson, Brown, Frantzeskaki, de Haan, & Deletic, 2013). Now Melbourne has moved beyond this and is including the objectives of being resilient to climate change and becoming a water sensitive city (City of Melbourne, 2016). An important characteristic of a resilient city is flexibility, e.g., having a number of alternative ways to provide services and respond to changing circumstances as these arise (City of Melbourne, 2016). It allows the city to respond to future needs from climate change as well as changes in objectives.

An effective WSC requires a process that incorporates flexibility into planning, implementation and operation. The context-first approach adaptation planning process (e.g. Thames Estuary project TE2100) makes adaptation flexible using a high level route map of adaptation measures (Reeder & Ranger, 2011). Techniques such as real in options (RIO) (e.g. Woodward, Kapelan, and Gouldby (2014)) value the flexibility built into a (flood risk management) system in monetary terms. However, these approaches do not identify the optimal places where flexibility can be embedded. Hence, in addition to the value it is necessary to know where, how and when to incorporate flexibility to achieve the objectives of a WSC.

This paper develops a novel approach to identify where flexibility can best be embedded in urban flood risk management systems. This has been developed by drawing on knowledge and procedures from the automobile and aerospace industries, where flexible adaptation planning is everyday practice (Suh, de Weck, & Chang, 2007). The flexible physical components are selected based on the components' ability to propagate change in the urban system (Eckert, Clarkson, & Zanker, 2004). An adaptation response is an ideal flexibility 'candidate' when it minimises negative impacts or maximises positive impacts throughout the area under consideration (i.e. change propagates throughout the system) and not just in the vicinity of the adaptation response. For example, a dewatering pump reduces flooding in a neighbourhood (reduces negative impact), whereas green roofs in addition to reducing the peak flow during rain, also have ecosystem service benefits in the neighbourhood (increases positive impact). Both these urban water management adaptation responses are capable of propagating change throughout the neighbourhood either by reducing negative impacts or by increasing the positive impact and contribute towards increasing resilience in the urban system. Further, prior identification of flexible adaptation responses makes the response to change rapid, i.e. making the change process agile (Pathirana, Radhakrishnan, Ashley, Quan, & Zevenbergen, 2017). In this context, agility is defined as the ability of the adaptation system to respond quickly to uncertainties, threats and opportunities.

The sections in the paper explain: (a) the relevance of flexibility in flood risk management; (b) methods that are used in embedding flexibility in the manufacturing sector; (c) the need for a planning process that ensures that adaptation is flexible in a WSC context; (d) development of a flexible adaptation planning process (WSCapp) for identifying WSC elements or components where flexibility can be embedded; and (e) theoretical and practical considerations for applying this flexible adaptation planning process.

## 2. Flexibility in contemporary flood risk management practices

Flexibility is often considered as a valuable capacity to cope with uncertainty and change, although there is no consensus about what

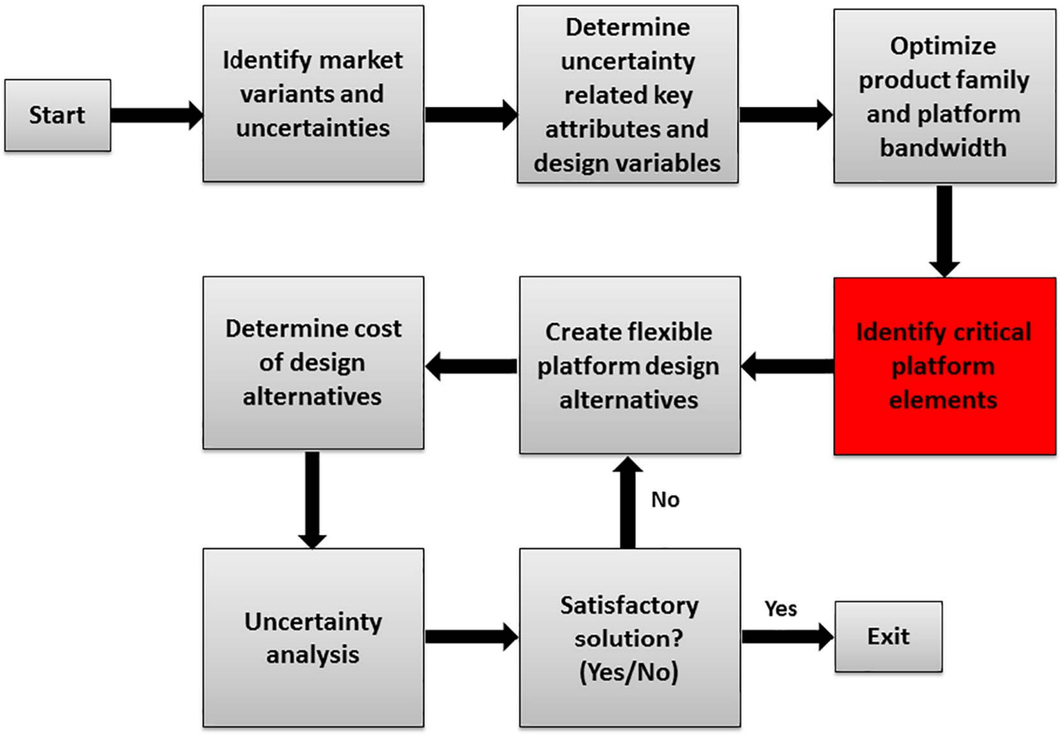


**Fig. 2.** Flexible platform design process in the automobile manufacturing sector.
(Adapted from Eckert et al. (2004))

constitutes flexibility in literature or practice (Anvarifara et al., 2016). It is context and domain specific. Flexibility applies to both the planning/design process itself as well as to the attributes of the key components or artefacts being planned and designed. For example, the Delta programme in the Netherlands is based on adaptive delta management and recommends a flexible approach as a means for creating options in terms of implementing measures in the immediate term or in the future – i.e., speeding up or deferring the implementation of adaptation measures, or implementing other measures that can prevent the risk of over or under investment (Deltacommissaris, 2014; Zevenbergen, Rijke, van Herk, & Bloemen, 2015). The incorporation of flexibility with respect to implementation of climate adaptation measures is provided in various ways as illustrated in the following examples: allowing midterm adjustments and modifications of structure – structural flexibility (van Buuren et al., 2013; Woodward et al., 2014); keeping investment or implementation options open for future adaptation – managerial flexibility (Haasnoot, Middelkoop, Offermans, Beek, & Deursen, 2012b; Zhang & Babovic, 2012); postponing adaptation until the time when the cost of further delay would be more than the benefits – also managerial flexibility (Felgenhauer & Webster, 2013). There are also other approaches such as functional flexibility, operational flexibility and strategic flexibility (Radhakrishnan, Ashley, Gersonius, Pathirana, and Zevenbergen (2016).

