Challenges of water and wastewater management in the desert megacity of Lima/Peru – how can macromodelling help?

Les défis de la gestion de l'eau et des eaux usées à Lima (Pérou), mégalopole désertique : comment se servir de la macromodélisation ?

M. Schütze, G. Robleto

ifak - Institut für Automation und Kommunikation e.V. Magdeburg, Werner-Heisenberg-Str. 1, 39106 Magdeburg, Germany, manfred.schuetze@ifak.eu

RÉSUMÉ

La planification, la conception et la gestion des infrastructures de l'eau ont toujours constitué un grand défi. Cela est particulièrement vrai dans les mégapoles confrontées au changement climatique. Il est recommandé de considérer le système de l'eau comme une entité globale pour l'approche des divers scénarios et le développement d'options stratégiques. Ceci permet d'envisager les nombreuses interactions entre les sous-systèmes et de parvenir à des options de solutions globales. L'application de la macromodélisation permet de prendre en compte la complexité : la modélisation et la simulation de toutes les parties du système d'eau urbain permettent de l'analyser comme une seule entité. Un simulateur de macromodélisation a été développé sur la base des principes de modélisation de flux de la ressource. Son application au système d'eau, d'assainissement et d'électricité de Lima – un système soumis à des conditions limites particulièrement difficiles – permet des discussions et des prises de décision informées impliquant les parties prenantes concernées.

MOTS CLÉS

Changement climatique ; Lima ; macromodélisation ; participation des parties prenantes ; gestion urbaine de l'eau

ABSTRACT

Planning, design and management of water infrastructure always has been a challenging task. This holds true in particular for megacites facing the challenges of climate change. As a means of considering various scenarios and developing beneficial acting options, consideration of the entire water system as one entity is advocated. This allows to consider the numerous interactions between the subsystems and to arrive at global solution options. In order to cope with complexity, macromodelling is applied here: Modelling and simulating all parts of the urban water system allows its analysis as one entity. Based on the principles of resource flux modelling, a new, versatile macromodelling simulator is developed. Its application to the water, wastewater and energy system of Lima/Peru – a system with particularly adverse boundary conditions –allows informed discussions and decisions involving also the relevant stakeholders.

KEYWORDS

Climate change; Lima; macromodelling; stakeholder participation; urban water management

1 INTRODUCTION

Planning, design and management of water and wastewater infrastructure always has been – and is and always will be - a challenging task. Traditionally, the related tasks have been subdivided in subtasks, focusing, for example, on planning, design and management on one hand and on the various parts of the water system on the other hand (cf. Figure 1). Such partition often results in specific knowledge and expertise being applied to specific (sub-)problems of urban water management, thus contributing to (more or less) good solutions for each subsystem. On the other hand, such "sectorisation" leads to loosing the oversight and overview of the entire water system and tends to neglect the interactions between its subsystems. In many cases, for example, it leads to the fact that different departments of the water company (or even different companies) are responsible for different subsystems, with the interactions between the subsystems not anymore being considered to an appropriate extent. Examples are abundant, also alone within the field of urban wastewater management, and have been discussed elsewhere (Lijklema, 1993; Rauch *et al.*, 2002; Muschalla *et al.*, 2009).

	Planning	Design	Operation	Asset management
River basin management	X	X	X	X
Drinking water reservoirs	X	X	X	X
Groundwater wells	X	X	X	X
Water supply system	X	X	X	X
Stormwater infiltration	X	X	X	X
Wastewater collection	X	X	X	X
Wastewater treatment	X	X	X	X
Wastewater reuse	X	X	X	X
Sludge processing	X	X	X	X
Customer relations and billing	X	X	X	X
…	X	X	X	

Figure 1. Some subsystems and tasks in urban water management, often dealt with by different organisational units

However, as systems and/or cities grow (if currently perhaps not so much in central Europe, but more so in other parts of the world), it is even more difficult to maintain an overview and holistic consideration of the system. This holds true for, at least, three principal reasons:

- Optimum solutions for subsystems do not necessarily represent solutions which are optimum for the entire system. Consequences of potentially sub-optimum decisions and/or measures taken can be even disastrous. For example, construction of a new water purification plant with larger capacity, without however considering enlarging the subsequent water supply mains, represents just a simple, but real, example.

