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ORIGINAL ARTICLE

Adapting to climate change through urban water management: a participatory case study in Indonesia

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Abstract The benefits of integrated approaches to climate risk and adaptation studies are increasingly recognised. Thus, there is an increasing need for practical examples of such work in the literature. This paper describes a practical application of an integrated framework for climate change impacts on regional surface water resources and the urban water system in the Mamminasata metropolitan region, Indonesia. Two main features of the framework are: the integration of both climate and other physical and social considerations in the assessment; and the high stakeholder involvement before, during and after project implementation. Although the study is concerned with the Mamminasata region, the overall methodology is transferable to any region in Indonesia or internationally. Key outcomes from this study are: (1) creation of information for Mamminasata planners and water resources managers for when, and under what conditions, the water supply may or may not meet the demand; (2) a clear consensus and shared learning of the problems facing the region among cross-institutional stakeholders; and (3) identification of adaptation options for the urban water system and knowledge gaps and strategies for their implementation. Results of stakeholders' surveys conducted at the mid-point and at the end of the study indicate that these outputs will provide valuable guidance for future planning and management of Mamminasata regional water resources.

Keywords Climate adaptation · Integrated urban water management · Makassar · Stakeholder engagement · Urban areas · Water security

Introduction

Surface water from regional rivers is typically the main source of clean water for many cities around the world.

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Historically, water managers and planners used past climate and water data for planning activities. However, considering projected future climate variability, planning which is based solely on the historic data may create unreliable water supply systems (e.g. Bates et al. 2008; Milly et al. 2008). Urban communities need to better understand and manage water security, adapting to changes in regional climate as well as other factors such as population increase, economic development and urbanization trends. Adaptation options are particularly critical in developing countries, which also experience severe financial and institutional constraints (Ujang and Buckley 2002).

Adaptation requires both facilitation and implementation activities (Füssel and Klein 2006). Facilitation refers to activities that enhance adaptive capacity such as scientific research, promoting awareness, capacity building, institutions and governance. Since adaptation to climate change is a local to regional scale issue (e.g. Füssel 2007), a key challenge for local actors is to understand the nature of future climate risks in their region (e.g. Uittenbroek et al. 2012). However, most climate modelling studies are global or large scale and thus do not provide detailed information required for adaptation actions on regional or local scale (e.g. Bates et al. 2008; Birkmann and Teichman 2010; Pandey et al. 2010). If available at all, studies undertaken at lower scales are mostly qualitative in nature and tend to concentrate on the impacts of floods and sea level rise risks (Hunt and Watkiss 2011).

Urban water systems are a typical example of a complex social–ecological system, which consists of a linked 'bio-geo-physical' unit managed by multiple actors or agencies. Previous climate impact studies related to urban water provision typically do not consider contributions from non-climatic factors, such as new infrastructure and river regulation (Bates et al. 2008), and thus Ekström et al. (2012) call for the consideration of both biophysical and social dimensions when undertaking climate assessments in the water sector. Moreover, the literature suggests that research informing climate adaptation policy for urban water systems should adopt a transdisciplinary integrated approach in which researchers from a range of disciplines work together with stakeholders (e.g. Kasperon 2006; Kemp and Rotmans 2009; Pohl 2011). However, practical applications of transdisciplinary stakeholder-driven approaches to the exploration of complex problems, such as climate change and its impacts, are still relatively rare (e.g. Ekström et al. 2012; Podestà et al. 2012; Romero-Lankao et al. 2012). Stakeholder engagement is typically conceived as a marginal add-on or afterthought (Beirele and Cayford 2002) and is relatively ad hoc and unplanned (Carney et al. 2009).

The research project, Climate Adaptation through Sustainable Urban Development (SUD), presented in this paper, is an example of a practical application of transdisciplinary stakeholder-driven research to a problem of urban water security in the context of climate change. The project was undertaken in the Mamminasata metropolitan region in South Sulawesi Province, Indonesia, and was led by the researchers from the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Australia, in collaboration with the Hasanuddin University (UNHAS), Indonesia. The SUD project aimed to inform policy formulation to improve access to clean water and to manage the impacts of development and climate change in the main regional city, Makassar (CSIRO 2012). SUD firstly developed information on future regional climate and its impact on streamflow of rivers over the Mamminasata metropolitan region. Subsequently, this information was integrated with the projections of key socio-development variables in order to estimate future water security in Makassar. Finally, SUD identified potential adaptation options and strategies for their implementation. All of these were undertaken by an interdisciplinary research team who worked closely with stakeholders from project inception to implementation, integrating social and physical aspects of the water security. This paper contributes to the literature by describing practical application of an integrated research framework. Thus, the main focus of this paper is on the process, that is, the implementation of the project, rather than on the research results.

Regional context of the case study

The Mamminasata metropolitan region encompasses city of Makassar and three other municipalities i.e. Gowa, Maros and Takalar (Fig. 1). With a warm tropical climate, the rainfall is dominated by the Asian monsoon with a distinct wet (around November–May) and dry season (around June–September). Makassar is by far the largest city in the metropolitan region and is located on the west coast of the Sulawesi Island, has an area of around 176 km^2 and hosted 1.27 million inhabitants in 2009, with expanding economic, government and educational activity (Barkey et al. 2011). The Mamminasata region relies on surface water of three main regional rivers, Jeneberang, Tallo and Maros (Fig. 1), as the major water sources. For example, around 80 % of the current water supply to Makassar city is provided by the Jeneberang River through the Bili–Bili dam. Groundwater is also an important source for most of the population and economic activities; however, its exact usage is not known as it is not metered or measured in a reliable way.