The context-first approach adaptation planning process (e.g. Thames Estuary project TE2100; Reeder and Ranger (2011)) identifies the need for flexibility and incorporates it in the form of a high level road map of adaptation measures. Context-first adaptation approaches (e.g. Ranger et al. (2010), Dessai and Sluijs (2007)): (i) encourage the decision makers to begin at the level of the adaptation problem (or opportunity); (ii) specify the objectives and constraints; (iii) identify appropriate adaptation strategies; (iv) and only then appraise the desirability of adaptation measures against a set of climate change projections. The adaptation pathways approaches (Haasnoot, Middelkoop, Offermans, Beek, & Deursen, 2012a), dynamic adaptation policy pathways (Haasnoot, Kwakkel, Walker, & ter Maat, 2013) and model based adaptation pathway approach (Kwakkel, Haasnoot, & Walker, 2015) also fall into the category of context-first adaptation planning processes (Veerbeek, Gersonius, Ashley, Radhakrishnan, & Rodriguez, 2016). However, these context-first approaches fall short in identifying the adaptation responses of the system, especially where flexibility can be incorporated.

The real in options (RIO) techniques applied to urban flood risk management (UFRM) help to specifically respond to exogenous uncertainties and to value flexibility. For example, Gersonius, Ashley, Pathirana, and Zevenbergen (2012); Gersonius et al. (2013); Woodward et al. (2014); Zhang and Babovic (2012), focus on creating flexible alternative designs and determining the cost of alternative designs. These approaches do not identify where, when and how to embed flexibility. This may be attributed to the reductionist way of approaching complexity from a traditional engineering perspective and the consequent managerial approach (Fratini, Geldof, Kluck, & Mikkelsen, 2012; Malekpour et al., 2015). The RIO application in the UFRM domain has to be customised to include the comprehensiveness of a WSC approach. Liveability and resilience as part of sustainability are the essential aspects of WSC (Ashley et al., 2013). Although RIO methods address resilience and sustainability to an extent (e.g., Zhang and Babovic (2012)), they do not fully address the aspects of liveability. Where liveability—the most visible and appreciated quality of any city—is the totality of features that add up to the citizens' quality of life; comprising their experience of the natural and built environment, together with services (Salama & Wiedmann, 2016).

## 3. Flexibility in manufacturing

Addressing the combination of strategy transitions and uncertainty of drivers is a challenge that is not specific only to the domain of urban water management. Similar challenges have been faced by manufacturing industries and software developers (Bernardes & Hanna, 2009; Koste & Malhotra, 1999; McGaughey, 1999; Sánchez & Pérez, 2005). Businesses and organizations such as these face a volatile environment that is highly uncertain with challenges such as increased competition, globalized markets, technology obsolescence and dynamic customer requirements. The strategy transitions in urban water management can be compared with the evolution of new car models. For example, the change of focus from reducing pollution and conserving water in urban water management to sustainable water management can be compared with the change in preference for cars with more power towards the preference for cars which pollute less or electric cars.

The automobile manufacturing sector uses product platform strategies to save costs by sharing core elements among different products in a product family (Simpson et al., 2006; Suh et al., 2007). Suh et al. (2007) have developed a seven step flexible platform design process (Fig. 2) to deal with uncertainty and product variants in order to ensure continuity in production and maximise profit for the automotive industry. The uniqueness of this approach is the identification of the most appropriate subset of physical components, i.e., the parts of the vehicle or machine, where the necessary flexibility can be embedded (step IV in Fig. 2). The identification of flexible adaptation responses is based on the magnitude of change that the components propagate throughout the system when modified (Eckert et al., 2004).

According to Eckert et al. (2004) the physical components that are capable of propagating greater change are to be assessed carefully before being selected as candidates for embedding flexibility. For example, in the design of an automobile chassis the width is kept constant for all the variants to limit change propagation. This is because change in width has a direct bearing on the stability of the vehicle. One of the parameters that determines the chassis dimensions - the length and breadth - is the dimensions of the engine, which in turn depends on the number of cylinders. Hence the width of the chassis is generally increased and fixed for all future variants, by taking into consideration the possible increase in width of the engine, thereby avoiding major impacts on the stability of the vehicle. However, the length of the chassis is designed to be flexible so that it can be changed in accordance to the dimensions of the new engine as the impact on stability due to change in length is minimal. Enabling flexibility in such design parameters requires initial investment in design, tooling and assembly equipment and is similar to using real in options (RIO) analysis in chassis design (Suh et al., 2007). Wherever possible, change propagation is limited by means of providing sufficient margins or excess headroom (i.e. redundancy) in the design parameter to limit the change propagation within these systems. Provision of redundancy is used when the engineering cost of design changes, additional fabrication, assembly tooling and equipment investment to make these changes are higher than the cost of designing and manufacturing a product with a significant degree of redundancy. Change propagation is similar to "Building information modelling" used by architects and planners where the effect of changes made to the physical elements such as wall or windows on lighting, ambience, spatial relationships, interaction between the various architectural elements; as well as the effect of changes in the fabrication and construction of physical elements (Lu & Korman, 2010).

## 4. Flexible adaptation planning process in WSC context

In a WSC context, various urban water systems (and other urban systems) are interconnected and change in the positive or negative impacts in one system will propagate to other systems. A change rarely occurs in isolation and impacts other systems. This change propagation is important as it may have unintended consequences affecting the functionality of the systems, such as non-compliance with design standards, including flooding or increased flood damages; or a reduction in liveability aspects due to the presence of stagnant water. The components or sub systems in the WSC have to be analysed from the aspect of change propagation.