- Sometimes, suggested solutions are also driven (and promoted) by particular interests – take as an example a company selling desalination equipment. It is more than natural that such company would suggest seawater desalination as a means to tackle water supply problems. Obviously, there is nothing wrong with promoting such (commercial) interests, however, an overall evaluation of the system and potential solutions should put a solution option in the overall context, analysing its effects on the entire system and compare with, if available, other solution alternatives as well. This again supports the need for overall consideration of the entire system.

- Furthermore, urban planning (which is not always existent to a full extent) increasingly tends to include various aspects and disciplines in order to enhance quality of urban life.

> Cooperation between various disciplines, not only from engineering (e.g. for the various urban lifelines – water, energy, solid waste, transport – and their interactions), but also from urban planning, landscape architecture, social sciences, economics (both, on micro and on macro levels), to name but a few, is increasing. Considering the water and wastewater system within such a context requires an overall and integrated view and perspective of the lifeline-related issues.

Such need for overall consideration of the system in order to achieve optimum system performance is nothing new, but holds true in particular for densely populated megacities, these being complex systems affecting the quality of life of millions of people. Also challenges such as achieving sustainability and addressing present and future global changes – such as, for example, climate change and migration streams – require the overall consideration of the critical lifelines, including the water and wastewater system. For some aspects, relevant studies have been carried out, indicating, as a study shows for the UK, the need for technological solutions in the short term and limiting urbanisation and better stakeholder engagement for the long term (Tait *et al.*, 2008).

Modelling a system offers the option to deal with a system's complexity: First of all, a model serves as (and, in fact, is) a formal description of the system; setting up a model urges to describe the system in a concise, formal sense. Secondly, applying a simulation model of the system allows, after issues of model "calibration" and validation (or, at least, plausibility check) have been addressed, to see the effects of input variations (these representing, for example, scenarios of climate change or population growth, but also various acting options).

However, considering the system and finding an optimum (in whatever sense) solution or, at least, best acting option under given framework conditions, is not sufficient for good water management. Increasingly, it is being recognised that, for successful decision making and project completion, the involvement (and free conviction) of the relevant stakeholders is not only beneficial, but, in the end, necessary (Renn, 2004), whilst the need is remaining to obtain a good balance between engineering and "soft skills" is essential (Parkinson *et al.*, 2007). In order to facilitate such discussion processes, a system model can serve as a base – and as a tool – to develop ideas, analyse and discuss options, estimating their effects and, eventually, coming to a joint decision which has great support by the stakeholders involved.

Based on these initial considerations, a modelling system has been developed for urban water, wastewater (and energy) systems in a megacity context. It is being applied for the case of Lima, Peru. Hence the subsequent section gives a brief overview of Lima's particular characteristics.

2 WATER IN METROPOLITAN LIMA/PERU

Lima (strictly speaking: the Metropolitan area of Lima and Callao; for the sake of brevity, in the sequel the term "Lima" will be used) is situated on the Pacific coast in Peru. This urban agglomeration has 8 million inhabitants, thus comprising of almost one third of the population of the entire country. The population is growing rapidly (the annual growth rate lies at above 2 %), mainly by migration of people from the provinces to the capital, in the 1980s fleeing from terrorist activities, nowadays mainly driven by the hope of finding economically better living conditions. The coastal zone of Peru is a desert area, with Lima having an annual rainfall of 9 mm, thus leading, for water supply, to a high dependency on (already overexploited) groundwater resources and to a use of the Andean rivers (both, from the Pacific as well as from the Amazonian watershed) as a water source. Effects such as El Niño and Southern Oscillation will lead to future water supply problems even more pronounced than today. As a means to ensure water supply, a number of reservoirs is in operation (linked by a Trans-Andean tunnel), capturing water and leading it – via the three rivers Rio Rímac, Río Chillon and Río Lurín - to the capital. These reservoirs are also used for hydropower generation, thus leading to conflicting use patterns of the water and electricity companies.

Water supply and management in most parts of Lima is done by the governmental water company SEDAPAL, whilst electricity rests with the private company EDEGEL. About 91 % of Lima's population are connected to the public water supply network (León, 2009). The remaining part of the population, mainly living in the hilly and dry periurban areas, get drinking water (sometimes of questionably quality) from private water trucks at high prices. The sewerage system covers about 86 % of the population, leading the wastewater to 18 wastewater treatment plants (which currently are covering 15 % of the wastewater production), whilst the large remaining part is discharged to the Pacific Ocean. The construction of a new large wastewater treatment plant is under preparation. Due to water shortage, also untreated wastewater is used for irrigation purposes (vegetable, parks) at some locations.