The Makassar municipal water company (PDAM) treats the surface water from the Maros and Jeneberang Rivers to supply around 62 % of the population. The supply capacity

Fig. 1 Location of the Mamminasata metropolitan region, which encompasses one city (Makassar), three municipalities (Maros, Gowa and Takalar) and three rivers, in South Sulawesi Province, Indonesia

of the PDAM is already subject to problems such as seasonal rainfall availability, water turbidity due to erosion and landslides. Additionally, the city is expected to experience increased pressure from urbanisation, population growth, limited economic resources and climate risks (Tjandraatmadja et al. 2012a). A global sea level rise projections of 56 cm, for example, could inundate an area of over 900 hectares in Makassar City (Tamin 2010, *pers comm*).

The Indonesian government plans to develop Mamminasata region into a model metropolitan region and an exemplar of urban development for Indonesia (Presidential Regulation Number 55 Year 2011). Future development of the area aims to enhance the standard of living of the population, to promote economic development and to preserve their environment and amenities through the adoption of best practices of urban development around the world and consideration of available resources and capabilities. Achieving the Millennium Development Goals (MDG) for water and sanitation access is one of the key challenges for authorities, with provision of clean water being the first of six priority programs for the Mamminasata region. Makassar's own MDG target is to increase the access to clean water supply from 62 to 78 % of population by 2015. To achieve these targets, strategies outlined in the current Mamminasata Regional Masterplan include infrastructure updates, leakage reduction, water capture and treatment capacity upgrade as well as changes to water treatment plant service zones. Currently, climate change impacts are not considered in the Masterplan, nor any other assessment or water supply services planning, mostly because there has been no available information prior to this project. However, the Indonesian National Action Plan for Climate Change (Ministry of the Environment 2007) encourages regional governments to integrate climate risks into their regional development planning.

The conceptual framework

Guidelines for assessing climate change impacts and adaptation such as those authorized by the Intergovernmental Panel on Climate Change, IPCC (e.g. Carter et al. 1994) and the United Nations Environment Programme (UNEP) (Feenstra et al. 1998) are currently considered the standard approach (Burton et al. 2002). The seven steps are as follows: (1) define problem, (2) select method of assessment most appropriate to the problem, (3) test methods/conduct sensitivity analysis, (4) select and apply climate change scenarios, (5) assess biophysical and socio-economic impact, (6) assess autonomous adjustments and (7) evaluate adaptation strategies. However, the standard approach has been widely critiqued for its inability to provide adaptation responses and policy options, largely because it lacks attention to key actors or stakeholders or the policy context of adaptation (e.g. Burton et al. 2002; Dessai et al. 2009). To overcome this drawback, the use of risk management frameworks, such as those recommended by the Australian and New Zealand Standard AS/NZS 4360 Risk Management, has been increasingly proposed and accepted (e.g. Jones 2001, 2010; UNDP 2005). The main elements of the AS/NZS 4360 Risk Management process are similar, namely: (1) scoping exercise where the context of the assessment is established; (2) risk identification and identification of scenario development needs; (3) analysis of risks, their consequences and likelihoods; (4) risk evaluation and prioritisation; and (5) identification and selection of options to 'treat' the risks (adaptation and/or mitigation options). Importantly, however, in addition to these elements, the risk management framework proposes introduction of two overarching activities designed to span life of the project: (a) researcher–stakeholder interaction and communication with stakeholders and the wider community; and (b) monitoring and review where measures are assessed, and the decision to reinforce, re-evaluate or repeat the risk assessment process are made.

The SUD project had an important focus on urban water security; hence, a number of conceptual frameworks were explored that were relevant to the regional/local water context. One framework gaining traction in recent years is integrated urban water management (IUWM). IUWM is a subset of the integrated water resources management (IWRM) introduced by the United Nations (1992). While IWRM helps in making decisions on regional water allocations by considering the needs of all the competing catchment users, IUWM specifically aims to improve the adaptation capability of urban water systems to multiple drivers such as climate change and urban population growth (Maheepala and Blackmore 2008; Maheepala et al. 2010). The IUWM proposes adoption of a 'total water cycle' approach, where sustainable urban water provision is achieved through the integration of water supply, wastewater and storm water. Similar to climate and risk assessment frameworks, IUWM proposes a series of activities, starting with the set-up of a key stakeholder group responsible for overseeing the IUWM process and comprising representatives from critical organizations. In Activity 2, the agreement is reached on objectives, measures of success of the project and methods of analysis. Activity 3 involves understanding the current system, so that analysis can be undertaken in Activity 4. Finally, in Activity 5, the outputs are documented and plans are made for implementing the outcomes.