The adaptation responses that are capable of propagating more change (i.e. positive or negative impacts) when modified are the critical responses and thus potential candidates for incorporating flexibility. Change propagation can be used to assess the crucial changes (positive and negative impacts) that might propagate in the urban water system due to changes in components. For example, the use of Sustainable Drainage Systems (SuDS) can be analysed using this concept of change propagation in Australian urban catchments where there is risk of flooding and droughts. SuDS are more flexible than buried piped systems (Ashley et al., 2015). The change in the type, size or number of SuDS components - such as green roofs and rain barrels - will have positive as well as negative impacts on increasing use or size of SuDS measures: (i) reduces runoff (i.e. reduction of negative impacts throughout the catchment); (ii) can lead to downsizing or deferring the expansion of conventional downstream measures such as large-scale detention systems or pumping arrangements (i.e. increase in positive impacts in the catchment and in cities investment planning); (iii) can yield desirable benefits such as enhanced aesthetics, improvement in water quality, etc., (i.e. increase in positive impacts in the catchment and in downstream catchments); (iv) but can lead to undesirable effects such as odour nuisance or more mosquitoes (i.e. increase of negative benefits throughout the catchment); and, (v) can increase the risk of fire during droughts due to dry vegetation that necessitates additional watering and strain on water resources (i.e., propagation of negative impact even beyond the catchment).

Similarly change propagation analysis can be undertaken for conventional infrastructure measures such as the pumps at the outfall, where the reduction in negative impacts such as reduced flooding or high dependence on SuDS might propagate upstream depending upon the capacity of pumps. Also there are no other positive changes which propagate from pumps such as the additional benefits from SuDS measures during normal operations. However, change propagation can also be used from the perspective of controlling or minimising the change that propagates in the system. The limitation of a pump can be turned into an advantage as it is a standalone centralised component where the incorporation of flexibility into a pumping station, by means of additional bays for pumps for the future, is easier to implement. Also this might be economically cheaper than investments in distributed SuDS measures upstream. Thus change propagation can help in identifying the main flexible adaptation response locations (where) and measures for maintaining flexibility in future adaptation response (which). This is a balancing act between the (unwanted) physical suppression of future change propagation, where it is not wanted and investment in flexibility where this is wanted.

Consideration of change propagation due to the transition in vision – such as the transition of a city from a 'water supply city' to a WSC (Brown et al., 2009) – is as equally important as the consideration of change propagation due to any change in system components. Exploring the design, implementation and maintenance of the water sensitive or flood resilient systems such as water plazas (e.g. place making) or water retaining pavements (e.g. streetscape design) that are implemented in cities such as Copenhagen and Rotterdam (EEA, 2016), can help in understanding how change – in architectural features, aesthetics, amenities, built environments, open space, streetscape – propagates in a complex urban environment. For example, such studies can help cities to understand change propagation when the required functions of, for example, the use of a wetland system changes in regard to societal needs as a transition from water quality improvement or drought resistance to a broader WSC perspective. Change propagation can be examined through mapping the relationship between the systems or the adaptation measures. For example, in order to improve the resilience of infrastructure, the State of Victoria in Australia is pooling together various infrastructure options (Victoria, 2016a). How each option works with others, in terms of how they might enable, complement or inhibit one another in advancing one or more of the needs is referred to as relationship mapping (Victoria, 2016b). Such relationship mapping between adaptation measures is a good starting point for ascertaining change propagation in urban water or other systems.

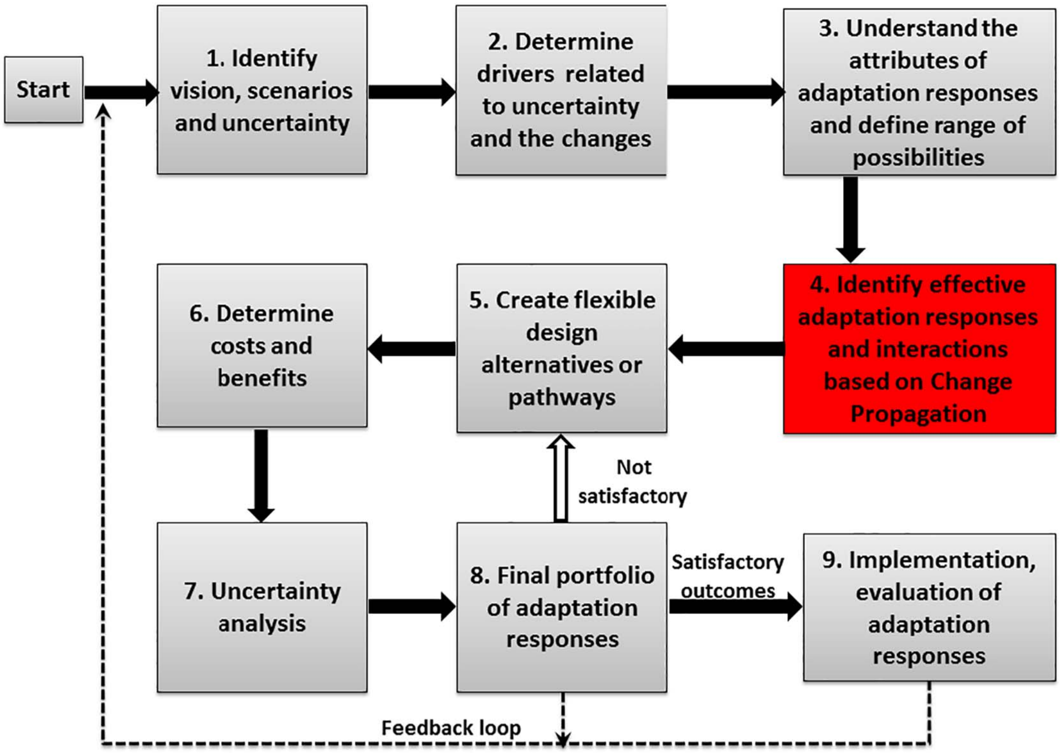


**Fig. 3.** Flexible adaptation planning process for water sensitive city (WSCapp). The black arrows represent the sequence of steps in the WSCapp (clockwise). The dashed line from step 8 and step 9 to step 1 represents the feedback to the vision cycle when a change in vision or objective happens over the time. The white arrow enclosed with black lines from step 8 to step 5 represents the iteration with in the WSCapp, in case the final portfolio of measures obtained after the first run are not satisfactory.

## 5. Development of flexible adaptation planning process for WSC

Inspiration is drawn here from the flexible platform design processes and complex change management processes (Eckert et al., 2004; Suh et al., 2007) that are prevalent in the automobile manufacturing sector in order to customise the context-first approaches to the WSC context. The adaptation planning process for incorporating flexibility in a WSC context using the principles from 'context specific adaptation approaches' and the flexible platform design process is presented in Fig. 3. The adaptation planning process presented here resembles or is very similar to the urban adaptation planning process such as Dynamic adaptation planning process – DAAP – (Haasnoot et al., 2013) and CRIDA steps in adaptive management cycle (CRIDA Under review). In addition to the stress test and performance of the responses recommended by these adaptation planning processes (e.g. Kwakkel, Haasnoot, and Walker (2016)), the emphasis in WSCapp is on changes in the resilience, liveability and sustainability aspects in a WSC context that are propagated by the responses in the urban environment (Step 4 of Fig. 3). Hence in addition to how and when the flexible adaption responses can be incorporated, WSCapp also identifies '*where*' flexibility can be incorporated.