Water tariffs are regulated by the governmental regulator SUNASS. As the water company is governed by the national government, the municipalities (city district councils) have lesser influence on water management in Metropolitan Lima. The NGO sector plays an important role in Peru, also by assisting the periurban population in getting water of reasonable quality (FOVIDA, 2004), by promoting ideas of ecological sanitation, and by contributing technical expertise in general. International development cooperation contributes significantly to the country's development with many donor organisations being present in Peru. Recently Peru has been classified as "Upper middle income" country (World Bank, 2009), thus, according to this statistical classification, just having been "upgraded".

In summary, water and wastewater management in Lima faces, among others, the following particular challenges: Water scarcity (expected to increase in future years), increase in water demand due to population growth, high percentage of reuse and final discharge of untreated wastewaters.

Questions of pressing need in Lima include the following: which will be the predicted water demand in the future? Which measures will be necessary to meet such demands? How much water will be available in future? Can reduction of leakages and water saving campaigns, together with other approaches, achieve satisfying water and wastewater services also in the future? Which impacts are to be expected by various solution options and strategies?

3 MACROMODELLING SIMULATOR

In order to facilitate analysis of the complete urban water and wastewater system, including its interactions with the energy system, a macromodelling simulator has been set up.

The term "macro-modelling" is used here, in order to distinguish modelling of the entire system from modelling which goes down to pipe-level ("micro-modelling"). Even though, it would theoretically be possible to model each single pipe of the water supply and wastewater networks, doing this would not be beneficial for an overall analysis of the water system, as one would get lost in minute details. In order to achieve the overall objective of representing the entire water and wastewater system in one single model, the approach using the level of detail employed here, is far more beneficial. For detailed studies of individual parts of the system, which will result as the subsequent step of water management (e.g. for detailed planning of construction works), of course, more detailed models of subsystems can (and will) be applied.

The modelling system is based on the principles of resource flux modelling (e.g. Baccini and Bader, 1996; Montangéro et al., 2004). Flows and fluxes are represented by a system of algebraic equations, which is solved either by solving the corresponding system of linear equations or, in case of feedback loops within the system, by an iterative method (Newton-Raphson). In order to consider future changes, inputs can be defined as time-series, thus allowing future scenarios, such as use patterns, climate change impacts, to be modelled directly. The setup of the simulator deliberately has been designed in order to meet the following two objectives:

- High degree of flexibility, both for the user and for the model developer
- Model setup and modification can be done easily (without programming knowledge).

In order to meet these requirements, this simulator has been developed without drawing upon any (costly) commercial software. Furthermore, as flexibility is of utmost importance, it has been designed in such a way that the user and the model developer can easily add and extend the modelling system.

The macromodelling simulator represents the system by building blocks for each of its main elements (e.g. water purification plants, groundwater wells, water supply network, city districts, wastewater trunk sewers, wastewater treatment plants etc.). Additional modules, e.g. reservoir lakes, water reuse plants, desalination plants, will complete the set of modules required. Main parameters describing, for example, city districts include, among others, population number, distribution to social levels, water consumption patterns, percentage of non-revenue water. Besides water quantity, also water quality (in water supply and in wastewater) as well as energy fluxes are considered. Additional fluxes as well as Global Warming Potential can also be included. As any analysis of variants also includes a cost-evaluation, costs are also included in terms of capital and operational expenditure. For the cost evaluation, the cost categories of the water company have been implemented.

As the simulator is to be used also in a developing country context, its setup should not require external (potentially costly) software modules. Considering these requirements, the simulator not only allows to use existing building blocks to describe the water systems, but also to define additional fluxes (e.g. additional water quality parameters) and new modules, including calculation algorithms, easily. Internally, modules are represented by XML-files. As the simulator is to be used also in stakeholder discussions and on decision makers' level, visualisation of results is of outmost importance. Therefore, additional features of the simulator include interfaces to Google Earth for geo-referenced representation of results, viewing results by Sankey-diagrams, generation of HTML reports, and export of results to Excel spreadsheets. Furthermore, design formulas (e.g. for treatment plants) are directly integrated, thus facilitating options such as the construction of additional plants to be modelled and simulated easily. Therefore, the chosen approach ensures its applicability also for other urban agglomerations of the world. Language settings allow the system to be used in different languages, with additional languages being added easily.