These three frameworks served as a basis for the development of the SUD project integrated research framework, presented in Fig. 2. Table 1 summarises how the three conceptual frameworks are adapted and integrated into SUD methodology. In this case, the SUD project framework integrates the regional and local water cycle, in accordance with IUWM principles, with climate change considerations such as regional climate change risks and their impacts on regional rivers, and the potential adaptation options. The

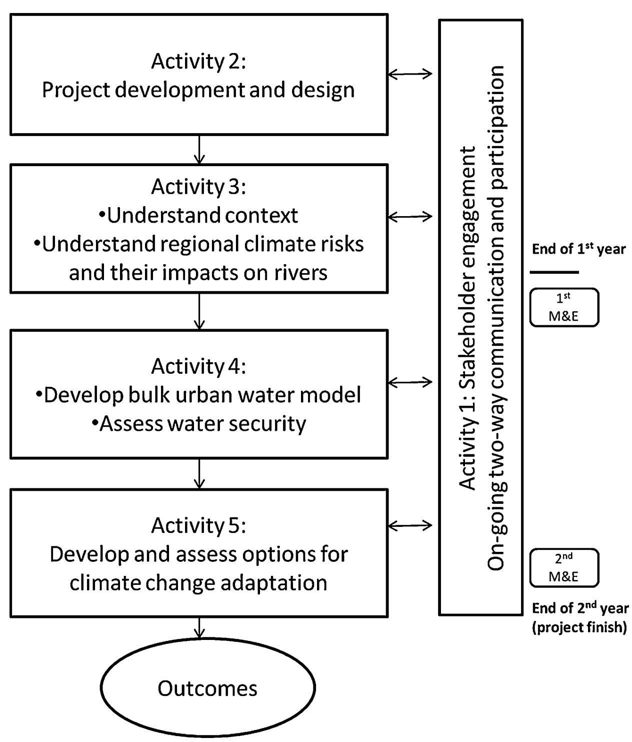

Fig. 2 Framework of the SUD project, based on the principles and steps proposed for climate change assessments (Burton et al. 2002), risk management (Jones 2010) and integrated urban water management (Maheepala et al. 2010). *M&E* monitoring and evaluation

SUD framework also calls for strong understanding of stakeholders' concerns and needs, as well as their involvement in the planning process and inclusion in monitoring, evaluation, and review of process and decisions. The application of this enhanced framework is discussed in more detail in the following section.

The SUD research framework

Activity 1: Stakeholder engagement

Stakeholder engagement is an overarching activity and plays a key role in all other activities. Initially, the process identified champions from two critical institutions in Indonesia and in South Sulawesi Province prior to project development (Fig. 3). The champions assisted the initial project scoping conducted in Activity 2. Once the project started, a comprehensive identification of key stakeholder groups was conducted by the researchers through stakeholder workshops, review of government documents and interviews with the representatives of government organisations (Larson et al. 2012). SUD defined stakeholders as individuals or groups who are affected by, or can affect, the outcomes of the project.

The stakeholders formed three groups, depending on their role, level of interest and anticipated engagement. The research partner group consisted of researchers from CSIRO—Australia and UNHAS—Makassar. The project partner group consisted of organisations which could contribute to the implementation of the project and which were end users of the outputs, and thus mainly comprised project beneficiaries (these agencies are listed in the Acknowledgements). The 'other' stakeholders group was defined as organisations which may in some way be affected by and/or may affect the outcome of this project, and included more than 40 government and non-government organisations, and academics. A full list of stakeholders can be found in Larson et al. (2012).

To facilitate an effective and strong participation of stakeholders as well as partnership among researchers, the research team developed a stakeholder engagement plan (Krick et al. 2005). The plan aimed to provide a strategy and timetable for sharing information and consulting with each stakeholder group and among research partners during various phases of the project, and to document processes and results of engagement activities as well as internal and external evaluation activities. The plan was designed as a 'living document' to be continuously updated throughout the SUD lifetime to record progress and outputs of the stakeholder engagement activities.

Figure 3 also summarises how the stakeholder engagement underpins all activities in SUD. By the end of the project, SUD had engaged more than 500 people from government and non-government organisations and academia to provide their opinion and feedback. Knowledge sharing and training were provided to a total of 233 people through four stakeholder workshops: one international knowledge sharing workshop in Makassar and three training workshops in Melbourne, Australia (Fig. 3), funded by

Table 1 Summary of how the three conceptual frameworks are adopted for the SUD research framework

Conceptual frameworks			Applied SUD framework
Climate change impact and adaptation standard approach	Risk management	IUWM	
	Overarching steps: Communicate and consult; Monitor and review	Activity 1: Convene stakeholder group	Activity 1: Stakeholder engagement; On-going two way communication and participation; two Monitoring and Evaluation processes
Step 1. Define problem	Establish the context	Activity 2: Agree on objectives, measures and criteria	Activity 2: Project development and design
Step 2. Select method	Identify the risks	Activity 3: Understand the current system	Activity 3: Understanding context; Understanding regional climate risks and their impacts on rivers
Step 3. Test method/sensitivity	Analyse the risks		
Step 4. Select scenarios			
Step 5. Assessment of impacts			
Step 6. Assess autonomous adjustments	Evaluate the risks	Activity 4: Assess system performance	Activity 4: Develop bulk urban water model; Assess water security
Step 7. Evaluation of adaptation strategies	Treat risks	Activity 5: Implementation planning	Activity 5: Develop and assess options for climate change adaptation