The explanation of the individual steps in the flexible adaptation planning processes for a WSC, termed WSCapp, in an urban flooding context, developed from the previous discussions, is presented in Table 1.

## 6. Theoretical and practical considerations for applying WSCapp

WSCapp has been designed deliberately to resemble the steps in the contemporary adaptation planning process such as dynamic adaptive policy pathways and CRIDA steps in adaptive management cycle (CRIDA Under review; Haasnoot et al., 2013). This might lead to easier understanding and acceptance of WSCapp as an improvement of the existing adaptation planning processes, which is the overall aim of the research presented here. Hence, the emphasis in WSCapp is on the selection and assessment of flexible adaptation responses using the concept of change propagation (Step 4 in Fig. 3). This is an important theoretical contribution to the adaptation planning process as WSCapp addresses the current gap on "where" flexibility can be incorporated. WCSapp will enable urban planners to analyse the impact of changes – such as change in architectural forms, open spaces and streetscapes – on liveability, sustainability and resilience. Also it is possible to visualise these changes due to urban design using outdoor augmented reality techniques (e.g. Calabrese and Baresi (2017).

Although it is not possible to accurately predict and model the changes in an urban environment, unlike in a factory setting, the results from the assessment can lead to informed decision making. There are examples and precedents in adapting concepts from other domains for planning and assessment of adaptation responses in urban adaptation. The concept of real options for valuing flexibility of adaptation responses (e.g. Zhang and Babovic (2012)) was adopted from valuing portfolios in stock markets. The agile urban adaptation technique that can be used for quickly responding to change and learning in an uncertain environment is based on software development techniques (Pathirana, Radhakrishnan, Ashley, et al., 2017). The assessment based on change propagation is both complex and computationally intensive as all the adaptation responses in various combinations in various scenarios have to be tested. However, once conceptualized, such computations are feasible with today's powerful computing techniques.

Some of the practical aspects that are be considered alongside the change propagation are the mainstreaming and the 5DA approaches that are used in adaptation planning (Gersonius et al., 2016; Rijke et al., 2016). Mainstreaming is suggested as an opportunity 'to adapt wherever we can, instead of wherever we have to' based on experience from cities such as Hamburg, Rotterdam, Malmo and New York (Rijke et al., 2016) (Table 1, Step 4 in Fig. 3). Creatively embedding flexibility through mainstreaming by making modifications at the same time as other changes to the system may not increase upfront cost or the net

**Table 1**
Flexible adaptation planning process for water sensitive city (WSCapp) for incorporating and assessing flexibility in an urban flooding context.

| Required steps (Fig. 3) | Description | Resources for additional guidance on individual steps in WSCapp |
|---|---|---|
| 1. Identify vision, scenarios and uncertainty | Ascertain what the visions for the city are, such as WSC, resilient and climate proof city based on ideas such as liveability, resilience and sustainability. Explore the possible scenarios in the future due to stressors such as climate change, socio-economics and the uncertainties associated with these. | Flood resilience in a water sensitive city context (Gersonius et al., 2016)<br>Transitions in a water management context (Ferguson et al., 2013). |
| 2. Determine drivers related to uncertainty and the future changes anticipated | Methods such as adaptation pathways based on adaptation tipping points help in determining the impact of uncertainty on meeting the required objectives based on 'stress tests' in an urban area using physically based numerical models. Tipping points are the physical boundary conditions or the time at which the technical, economic, spatial or societal acceptable limits are exceeded (Haasnoot, Middelkoop, van Beek, & van Deursen, 2011); i.e. when the system no longer provides the required service levels. | Stress testing and adaptation tipping points (Rodriguez, Radhakrishnan, Ashley, & Gersonius, 2016) |
| 3. Understand attributes of WSC components and define range of possibilities | Flexibility attributes of the measure pertains to time, cost and effort required to change the scale, location and function of a measure. | Estimating annual flood damage Olesen et al. (Under Review).<br>Examples of attributes related to flexible design (Eckert et al., 2004; Spiller, Vreeburg, Leusbrock, & Zeeman, 2015; Suh et al., 2007) |
| 4. Identify critical WSC systems or components and interactions based on change propagation | Carry out relationship mapping between the adaptation measures.<br>Determine the potential for change propagation in the urban system: A change rarely occurs in isolation and impacts other systems. The adaptation responses that are capable of propagating more change (i.e. positive or negative impacts) when modified are potential adaptation responses for incorporating flexibility. | Mapping of relationships between adaptation measures - Infrastructure Victoria (Radhakrishnan, Pathirana, Ashley, & Zevenbergen, 2017; Victoria, 2016a; Victoria, 2016b).<br>Change propagation in complex engineering systems (Eckert et al., 2004)<br>Flood resilience in water sensitive cities (Gersonius et al., 2016).<br>Adaptation mainstreaming - an opportunity "to adapt wherever we can, instead of wherever we have to" (Rijke, Ashley, & Sakic, 2016). |
| 5. Create flexible design alternatives or pathways | Adaptation pathways should be generated using the subset of adaptation measures based on relationship mapping and functionalities. | Adaptation pathways (Veerbeek et al., 2016)<br>Pathway generator tool (Haasnoot & Van Deursen, 2015) |
| 6. Determine cost and benefit of design alternatives or pathways | The cost and benefits (also non-monetary) of implementation of adaption measures also includes the cost and benefits of switching from one measure to another in all possible scenarios. | Discounted cash flow analysis methods (e.g. Appendix B in De Neufville and Scholtes (2011)).<br>Benefits of flood resilient adaptation measures -Gersonius et al. (2016) and BeST user manual (Horton, Digman, Ashley, & Gill, 2016). |
| 7. Uncertainty analysis | The present value or cost and benefit of pathways depends upon their performance in a scenario. As there are multiple future scenarios, the performance of pathways is likely to change leading to change in the tipping points. | Scenario planning for robust flood risk management (Brisley et al., 2016).<br>Standard sensitivity analysis techniques - Monte Carlo Simulation (e.g. Appendix D in De Neufville and Scholtes (2011))<br>Model based performance analysis (e.g. Löwe et al. (2015)) |
| 8. Final portfolio of components defined and selected for WSC | Notwithstanding the benefits and costs outcomes, decision makers may decide to select a preferred strategy that is not cheaper in financial terms but may be their favoured strategy for other reasons. | Selection of preferred options - Gersonius et al. (2016) |
| 9. Implementation and evaluation of adaptation response | The selected adaptation responses can be implemented based on the needs as well the capacities of the stakeholders. Some of the criteria that should be taken into account while implementing adaptation responses are the effectiveness, flexibility and agility (i.e., the speed with which changes can be made) of the responses; and the motivation and ability of the stakeholders in implementing the responses | Needs for adaptation responses – Pathirana, Radhakrishnan, Quan, and Zevenbergen (2017)<br>Agile urban adaptation – Pathirana, Radhakrishnan, Ashley, et al. (2017)<br>Motivation and abilities - Phi, Hermans, Douven, Van Halsema, and Khan (2015) |

