Modelling and scenario building of urban water and wastewater systems – Addressing water shortage in Lima

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ABSTRACT
Water management of metropolitan urban regions represents an ever challenging task, particularly under the increasing pressures of climate change and population growth. This paper presents a methodology and tools developed for and applied for sustainable water and wastewater management in Lima/Peru. Regionalized climate models and techniques of scenario building are feeding into simulations using a water system simulator, covering the entire water and wastewater system of Lima. Modelling serves as an integral part of stakeholder involvement and participation and, thus, contributes to informed discussions and participatory decision finding.

KEYWORDS
Climate change; Cross-Impact balance; Lima; macromodelling; megacity; scenario

INTRODUCTION

Management of water resources is a task of ever increasing importance. This holds true not only in river catchments (such as in Integrated Water Resources Management), but also in particular for large urban agglomerations in arid areas. Some of them already suffer from water scarcity, a situation which may be exacerbated by climate change. Therefore, there is a pressing need to prepare the city's water (and wastewater) system for the future, in order to adapt for climate change. However, as the city's water system is rather complex and as it has manifold interactions with social, economic and ecological aspects, the challenge lies not only in technical issues (such as, for example, of water supply) and in the uncertainty of climate change impacts, but in the consideration of the entire (mega)urban water system and its interrelations between the various parts and subsystems. Furthermore, challenges are given not only by the task of finding appropriate solutions and measures for combating the challenges of the future (e.g. climate change, population growth), but also by implementing them. As experience suggests (see also the discussion in Ribarova *et al.*, 2011), measures implemented without the support of the local stakeholders will not lead to successful implementation. The present contribution presents work and results of a Peruvian-German project "Lima Water – LiWa", which aims to provides methodologies and tools assisting in tackling these challenges. Although this project puts particular emphasis on the water system of Lima, its methodology and tools are generic and can be applied also to other cities throughout the world. The need to consider such issues conjunctively also for urban agglomerations has been recognised recently also by a number of other institutions, having embarked on this topic (e. g. IWA's "Cities for the Future" initiative).

WATER IN LIMA METROPOLITANA

Lima (strictly speaking: the Metropolitan area of Lima and Callao; for the sake of brevity, the term "Lima" will be used in the sequel) is situated on the Pacific coast in Peru. Some main characteristics of this city's water system are summarized here in bullet points:

- *Population*: 8.5 million (National census data of 2007)
- *Population growth*: around 2 %, mainly by migration from the provinces to the capital
- *Climate characteristics*: annual precipitation: 9 mm; significant effects of El Niño and Southern Oscillation
- *Water supply*: mainly from superficial waters (rivers Rimac, Chillón and Lurín), also groundwater abstraction; part of water supply from the Amazon catchment, by means of Transandean tunnels); high leakage losses; 91 % of the city's population connected to the public water supply network; 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 vendors at high prices.
- *Wastewater*: 86 % of population connected to sewerage network, 18 wastewater treatment plants (treating, however, only a small fraction of the wastewater production; Some use of wastewater for park and vegetable irrigation
- *Administrative framework*: governmental water company SEDAPAL, water tariffs also strongly influenced by the governmental regulator SUNASS; 49 city municipalities, which are involved in water management only to a limited extent

Obviously, there are also a number of potential measures which might have potential to contribute to addressing such challenges. These range from infrastructural measures (e. g. extending the networks, construction of new central or decentralised plants, leakage reduction) to non-structural measures (such as water saving campaigns, different use patterns), but also to modification of the water tariff system, thus indirectly changing water use characteristics whilst maintaining affordable water tariffs. Thus, identification and implementation of prudent solutions represents a task, which, in practice often is influenced by particulate interests (e. g. of vendors promoting "their" technology, without always consideration being given to the entire system).

In summary, it can be stated that Lima faces particularly adverse boundary conditions in the area of water management. The complexity of the water system and of the challenges to the management of its precious water resources demands an overall approach, involving all relevant stakeholders into the discussion and decision process, yet providing them with a sound base of information. A methodology and a set of tools (scenario method, climate model regionalisation methods, macromodelling simulator) have been developed within the LiWa project, which will be discussed in the subsequent section.