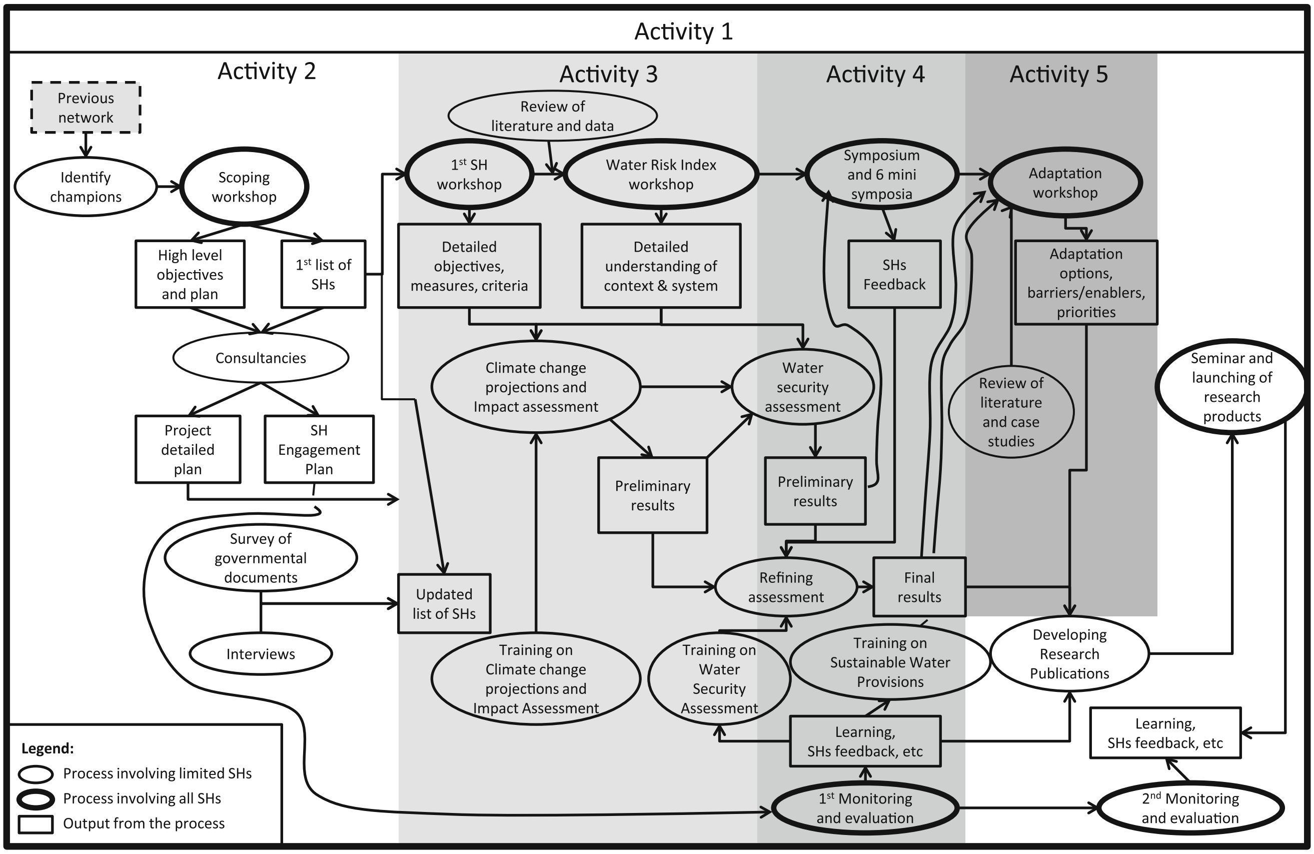

Fig. 3 Summary of stakeholder (SH) engagements processes that underpin all activities in SUD project

the SUD project. In addition, information dissemination and results sharing activities included one symposium, six mini symposia, and a seminar attended by additional 295 delegates. A stakeholder mailing list was developed and used to disseminate the project newsletter. This high level of engagement through the events indicates the high level of interest generated by SUD.

Activity 2: Project development and design

Following consultation with the project champions, the project development was initiated through a stakeholder workshop attended by 30 high-level representatives from variety of governmental agencies (at national, provincial and city level), NGOs, business enterprises, donor agencies and researchers in Makassar. The workshop agreed for SUD to focus on water security (i.e. reliability of water supply). Three main knowledge gaps were identified: projections of climate change and its medium-term (2030s) impacts on surface water; water supply system performance under climate change conditions; and potential adaptation options that would increase urban water security. A focus on these issues was considered consistent with the agenda of the Indonesian National Action Plan for Climate Change (Ministry of the Environment 2007), and SUD was expected to help building the Mamminasata capacity to mainstream climate change considerations into planning and development.

As a result of the stakeholder consultation, CSIRO researchers, with some input from the UNHAS researcher team, redesigned the original SUD project plan to focus more strongly on climate change impacts on regional surface water resources and on adaptation options. The process of assembling the research team was driven by the range of tasks and approaches envisioned during project development, and the final research group consisted of CSIRO and UNHAS researchers and students trained in climatology, engineering, economics, hydrology, forestry, regional and urban planning, environmental science, anthropology and communication science.

Activity 3: Understanding the context

The purpose of this activity was to understand the current and future water system (water supply, wastewater and storm water) context. This included understanding of system boundaries (both physical and non-physical), water service challenges, data availability and additional knowledge gaps. This task was achieved through an extensive literature review, information obtained through the stakeholder engagement processes and surveys, and analysis based on the available data and/or modelling.

Selected aspects of the context of the study region are described in section 'Regional context of the case study' and in Table 2. Information about climate change and its impacts on future streamflow characteristics were not available (Table 2) and were identified as one of the main data gaps during the project development stage (Activity 2). SUD undertook analysis and modelling work to develop this information. Figure 4 presents details of the methodology developed to further our understanding of the current and future regional hydroclimate and to assess future water security under a variety of scenarios. The hydroclimate modelling methodology is presented in steps leading to outputs 1–4 (Fig. 4), while hydroclimate modelling results are summarised in Table 3 (see also CSIRO 2012). Figure 4 also presents the methodology for assessing water security, discussed in the following subsection.