cost, i.e., the cost of base elements together with the urban water element that is being mainstreamed with the base element. Also, mainstreaming is a collaborative effort where the requirements of multiple stakeholders are to be considered without compromising the interests of the asset owners. For example, a housing development project might give an opportunity to mainstream flood resilience in the form of blue-green infrastructure in courtyards. However, the risk is that the increase in natural ecological vitality provided by blue-green infrastructure may lead to a drainage facility becoming designated as protected against change to preserve the ecosystems, thus inhibiting the ability to adapt. Inspiration for resolving such impasses can be found from the manufacturing sector. For example, in the manufacturing of defence equipment such as helicopters there is a practise called 'offsetting' to avoid conflicts of interest of stakeholders (Eckert et al., 2004).

Offsetting is a practice where the components earmarked by clients are maintained (ring-fenced) even though they have the potential for flexibility. Instead, the manufacturer minimises the change propagated from ring fenced (i.e., offset) systems by embedding flexibility or redundancy in the rest of the system that is not ring-fenced. For example, in a helicopter the radar and avionics systems are outdated quickly and have to be upgraded frequently to improve the performance of the helicopter. The manufacturer takes in to consideration the future upgrades – similar to car engine development – while finalising the overall design of helicopter. However certain buyers of helicopters such as military establishments many not prefer frequent changes as, it involves training their personnel to changing radar and avionics systems; there is a risk in not getting the upgrade done in time leading to reduction in serviceability of the helicopter; and, sanctions in future might hinder the procurement of the upgraded components in an ever changing political context. All these aforementioned factors affect the operational readiness of the aircraft, i.e., the capability to perform assigned flight missions (Verhoeff, Verhagen, & Curran, 2015). Hence these buyers insist for a fixed radar-avionics configuration and prefer a design where flexibility can be incorporated in physical components which do not have the aforementioned drawbacks. A parallel can be drawn between offsetting in helicopters and urban flood risk management. For example an open area in a city which can be converted into a wetland for retaining excess water to flooding, which can eventually converted into a nature reserve. This conversion can lead to jurisdictional issues in the future between different city departments such as estate department and parks and natural reserves department. Hence instead of converting the open area into a natural reserve the decision is offset, whereas an existing park is land scaped so that it can serve as a detention facility to hold excess water during heavy rainfall events. This arrangement prevents jurisdictional issues. This practice of offsetting is heavily context dependent and time dependent. Ascertaining the characteristics and the nature of flood resilience measures will help in identifying the measures that can be mainstreamed or need to be offset. For further details on offsetting in an urban context refer to Radhakrishnan et al. (2016).

Gersonius et al. (2016) recommend the 5 domains approach (5DA) to select flood resilience measures according to the nature of rainfall or stream discharge (see also Digman and Ashley (2014)). This includes the following related to environmental loadings: (i) day- to day events – potentially beneficial events which cause no damage; (ii) design events for which the system is designed according to set standards; (iii) exceedance events – which cause no or very little damage if managed effectively; (iv) extreme events – which cause substantial damages but within the recovery range; (v) unmanageable extreme events from which recovery is not possible. The 5DA classification is an improvement of the four domains approach – 4DA, Fig. 4 (Digman & Ashley, 2014). From Fig. 4 it can it can be seen that the pressure and impact can be classified in to four domains based on the magnitude of impact and pressure the system is subjected to. The first three domains: (1) day to day domain; (2) design event domain; and (3) extreme domain with manageable damages are the domains where recovery is possible by means of resilience. Whereas, the unmanageable extreme events domain is beyond the recovery threshold and recovery is not possible. This classification can assist in ascertaining the effectiveness of the adaptation measure through determining the domain which the measure can be classified as the change propagated by the measure either within or across the domains. This can subsequently lead to the identification of where and how flexibility can be provided. For example, 5DA assessment in combination with change propagation assessment can be used to: (i) decide the locations where place making (e.g. water plaza) and landscaping roof terraces (e.g. green roofs) can be deployed, as they can efficiently cater to day to day and design events; and also to (ii) decide where the streetscapes (e.g. multi-functional streets) and open spaces (e.g. parks) can be modified and new architectural forms (e.g. amphibious dwellings) can be created as these responses can effectively cater to exceedance and extreme events. The aforementioned urban planning interventions/adaptation measures impact sustainability, resilience and liveability at varying levels and have a direct or “knock-on” effect depending on weather events such as heat waves, droughts or floods.

Creativity in embedding flexibility is important as the best flexible designs when aligned with aspects such as mainstreaming or liveability, can increase the aesthetics and amenity value of the urban environment both now and in the future (e.g. Ashley et al. (In Press)).