THE LIWA METHODOLOGY

Figure 1 illustrates the underlying methodology and the various results of the LiWa project. Using global climate models and downscaling them to the Peruvian river catchments, possible scenarios of climate change impacts can be derived. However, scenario building – driven by the question "How could Lima look like in the year 2040?" – is a far more complex task. This will be addressed in more detail in the subsequent sections. Scenario definitions and catchment modelling results under climate change influences serve as input to modelling of the Lima water and wastewater system. A water system simulator, based on the fundamental principles of resource flux modelling and material flux analysis, has been set up by ifak in close cooperation with the water company SEDAPAL, allowing to represent the water and wastewater system of Lima in one single model. Water and wastewater flows, pollutant fluxes, but also energy production and consumption within the water system, are modelled. This allows to analyse various scenarios and acting options and their impacts on the entire water system. Hence, modelling and scenario building assists informed discussions and thus supports towards participatory decision processes, resulting in decisions borne and supported by the various stakeholders. An analysis of the tariff structure and the development of new tariff structures, in close cooperation with the regulatory agency SUNASS, complements the project. Integration of tariffs in the water system simulator allows the effects of tariff systems to be evaluated for the entire system. A capacity building component of the project ensures that the project's findings will be transferred to engineering practice. An eLearning platform ("LiWa Academy") has been set up and will be used in a professional development course held in Lima in May 2011.

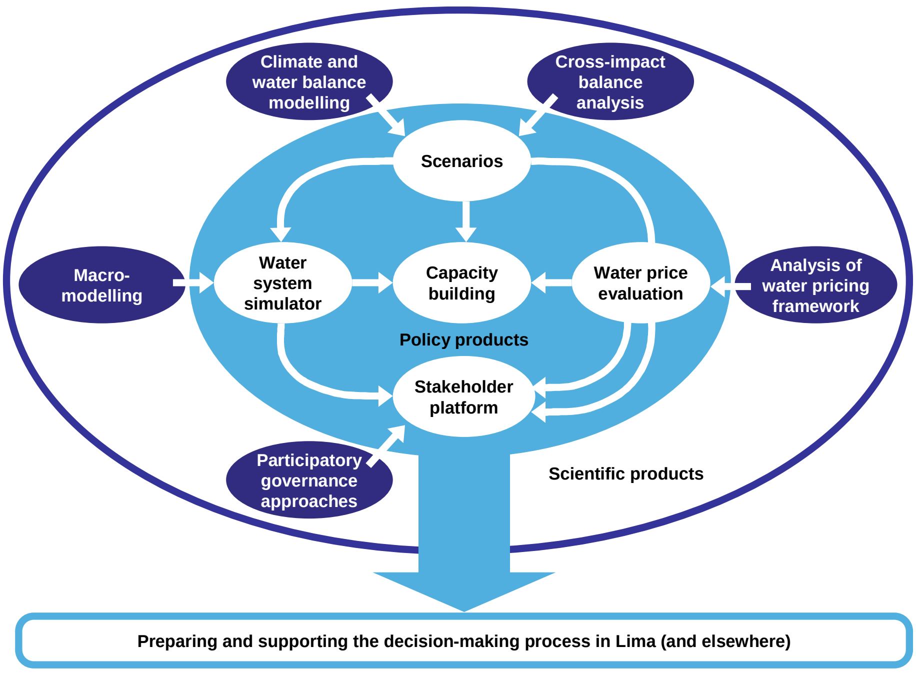

Figure 1: The LiWa methodology and project results

SCENARIOS – HOW COULD LIMA LOOK LIKE IN THE FUTURE?

Scenarios have proven to be a particularly beneficial instrument in those areas where developments cannot be forecast, owing either to their high range of uncertainty, their complexity, their susceptibility to interference, or their dependence on human decisions (Ringland, 1998). As the water sector in Lima is a complex system, interconnecting natural, technical, economics, political and social components, the LiWa project develops a set of scenarios for the water situation in Lima Metropolitana by the year 2040. The scenario building process comprises of the definition of assumptions and driving forces and the assessment of interdependences. The determination of these aspects cannot be done only from a scientific point of view. Thus, the scenario building process in LiWa has also been used to promote stakeholder participation and communication among the German and Peruvian partners of the LiWa project. In several workshops organised in Lima between 2008 and 2010, representatives of the local water utility (SEDAPAL), the National University of

Engineering (UNI), representatives of NGOs and invited experts discussed about the assumptions to build consistent scenarios. The workshops were moderated by the Peruvian project coordinator (ZIRN). Significant input was given by the Peruvian partners in compilation of information and in providing input from the Peruvian context into scenario workshops (e.g. Acevedo, 2010).