Activity 4: Assessing water security

Information gathered in Activity 3 was used by the researchers, in consultation with the practitioners, to develop a representation of Makassar's bulk water supply system in 2010 and in 2020. The bulk water supply (from surface water) and demand for Makassar city were modelled using the REsource ALlocation Model (REALM) software. REALM is a generalised simulation computer software package that models the harvesting and bulk distribution of water resources within a water supply system (Perera and James 2003). It configures the elements (such as reservoirs, demand centres and carriers) of the water supply system into a network of nodes and arcs, and solves the water allocation using a network linear programming algorithm.

In SUD, REALM was used to combine physical (e.g. climate and streamflow) and non-physical (e.g. population projections, infrastructure plan and operational rules) information to develop future scenarios of water supply and demand for 2020–2039 (Fig. 4, output 5a). Subsequently, the scenarios can be used, for example, to assess the monthly and annual water supply–demand changes with and without the planned infrastructure, and/or with various water use patterns under different climate scenarios (Fig. 4, output 5b) (for more details, see Tjandraatmadja et al. 2012b). The assessment did not include other competing demands (such as agricultural demand) as urban water supply was the priority demand.

The results reported in CSIRO (2012) indicated that problems related to the seasonality of streamflows are expected to continue. In addition, future water security will be impacted mostly by the increase in population and the associated increase in water demand. With or without climate change, there is a need to improve future water security, even after implementation of the infrastructure upgrade as outlined in the Masterplan. The findings indicated that currently planned infrastructure upgrades will only provide short-term security of supply, with further investment

Table 2 Summary descriptions of key aspects of water system in Mamminasata region (see Tjandraatmadja et al. 2012a for details)

Aspect	Descriptions
Water supply status	The region relies on surface water and groundwater
	Jeneberang and Maros Rivers feed five water treatment plants in Makassar
	Piped main water serves only 62 % of Makassar population
	Groundwater is widely extracted, but the exact use is unknown
Institutional set-up	Complex, with multi-level agencies sharing the jurisdiction and responsibilities over water resources, water delivery and sanitation
Data availability	Data on the state of the environment (e.g. water quality, groundwater condition and recharge levels, and river flows) and social conditions (e.g. water consumption patterns) are limited
	If available, data record periods may not be continuous and/or need to be checked prior to use
	Information on climate change risk and impacts were not available
Current and future challenges	Limited access to mains water. Financial constraints play a major role limiting capacity for the expansion of services
	Population is estimated to increase by 20 % by 2020, while water demand to increase by 120 %—outstripping the current piped water supply capacity and thus increasing use of groundwater
	Deteriorating groundwater quality, due to the larger pollution loads from waste water and solid waste generation, and quantity due to extraction
	Stakeholders recognise that climate change is happening, but climate risk and impacts on water resources have not been studied
Future development	Mamminasata Masterplan recommends some strategies to improve water supply service in the next 30 years. All infrastructure development is subject to external funding