## 7. Conclusions

This paper sets out an approach (WSCapp) to identify where flexibility can be embedded in urban flood risk management systems as part of the essential components of a WSC. Knowledge and practices have been drawn from the domain of manufacturing industries, including automotive and aerospace, where tackling uncertainty using flexible designs is common. Comparisons have been made between the nature of issues and contexts of the automotive industry and the adaptation planning process in the context of a WSC. Flexibility can be incorporated into a WSC through identification of flexible adaptation responses based on change propagation, a regular practice in

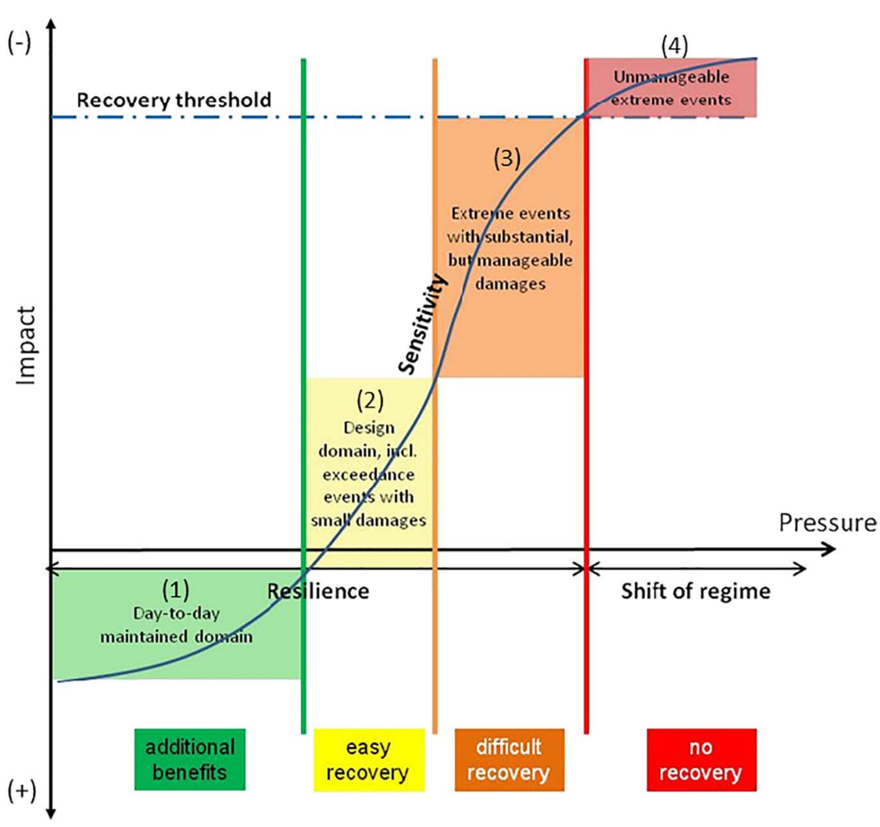


**Fig. 4.** The 4 domains approach - 4DA recommends that classification of adaptation measures according to the type of loading, which the adaptation measure can address effectively (Digman & Ashley, 2014).

automobile assembly planning and design. Change propagation, which is the assessment of propagation of positive and negative impacts of adaptation responses such as SuDS and dewatering pumps, can be applied in an urban water management context. The Flexible adaptation planning process (WSCapp) based on change propagation can enhance adaptation in cities, where it is possible to identify and select adaptation responses such as rain water tanks and wet proofing of houses which lead to flexible as well as economic adaptation pathways adaptation responses (Radhakrishnan et al. Under Review). Hence, WSCapp can be used by those who concerned with urban planning and urban adaptation to determine where the flexible adaptation responses can best implemented and to decide the nature of interventions such as enhancements to streetscape, place making or architectural forms that can contribute towards the objectives of a water sensitive city.

## Acknowledgement

This technical paper is an outcome of an ongoing research funded by Cooperative Research Centre for Water Sensitive Cities (CRC), an initiative of the Australian government. We thank Dr. Tushith Islam - Faculty of Technology and Policy Management, Technical University Delft - for introducing the concept of flexible platform design process.

## References

Anvarifara, F., Zevenbergen, C., Thissen, W., & Islam, T. (2016). Understanding flexibility for multifunctional flood defences: A conceptual framework. *Journal of Water and Climate Change*. http://dx.doi.org/10.2166/wcc.2016.064.

Ashley, R., Lundy, L., Ward, S., Shaffer, P., Walker, L., Morgan, C., ... Moore, S. (2013). Water-sensitive urban design: Opportunities for the UK. *Proceedings of the Institution of Civil Engineers: Municipal Engineer, 166*, 65–76. http://dx.doi.org/10.1680/muen.12.00046.

Ashley, R., Walker, L., D'Arcy, B., Wilson, S., Illman, S., Shaffer, P., ... Chatfield, P. (2015). UK sustainable drainage systems: past, present and future. *Proceedings of the Institution of Civil Engineers: Civil Engineering, 168*, 125–130. http://dx.doi.org/10.1680/cien.15.00011.

Ashley, R. M., Digman, C. J., Horton, B., Gersonius, B., Smith, B., Shaffer, P., & Baylis, A. (2018). Evaluating the longer term benefits of sustainable drainage. *Proceedings of the Institution of Civil Engineers: Water Management, 0*, 1–10. http://dx.doi.org/10.1680/jwama.16.00118 (In Press).

Bernardes, E. S., & Hanna, M. D. (2009). A theoretical review of flexibility, agility and responsiveness in the operations management literature: Toward a conceptual definition of customer responsiveness. *International Journal of Operations & Production Management, 29*, 30–53. http://dx.doi.org/10.1108/01443570910925352.

Brisley, R., Wylde, R., Lamb, R., Cooper, J., Sayers, P., & Hall, J. (2016). Techniques for valuing adaptive capacity in flood risk management. *Proceedings of the Institution of Civil Engineers: Water Management, 169*, 75–84. http://dx.doi.org/10.1680/jwama.14.00070.

Brown, R., Keath, N., & Wong, T. (2009). Urban water management in cities: Historical, current and future regimes. *Water Science and Technology, 59*, 847–855.

Calabrese, C., & Baresi, L. (2017). Outdoor augmented reality for urban design and simulation. In B. E. A. Piga, & R. Salerno (Eds.). *Urban design and representation: A multidisciplinary and multisensory approach* (pp. 181–190). Cham: Springer International Publishing. http://dx.doi.org/10.1007/978-3-319-51804-6_14.

Chu, E., Anguelovski, I., & Roberts, D. (2017). Climate adaptation as strategic urbanism: Assessing opportunities and uncertainties for equity and inclusive development in cities. *Cities, 60*(Part A), 378–387. http://dx.doi.org/10.1016/j.cities.2016.10.016.

City of Melbourne (2016). *Resilient Melbourne.* Melbourne: City of Melbourne.

CRIDA (2018). *Water resources planning & design for an uncertain future.* Alexandria, Virginia, USA: International Center for Integrated Water Resources Management, ICIWaRM Press (Under review).

De Neufville, R., & Scholtes, S. (2011). *Flexibility in engineering design.* The MIT Press.