4 MODELLING THE SYSTEM OF METROPOLITAN LIMA

As a first step to addressing the questions raised above (in Section 2), the existing and very complex water and wastewater system has been represented in the macromodelling simulator. The example discussed here considers one of the two most important seasons of the year (dry season) for the drinking water supply of the city. In the dry season also many groundwater wells are put into operation in order to meet the water demand. Close cooperation with the water company, who took (and continue to take) an active interest and contributed not only large amounts of their data but are also showing an active interest in model development, proved to be very useful. Data collections also involved communication with many different departments of the water company (being responsible for different subsystems).

The modelling system is currently being extended with the help of NGO partners, in order to include also the periurban settlements, which are not covered in 100 percent by the water company, in the model. At the same time, this also supports getting the various stakeholders together. As one of the intermediate results of the projects, it can be stated that water company and NGOs are now sitting more frequently than before on the same table.

In the following, a (simple) application example of the macromodelling procedure is presented: Figure 2 illustrates for the dry season some results of a sample model application by depicting a Sankey diagram representation of the flows in a part of Lima's water and wastewater system (parts of the Northern districts of the city). For the description of the system, building blocks (such as groundwater wells, water purification plants, water trucks, city districts etc.) have been used. With this information, and also using available data (e.g. National Census data of 2007) and making assumptions for the future (e.g. connection degree, percentages of non-accounted-for waters, water consumption patterns in the various districts, etc.), first, the current situation for the dry season is being modelled (base case). Now, using predictions (e.g. the projections by the water company of annual water losses reduction in each city district) and assumptions on future developments, for a time horizon of twelve years, the impact of an additional reduction of leakage losses has been analysed. For this exercise, it is been assumed that water losses are even more reduced (one additional percent-point more reduction) than currently being planned by the water company.

This is carried out in order to determine the volume of water that could be recovered, as well as the determination of the additional population that could be covered, taking into account the average water consumption of the population of each district. Figure 2 illustrates results of a simulation run by illustrating the main fluxes of drinking water (abstraction from ground water, river water purification and water supply by tanker trucks) and “production” of wastewaters. Within this study, the results indicate that, based on the assumptions made, that by this additional reduction of water losses (for example, in one of the most populated districts of the northern part of the city) water flows between 1126 and 1220 m3/d (years 2008 and 2020, respectively) could be recovered. Using this volume of water, and taking into account the average water consumption per capita per day, between 7460 and 8000 inhabitants could be supplied additionally with drinking water in the period under examination. It is obvious that also the construction of additional infrastructure required for the additional supply has to be considered in the planning process.