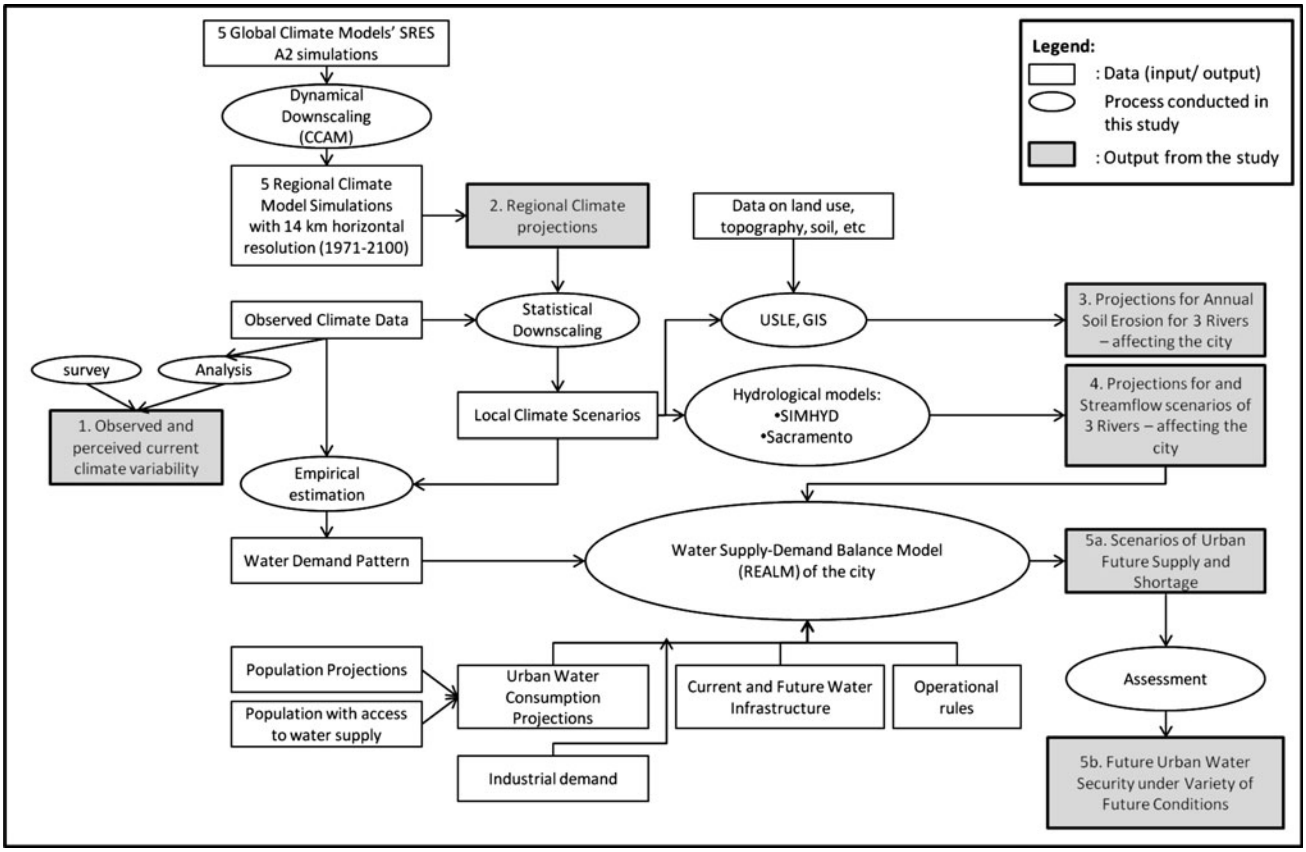

Fig. 4 Methodology to develop the understanding of current and future regional hydroclimate (leading to outputs numbered 1–4) and to assess future water security under variety of scenarios (leading to outputs 5a and 5b)

required from mid-2040s. Thus, there is a need to consider supply alternatives beyond the upgrade of water treatment plants alone: this was addressed in the next activity.

Activity 5: Identifying and assessing adaptation options

The identification was conducted through two methods. The first was a review of the literature and eight case studies on adaptation experiences in Makassar and around the world. The review, which focused on identifying technological and social tools already adopted, had two objectives. Firstly to examine the most common decentralised technologies for water supply, storm water and wastewater management in developing and developed countries; and secondly to examine climate change adaptation in urban areas. For each of the selected case studies, the review, reported in Tjandraatmadja et al. (2012c), discussed in detail the objectives, tools, implementation, benefits, challenges and key lessons. The key findings from the review were summarised into an adaptation review presentation designed to introduce the guiding principles for adaptation and examples of the various tool alternatives from around the world.

The second method used for the identification of adaptation options was a participatory approach through a stakeholder workshop which was attended by the representatives of government agencies at provincial, regional and municipal level; water utility managers; academics and NGOs. Outcomes of the previous project activities, including the adaptation review, were presented to increase the existing knowledge pool and also to develop a common knowledge base among participants. Armed with this information, a mix of individual, group and plenary activities were devised to elicit stakeholders' collective knowledge on the feasibility and relevance of various adaptation options to Makassar. Participants were encouraged to consider both locally developed adaptation tools and tools from the international arena to brainstorm potential adaptation options that could improve water and wastewater services for Makassar.

Participants identified more than ten adaptation options beneficial for Makassar (Table 4). Some of the proposed options were new (e.g. greywater treatment and use) while others were already in a planning (leakage reduction) or in the implementation (recovery tank at water treatment plants) stages. In small groups, participants also identified

Table 3 Summary of projected changes in climate, streamflow and soil erosion over the Mamminasata region, and water supply–demand balance for Makassar city in 2030s relative to the 1990s

Variables	Direction and range of changes
Based on modelling exercise in the project	
Climate	
Annual temperature	↑ (0.3–0.4 °C)
Dry season rainfall	↓ (around 36 %)
Wet season rainfall	No change
Wet season duration	Shortened (around 12 days)
Rainfall interannual variability	↑
Extreme rainfall intensity	↓
Potential evaporation	↑ (around 12 %)
Soil erosion	
Soil erosion volume	Slightly reduced overall
Distribution of area with a given soil erosion rate category	Little change
Streamflow	
Mean daily streamflow	
At Puca, near Lekopancing Weir	↓ (17–19 %)
To Bili–Bili Dam	↓ (4–7 %)
At the Mouth of Tallo River	↓ (34–39 %)
Flow characteristic at Puca, near Lekopancing Weir—intake for the municipal water company	
Mean annual flow	↓ (7–27 %)
Mean dry season flow	↓ (7–32 %)
Mean wet season flow	↓ (7–28 %)
Number of days with low flow (<2 m^3/s)	↑ (10–29 %)
Extremely high daily flow	Large uncertainty (+14 to −23 %), but likely to decrease (−4 %)
River supply	
Lekopancing Weir reliability	↓
Water inflows to Bili–Bili Dam	↓
Based on the inference from modelling results and/or the literature review	
Dry season storm water	↓
Groundwater recharge	↓
Groundwater extraction	↑
Water demand	↑
Water quality	
Jeneberang River	↓
Pollution	↑

potential barriers/enablers for implementation and ranked the adaptation options based on the perceived benefits to the sustainability of the water system in Makassar. Discussion was conducted in plenary to explore in greater details the top four options agreed among the groups: biopori; water reuse at the water treatment plants; changing mindset and increasing society's awareness of the water, climate and environmental challenges; and greywater recycling. Finally, participants analysed the top options and developed enabling strategies to overcome barriers and promote implementation. Detailed description of the methodology and results are provided in Tjandraatmadja et al. (2012d).