Deltacommissaris (2014). *Delta programme 2015: Working on the Dutch Delta in the 21st century: A new phase in the battle against the water.* The Hague: The Ministry of Infrastructure and Environment, The Ministry of Economic Afffairs.

Dessai, S., & Sluijs, J. P. (2007). *Uncertainty and climate change adaptation: A scoping study vol 2007.* the Netherlands: Copernicus Institute for Sustainable Development and Innovation, Department of Science Technology and Society Utrecht.

Digman, C. J., & Ashley, R. (2014). *Managing urban flooding from heavy rainfall – Encouraging the uptake of designing for exceedance – Recommendations and summary vol CIRIA RP991.* London: Construction Industry Research and Information Association.

Eckert, C., Clarkson, P. J., & Zanker, W. (2004). Change and customisation in complex engineering domains. *Research in Engineering Design, 15*, 1–21. http://dx.doi.org/10.1007/s00163-003-0031-7.

EEA (2016). *Urban adaptation to climate change in Europe: Transforming cities in a changing climate.* Copenhagen: European Environment Agency.

Felgenhauer, T., & Webster, M. (2013). Multiple adaptation types with mitigation: A framework for policy analysis. *Global Environmental Change, 23*, 1556–1565. http://dx.doi.org/10.1016/j.gloenvcha.2013.09.018.

Ferguson, B. C., Brown, R. R., Frantzeskaki, N., de Haan, F. J., & Deletic, A. (2013). The enabling institutional context for integrated water management: Lessons from Melbourne. *Water Research, 47*, 7300–7314. http://dx.doi.org/10.1016/j.watres.2013.09.045.

Fratini, C. F., Geldof, G. D., Kluck, J., & Mikkelsen, P. S. (2012). Three points approach (3PA) for urban flood risk management: A tool to support climate change adaptation through transdisciplinarity and multifunctionality. *Urban Water Journal, 9*, 317–331. http://dx.doi.org/10.1080/1573062x.2012.668913.

Gersonius, B., Ashley, R., Pathirana, A., & Zevenbergen, C. (2012). Adaptation of flood risk infrastructure to climate resilience. *Proceedings of the Institution of Civil Engineers: Civil Engineering, 165*, 40–45. http://dx.doi.org/10.1680/cien.11.00053.

Gersonius, B., Ashley, R., Pathirana, A., & Zevenbergen, C. (2013). Climate change uncertainty: Building flexibility into water and flood risk infrastructure. *Climatic Change, 116*, 411–423. http://dx.doi.org/10.1007/s10584-012-0494-5.

Gersonius, B., Ashley, R., Salinas Rodriguez, C. N. A., Rijke, J., Radhakrishnan, M., & Zevenbergen, C. (2016). *Flood resilience in water sensitive cities.* Clayton, Melbourne, Australia: Cooperative Research Centre for Water Sensitive Cities.

Haasnoot, M., Kwakkel, J. H., Walker, W. E., & ter Maat, J. (2013). Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. *Global Environmental Change, 23*, 485–498. http://dx.doi.org/10.1016/j.gloenvcha.2012.12.006.

Haasnoot, M., Middelkoop, H., Offermans, A., Beek, E., & Deursen, W. P. (2012a). Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change, 115*. http://dx.doi.org/10.1007/s10584-012-0444-2.

Haasnoot, M., Middelkoop, H., Offermans, A., Beek, E., & Deursen, W. P. A. (2012b). Exploring pathways for sustainable water management in river deltas in a changing environment. *Climatic Change, 115*, 795–819. http://dx.doi.org/10.1007/s10584-012-0444-2.

Haasnoot, M., Middelkoop, H., van Beek, E., & van Deursen, W. P. A. (2011). A method to develop sustainable water management strategies for an uncertain future. *Sustainable Development, 19*, 369–381. http://dx.doi.org/10.1002/sd.438.

Haasnoot, M., & Van Deursen, W. (2015). *Pathways generator. 2016*Deltares and Carthago Consultancyhttps://publicwiki.deltares.nl/display/AP/Adaptation + Pathways, Accessed date: 21 September 2016.

HM Government (2016). *National flood resilience review. 2016.* Crown copyright.

Horton, B., Digman, C. J., Ashley, R. M., & Gill, E. (2016). *BeST (Benefits of SuDS Tool) W045c BeST - Technical guidance. Release Version 3, vol RP993.* Griffin Court, 15 Long Lane, London, EC1A 9PN, UK: CIRIA.

Jabareen, Y. (2013). Planning the resilient city: Concepts and strategies for coping with climate change and environmental risk. *Cities, 31*, 220–229. http://dx.doi.org/10.1016/j.cities.2012.05.004.

Koste, L. L., & Malhotra, M. K. (1999). A theoretical framework for analyzing the dimensions of manufacturing flexibility. *Journal of Operations Management, 18*, 75–93. http://dx.doi.org/10.1016/S0272-6963(99)00010-8.

Kwakkel, J. H., Haasnoot, M., & Walker, W. E. (2015). Developing dynamic adaptive policy pathways: A computer-assisted approach for developing adaptive strategies for a deeply uncertain world. *Climatic Change, 132*, 373–386. http://dx.doi.org/10.1007/s10584-014-1210-4.

Kwakkel, J. H., Haasnoot, M., & Walker, W. E. (2016). Comparing robust decision-making and dynamic adaptive policy pathways for model-based decision support under deep uncertainty. *Environmental Modelling & Software, 86*, 168–183. http://dx.doi.org/10.1016/j.envsoft.2016.09.017.

Löwe, R., Urich, C., Sto Domingo, N., Wong, V., Mark, O., Deletic, A., & Arnbjerg-Nielsen, K. (2015). Flood risk assessment as an integral part of urban planning. *2nd water sensitive cities conference*.

Lu, N., & Korman, T. (2010). Implementation of building information modeling (BIM) in modular construction: Benefits and challenges. *Paper presented at the Construction Research Congress 2010, Banff, Alberta, Canada*.

Malekpour, S., Brown, R. R., & de Haan, F. J. (2015). Strategic planning of urban infrastructure for environmental sustainability: Understanding the past to intervene for the future. *Cities, 46*, 67–75. http://dx.doi.org/10.1016/j.cities.2015.05.003.

McGaughey, R. E. (1999). Internet technology: contributing to agility in the twenty-first century. *International Journal of Agile Management Systems, 1*, 7–13. http://dx.doi.org/10.1108/14654659910266655.