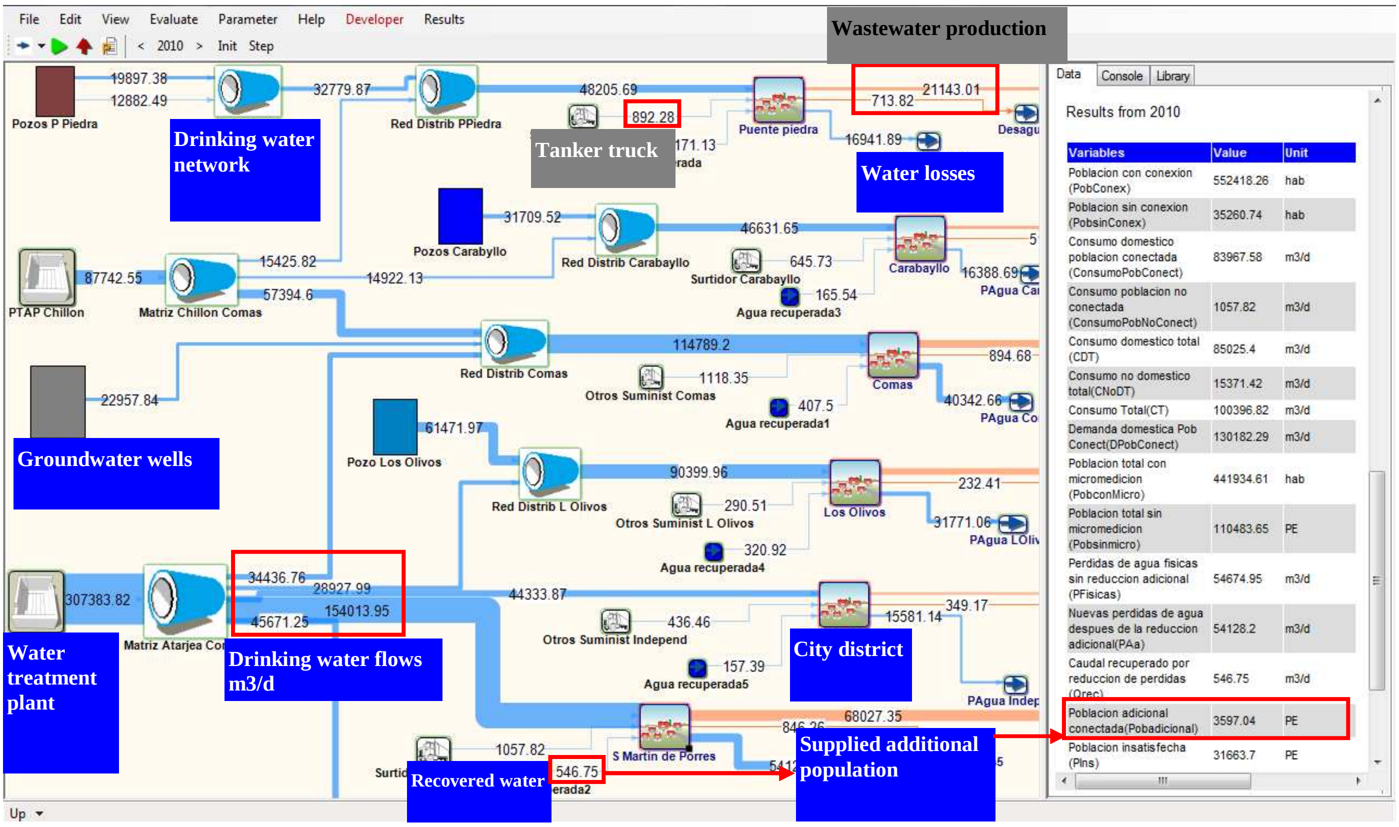

Figure 2: Model of the northern part of the city of Lima (results on water flows for the dry season in 2010 represented by a Sankey diagram)

5 APPLICATION OF MACROMODELLING IN A WIDER CONTEXT

It is obvious that the work on modelling the urban water system of Lima is embedded in a wider context. It forms an element of contributing to informed discussions and decisions, as is illustrated by Figure 3.

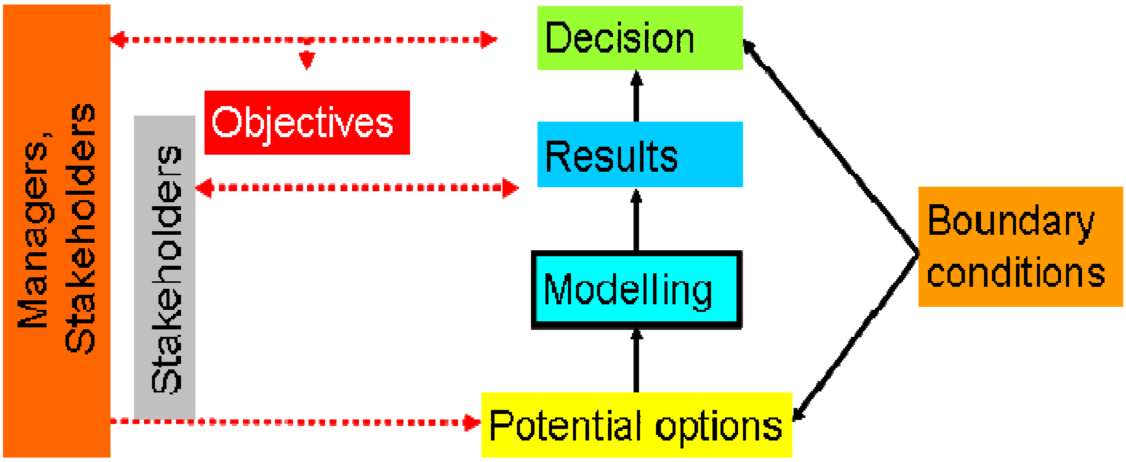

Figure 3. Modelling as core part of participatory decision finding

Overall, modelling contributing to participatory decision taking forms part of the Peruvian-German cooperation project "Sustainable Water and Wastewater Management in Urban Growth Centres Coping with Climate Change - Concepts for Lima Metropolitana (Perú) – (LiWa)" (see also www.lima-water.de for details). Project partners include, besides ifak, the University of Stuttgart, Ostfalia University of Applied Sciences, Campus Suderburg, the Helmholtz Centre of Environmental Research (UFZ) in Leipzig, Dr Scholz&Dalchow Consultant Engineers, the water and wastewater company of Lima (SEDAPAL), the National University of Engineering in Lima, the NGO FOVIDA and the association of NGOs and municipalities Foro Ciudades para la Vida in Lima.