Gauging the added value of stakeholder engagement and of the SUD project

All stakeholders attending any formal engagement event were surveyed on their learning from SUD and the particular activity they attended. A written survey used open and closed questions to ask about the value of the SUD project and its relevance for the stakeholder and their work.

As an illustration, a survey was conducted at a Symposium designed to present the preliminary results of the SUD project at the end of first year of the project. Seventy per cent of survey respondents indicated that information presented in the Symposium 'increased my understanding

Table 4 Adaptation options identified by stakeholder workshop participants

Strategy	Options	
Management and protection of existing water sources	For surface waters:	For groundwater:
	Reforestation of catchment	Protection: Wastewater infrastructure and treatment
	Manage water allocation with stakeholders	Recharge: Biopori (a groundwater recharge and infiltration technology)
	Wastewater treatment	
Efficient use of current resources	Operation and maintenance/storage: recovery tank at each water treatment plant	Mindset change
	Leakage reduction	
	Dredging of canals or rivers to reduce sedimentation	
New sources	Greywater treatment and reuse	
	Demonstration project of the use of treated wastewater	
Infrastructure	Large infrastructure construction (new dam)	

of climate change and its potential impacts on Makassar', while 20 % declared they were 'motivated to take action'. Further, around 50 % of respondents surveyed at the end of the project declared that the information from the study 'motivated them to take action' and 76 % believed that 'the information could be used for future planning and management of Mamminasata regional water resources'. Respondents also reported being 'intrigued', 'impressed' or 'concerned' to know the climate risks identified through the study and reiterated the need for follow-up and action in this area.

Both the engagement process and the SUD project were evaluated by the main project beneficiaries on two occasions: at the end of the first year and the second year, respectively (marked as M&E in Fig. 2, see also Fig. 3). These evaluations consisted of face-to-face semi-structured interviews with directors (or equivalent) and members of senior management staff (heads of sections) of the beneficiary agencies. Overall, SUD was perceived as extremely relevant and useful to stakeholders' work. There were also several suggestions that this work should be included in the next round of Mamminasata Regional Masterplan revisions in 2016. The beneficiaries recognised that the project was 'listening' and 'addressing' their needs and concerns. An example of suggestions for future improvement was 'the need to disseminate research results not only at the institutional level but also to the community level'. In this regard, there was a high level of commitment by the beneficiaries to continue dissemination of the project results within their agencies and to the others as well as to the community. Concurrent with the external evaluations, the project research team also conducted self-evaluations of both the engagement process and the project overall (see Larson et al. 2012 for more detail). These formal self-evaluations found that all the engagement objectives and planned activities were successfully completed, and that most of the potential obstacles identified at the start of the project were well managed throughout. The positive findings of self-evaluations were in agreement with the positive responses from external evaluations by project beneficiaries and other stakeholders (Larson et al., *under review*).

Discussion

The climate adaptation through SUD research project was intended to address the need for improving adaptation capability of the urban water system of the Mamminasata metropolitan region in Indonesia to multiple regional drivers (both climate and non-climate). As noted by Kiparsky et al. (2012), a common challenge for the studies of climate change lies in the translation of information at global scales (e.g. regimes of temperature and precipitation) to the relevant effects on what we care about (e.g. water supply). Thus, the conceptual framework developed for this project was inspired by both climate and risk management frameworks (Carter et al. 1994; Feenstra et al. 1998; Burton et al. 2002; Jones 2010) as well as a framework relevant for planning and managing urban water systems, IUWM (Maheepala and Blackmore 2008), and was applied at the scale relevant for adaptation action (Füssel 2007): physical boundary for the analysis of future climate and its impact of surface water was at the regional scale (Mamminasata metropolitan region) while that for water security and adaptation strategies was at a city scale (Makassar). Practical application of such a transdisciplinary approach required assembling a team of experts from a range of disciplines and extra investment, compared to traditional disciplinary approaches, in team building, communication and mentoring (Roux et al. 2010). Such collaboration between multiple disciplines allowed this project to address a range of multiple parallel drivers, such as urbanisation trends, infrastructure upgrades and institutional arrangements, in tandem with climate, a feat not always achieved in climate science research (Kiparsky et al. 2012).

Another key point of the SUD research framework was the high level of stakeholder involvement. Unlike most previous adaptation studies (Beirele and Cayford 2002; Carney et al. 2009), the SUD project carefully designed, implemented, monitored and evaluated stakeholder engagement activities. This engagement was able to foster multi-way modes of communication, participation and social learning, which are considered to be superior to one-way flows of information from science to practice (Pahl-Wostl et al. 2010). In applying this approach, there was co-production of knowledge between researchers and stakeholders, while at the same time building awareness and capacity of regional stakeholders on climate risks and adaptation. Co-production of knowledge facilitates stakeholders' 'buy in' which then increases the likelihood of integration of climate information into policy domains (Yuen and Preston 2010), whereas building awareness and capacity of local actors are important determinants for adaptive capacity of a region (e.g. Füssel and Klein 2006). Further, stakeholder survey results indicated that the project was perceived as extremely relevant to stakeholders' work and useful for future planning and management of Mamminasata regional water resources.