Pathirana, A., Radhakrishnan, M., Ashley, R., Quan, N. H., & Zevenbergen, C. (2017). *Managing urban water systems with significant adaptation deficits – Unified framework for secondary cities: Part II - The practice climatic change.* http://dx.doi.org/10.1007/s10584-017-2059-0.

Pathirana, A., Radhakrishnan, M., Quan, N. H., & Zevenbergen, C. (2017). Managing urban water systems with significant adaptation deficits – Unified framework for secondary cities: Part I - Conceptual framework. *Climatic Change,* 1–14. http://dx.doi.org/10.1007/s10584-017-1953-9.

Phi, H. L., Hermans, L. M., Douven, W. J. A. M., Van Halsema, G. E., & Khan, M. F. (2015). A framework to assess plan implementation maturity with an application to flood management in Vietnam. *Water International, 40*, 984–1003. http://dx.doi.org/10.1080/02508060.2015.1101528.

Radhakrishnan, M., Ashley, R., Gersonius, B., Pathirana, A., & Zevenbergen, C. (2016). *Flexibility in adaptation planning: Guidelines for when, where & how to embed and value flexibility in an urban flood resilience context.* Melbourne, Australia: CRCWSC - Cooperative Research Centre for Water Sensitive Cities.

Radhakrishnan, M., Lowe, R., Gersonious, B., Ashley, R., Arnbjerg-Nielsen, K., Pathirana, A., & Zevenbergen, C. (2018). Flexible adaptation planning in a water sensitive Melbourne. *Proceedings of the Institution of Civil Engineers: Municipal Engineer* (Under Review).

Radhakrishnan, M., Pathirana, A., Ashley, R., & Zevenbergen, C. (2017). Structuring climate adaptation through multiple perspectives: Framework and case study on flood risk management. *Water, 9*, 129. http://dx.doi.org/10.3390/w9020129.

Ranger, N., Millner, A., Dietz, S., Fankhauser, S., Lopez, A., & Ruta, G. (2010). *Centre for climate change economics and policy adaptation in the UK: A decision-making process*.

Reeder, T., & Ranger, N. (2011). *How do you adapt in an uncertain world? Lessons from the Thames Estuary 2100 project.* (World Resources Report).

Revi, A., Satterthwaite, D. E., Aragón-Durand, F., Corfee-Morlot, J., Kiunsi, R. B. R., Pelling, M., ... Solecki, W. (2014). Urban areas. In C. B. Field, (Ed.). *Climate change 2014: Impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel of climate change* (pp. 535–612). Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press.

Rijke, J., Ashley, M. R., & Sakic, R. (2016). *Adaptation mainstreaming for achieving flood resilience in cities.* Melbourne, Australia: CRCWSC - Cooperative Research Centre for Water Sensitive Cities.

Rodriguez, C. S., Radhakrishnan, M., Ashley, M. R., & Gersonius, B. (2016). *Extended ATP approach to include the four domains of flood risk managment - Manual with prototype software tool.* Melbourne, Australia: CRCWSC - Cooperative Research Centre for Water Sensitive Cities.

Salama, A. M., & Wiedmann, F. (2016). Perceiving urban liveability in an emerging migrant city. *Proceedings of the Institution of Civil Engineers - Urban Design and Planning, 169*, 268–278. http://dx.doi.org/10.1680/jurdp.15.00034.

Sánchez, A. M., & Pérez, M. P. (2005). Supply chain flexibility and firm performance: A conceptual model and empirical study in the automotive industry. *International Journal of Operations & Production Management, 25*, 681–700. http://dx.doi.org/10.1108/01443570510605090.

Schulz, A. P., Fricke, E., & Igenbergs, E. (2000). Enabling changes in systems throughout the entire life-cycle – Key to success? *INCOSE International Symposium, 10*, 565–573. http://dx.doi.org/10.1002/j.2334-5837.2000.tb00426.x.

Simpson, T. W., Marion, T., de Weck, O., Hölttä-Otto, K., Kokkolaras, M., & Shooter, S. B. (2006). Platform-based design and development: current trends and needs in industry. *ASME 2006 international design engineering technical conferences and computers and information in engineering conference* (pp. 801–810). American Society of Mechanical Engineers.

Spiller, M., Vreeburg, J. H. G., Leusbrock, I., & Zeeman, G. (2015). Flexible design in water and wastewater engineering – Definitions, literature and decision guide. *Journal of Environmental Management, 149*, 271–281. http://dx.doi.org/10.1016/j.jenvman.2014.09.031.

Suh, E. S., de Weck, O. L., & Chang, D. (2007). Flexible product platforms: Framework and case study. *Research in Engineering Design, 18*, 67–89. http://dx.doi.org/10.1007/s00163-007-0032-z.

van Buuren, A., Driessen, P. P. J., van Rijswick, M., Rietveld, P., Salet, W., Spit, T., & Teisman, G. (2013). Towards adaptive spatial planning for climate change: Balancing between robustness and flexibility. *Journal for European Environmental & Planning Law, 10*, 29–53. http://dx.doi.org/10.1163/18760104-01001003.

Veerbeek, W., Gersonius, B., Ashley, R., Radhakrishnan, M., & Rodriguez, C. S. (2016). Appropiate flood adaptation: Adapting in the right way. *The right place and at the right time*. Melbourne, Australia: CRCWSC - Cooperative Research Centre for Water Sensitive Cities.

Verhoeff, M., Verhagen, W. J. C., & Curran, R. (2015). Maximizing operational readiness in military aviation by optimizing flight and maintenance planning. *Transportation Research Procedia, 10*, 941–950. http://dx.doi.org/10.1016/j.trpro.2015.09.048.

Victoria (2016a). *All things considered.* Melbourne: Infrastructure Victoria.

Victoria (2016b). *Draft options book vol version two.* Melbourne: Infrastructure Victoria.

Woodward, M., Kapelan, Z., & Gouldby, B. (2014). Adaptive flood risk management under climate change uncertainty using real options and optimization. *Risk Analysis, 34*, 75–92. http://dx.doi.org/10.1111/risa.12088.

Zevenbergen, C., Rijke, J., van Herk, S., & Bloemen, P. (2015). Room for the river: A stepping stone in Adaptive Delta Management. *International Journal of Water, 3*, 121–140.

Zhang, S. X., & Babovic, V. (2012). A real options approach to the design and architecture of water supply systems using innovative water technologies under uncertainty. *Journal of Hydroinformatics, 14*, 13–29. http://dx.doi.org/10.2166/hydro.2011.078.