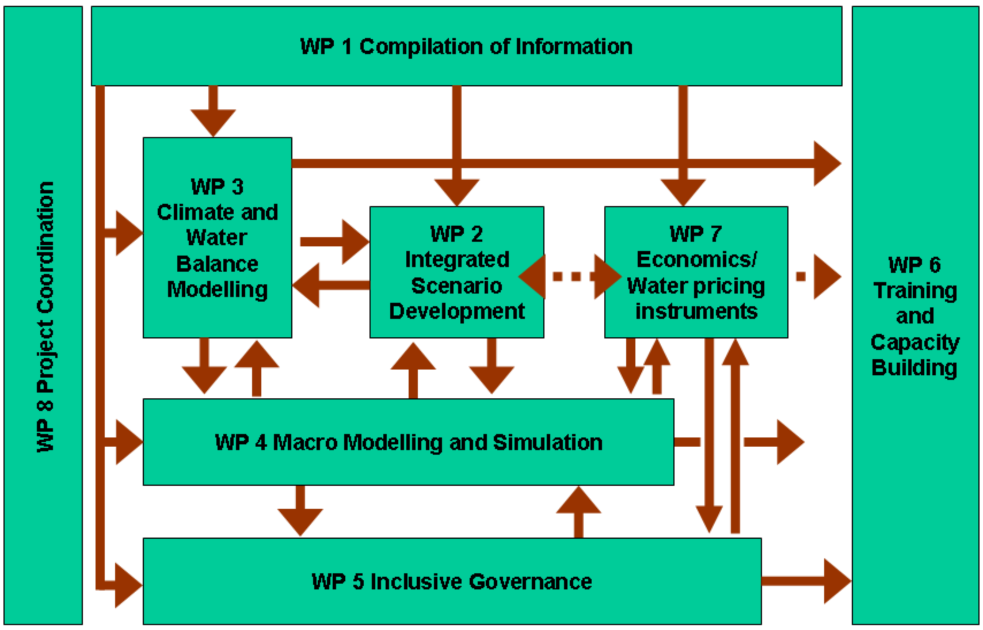

Figure 4. Structure of the Peruvian-German cooperation project "LiWa – Lima Water"

As Figure 4 shows, modelling of the urban system is closely interwoven with the other workpackages of the project: For example, as input data to the urban system, river flow data of the rivers, currently providing about 84 % of the city's water, are required. These are taken from available data, whilst for future scenarios of climate change, global climate models are regionalised to the Andean region and linked to catchment rainfall-runoff models (Chamorro and Bárdossy, 2009). Model building and application also is embedded in a process of scenario-building together with all stakeholders, which have been identified before. Scenarios have been defined based on 11 technological, social and economic descriptors, which have been agreed upon in a participatory process. Evaluations are supported by a detailed analysis of the structure of water tariffs in Lima (Lehmann, 2009). Finally, knowledge and experiences gained are feeding into the development of modules for Master courses in Peru and in Germany (Yaya-Beas *et al.*, 2007, Mennerich *et al.*, 2009). Furthermore, training courses on modelling of water systems in general and application of macromodelling in Lima in particular are also unter preparation.

6 CONCLUSIONS

Work on setting up the model is nearing completion, and evaluation of some scenarios has started, as illustrated above. Naturally, some modelling modules have yet to be added (e.g. desalination plants), in order to enhance the space of potential solutions and acting options. Modelling work will be extended to cover energy aspects in more details, as well as issues of reservoir operation in the river basin catchment, in order to address the use conflicts between water and energy industry, which clearly have an impact on water and energy availability in the metropolitan region, not only in the present, but also in the future. Also, the development of operating rules for better water allocation according to the various needs, will contribute to resolution of the use conflicts.

Even though, model development has been driven so far by the application case of Lima, it is not inherently limited to this case study. An application manual will also assist in its application to other urban regions. Due to the flexible and easy-to-apply nature of the simulator, this is believed to be easily possible. Potential is also seen for the application of the macromodelling simulator and methodology in assisting donor agencies in their evaluation of proposed investments.

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