An important outcome of this study is the new knowledge created, both on climate and hydrological projections in the Mamminasata region, and on the reliability of the Makassar's water supply system under a variety of integrated future scenarios. The information is now available to inform Mamminasata planners, water resource managers, municipal water company and other related institutions, for example, to estimate when and in what conditions the supply may or may not meet the demand. However, as Sarewitz and Pielke (2007) warn, integration between 'producers' and 'consumers' of knowledge is not always present, and thus a main challenge for climate adaptation in the water sector remains ensuring a match between the knowledge needed and the knowledge produced. Insistence of key stakeholders in this study on integrating knowledge generated in this project into the next round of revision of the Mamminasata Regional Masterplan in 2016, and other key government document (e.g. Mamminasata State of Environment report published by the Ministry of Environment) strongly supports suggestions in the literature that learning through knowledge sharing is one of the most effective ways to ensure the production of the 'right' knowledge (van Kerkhoff and Lebel 2006).

The clear consensus and shared learning among stakeholders—from variety of institutions—of the problems facing the region and the city, which developed as a result of this project, is another of its key outcomes. The study provided a platform that brought together diverse group of people (e.g. planners, water managers, environmental managers, engineers and researchers with variety of expertise) each of whom holds, or has access to, different bodies of knowledge, beliefs and experiences, and motivated them to exchange and share knowledge, beliefs and experiences about Mamminasata's water system's vulnerability to climate change and other impacts. Such cross-institutional communication may facilitate future cooperation and networking, and active social networks have been identified as an important enabler for adaptation (e.g. Hay and Mimura 2006; Pahl-Wostl et al. 2010; Larson et al. *under review*).

Thirdly, the research identified suitable adaptation options, knowledge gaps that need to be addressed and strategies for their implementation. In the discussion process that accompanied the development of options, participants had the opportunity to explore and discuss the advantages and disadvantages of the various options and the justification for their selection in small groups. The plenary also provided ample opportunity for rebuttal and sharing of perspectives from stakeholders from different technical backgrounds, thus raising new questions and issues for exploration. Some of the proposed adaptations were new, while others were already in planning or in the implementation pathway. For instance, recovery tank at the treatment plant was already being investigated by the plant operator for technical and cost feasibility and had the potential to increase water production at the plant by 10 %. On the other hand, greywater treatment and reuse had been largely unexplored in Makassar and will require a more extensive investigation to understand the science and socio-technical gaps (e.g. investigation of greywater characteristics, assessment of treatment viability and options, development of pilot trials and community acceptance) before a detailed feasibility assessment can be undertaken; yet, it could have the potential to address two key issues: pollution reduction and augmentation of water sources. Such an exercise was aimed at the development of conceptual options and pathways for implementation, which forms the starting point for the development of a more detailed options assessment exercise.

The outputs, as they currently stand, can inform policy formulation but are not sufficiently detailed as to inform policy implementation. Further assessment of the viability of the options proposed is still required, including those that have been implemented. Such an assessment should include scientific analysis and comparison of various proposed options based on a variety of criteria such as the status of knowledge, technical feasibility, cost and benefits with regard to the economy, environment and social acceptance. Subsequent study can assess the vulnerability to climate change considering the feasible adaptations, using the modelling tool developed through this project.

The IUWM principles require consideration of the whole urban water system. This means that all factors (e.g. environment, social, economic, regulation and institutional arrangements) affecting the performance of the water system must be taken into account (Maheepala et al. 2010). The SUD project considered all these factors when identifying water service challenges and adaptation strategies. However, only selected factors were considered when assessing the Makassar's future water security, simply due to the data availability. Considerable limitations of wastewater and storm water data (Barkey et al. 2011) meant that the assessment was performed on the water supply component only, rather than using total water cycle as proposed in IUWM. Gaps in data available for the analysis of water resources are a persistent problem in particular in developing countries, with data sets often limited in quantity, quality and relevance, thus impairing the ability of decision makers to design appropriate policy and achieve management outcomes (Larson et al. 2013).

The factors selected as affecting performance of the Makassar water system were environmental (climate and streamflow), social (population growth, population with access to water supply, water consumption pattern, operational rules) and institutional arrangements (infrastructure plan). The environmental projections were primarily model-driven, developed through SUD project, and intrinsically linked to global emission scenarios, while social and development projections were locally driven. Thus, the SUD project has combined both the top–down and bottom–up approaches in its climate risk assessment, contributing to a slim body of the literature that reports on practical application of the combined approach (Ekström et al. 2012).

Concluding remarks

An integrated framework has been applied to address specific knowledge gaps in the Mamminasata metropolitan region, Indonesia, and to inform policy formulation on the impacts of development and climate change on the water security of the main regional city, Makassar. Two main characteristics (i.e. interdisciplinary research teams working together with stakeholders, and an integration of climate and non-climate factors in the research) provided innovation to this framework. Both proved valuable additions and resulted in beneficial outcomes. First, there is new knowledge of climate and hydrological projections in the Mamminasata region, and of the reliability of the Makassar's water supply system under a variety of plausible scenarios. Further, this knowledge is viewed by key stakeholders as very relevant to decision-making processes and useful in providing adaptation responses and policy options, and is finding its way into key regional planning documents. Second, there is now a clear consensus and shared learning of the problems facing the region and the city among cross-institutional stakeholders. Third, the research identified a range of adaptation options: their suitability to the local context was deliberated with and agreed upon by the wide range of stakeholders. Further assessment of the viability of the options is, however, still required. Ultimately, feasible adaptations options can be assessed for their vulnerability to climate change, using the modelling tool developed through this project.

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