As a result, the driving forces that influence the water sector in Lima by the year 2040 have been identified. The first list of 35 factors was clustered and prioritised to reduce the number and to obtain a final list of 13 descriptors, which are now believed to represent the most important factors influencing the water sector in Lima and Callao:

Table 1: Descriptors of scenarios of Lima's water system

A Government	B Water company	C Water tariffs	D Demography
E Urban poverty	F Water demand	G Water losses	H Water catchment management
I Urban development	J Water deficit	K Wastewater treatment	L Water infrastructure
M Climate change			

In a further step, for each of the descriptors, several possible future developments have been formulated, which, in the following, are referred to as different assumptions of each descriptor. For example, the descriptor "M Climate Change" has three possible developments, as the results from climate and hydrologic modelling have shown (cf. Chamorro and Bárdossy, 2010). Furthermore, the interdependencies between the descriptors were specified. To ensure internal consistency of the scenarios, the LiWa project uses the Cross-Impact Balance analysis (CIB) to generate scenarios (Weimer-Jehle, 2006, 2008). CIB together with the corresponding software ("ScenarioWizard") was developed by the Center of Technology Assessment jointly with ZIRN. It provides a unique approach to conduct a causal system- and scenario analysis on a mainly qualitative level[1]. The CIB method was tested in numerous scenario projects and appears to be suitable also for fostering discussions between stakeholders. CIB includes the systematic evaluation of factor interdependencies using a qualitative concept of cross-impact judgements yielding a "cross-impact matrix".

For completing the cross-impact matrix, several workshops have been organised in Lima with participation of representatives from the water utility and civic society. Also results of the evaluation of water prices (including the level and tariff of the water price as well as overarching issues, such as economic growth, centralisation/decentralisation of economy, private/public supply of water services) have fed into setup of the scenarios and the cross-impact matrix. After completing the 1132 cross-impact judgements for all descriptor pairs, a set of plausible scenarios was constructed by the identification of internally consistent combinations of assumptions.
Using the tool "Scenario Wizard" (version 3.11, Weimer-Jehle 2010), the result of the Cross-Impact-Analyses were 10 scenarios, selected from a pool of approx. 200.000 possible assumption bundles. A surprising result is that the question, whether the population of Lima will suffer more or less water deficit in the year 2040, does not depend primarily on whether the water resources will decrease, maintain or increase in the future due to climate change, but rather on whether the government has or has not power to make decisions (respect to setting the necessary institutions – i.e. laws, regulations and organisations to establish an effective and efficient water governance) and the vision to take such decisions in an anticipated way.

[1] For more information see www.cross-impact.de.

The results have been condensed to 6 scenarios (Box 1) and discussed with the Peruvian partners.

I: Precaution and overshoot: Lima faces water surplus
An alarmed and capable society takes determined measures. A surprisingly favourable climate change (regarding the local water resources) may lead in the end to more than water deficit compensation. Although this scenario might be unlikely and should be not misunderstood as an appeal to inactivity, it is part of the space of possibilities.

II: Development without climate change stress
A moderate climate development avoids stress factors (water resource decrease, rural exodus) and issues no severe challenges to capable water governance. The water deficit can be safely compensated and the growing water demand of a prospering metropolis can be satisfied by determined infrastructure measures.

III: Climate change - a mastered challenge
An alarmed and capable society takes determined measures (organisational, infrastructure, savings) to respond to the challenge of a severe climate change stress (water resource decrease, rural exodus) and narrowly succeeds (although a failure was not impossible).

IV: Lucky escape: an unprepared society remains free from climate change stress
An inactive society tries its luck. No determined measures are taken to improve the water supply and to prepare for climate change. A positive climate development justifies the policy of inaction to some extent, but it leaves Lima behind with its unsolved home-made water problems.

V: Climate stress meets governance-disaster
An inactive society with unprepared water governance faces the cruelty of a severe climate change. Decreasing water resources, rural exodus and a neglected infrastructure combine to a desperate situation. This scenario marks the worst case of the LiWa scenario set. No final judgement was made so far whether it should be considered also as the non-suprise/trend scenario.

VI: The tragedy of isolated measures: Investment program in an adverse environment
In this scenario the water governance actors divide up into an active and an inactive part. While determined infrastructure measures are taken, other fields remain untreated and fail to back the undertaken measures with a supporting background.

Box 1: The six scenarios of possible future developments in Lima

DETERMINING IMPACTS OF SCENARIOS AND OF MEASURES - MACROMODELLING OF LIMA

The water system simulator set up for this project allows to represent the entire drinking water and the wastewater system in one single model, thus permitting to analyse effects of scenarios (e. g. climate change patterns) and acting options to be analysed in a comprehensive way.

The program allows to represent the system by building blocks for each of its main elements (e.g. water purification plants, groundwater wells, water supply network, tanker trucks, city districts, wastewater trunk sewers, wastewater treatment plants, etc.) (see also Figure 2). Additional modules, e.g. water reservoirs, desalination plants, various wastewater treatment technologies, will complete the set of modules required. City districts are characterised by, among others, population size, distribution of social levels, water consumption patterns (according to social economic level and connected and non-connected population) and percentage of population connected to the drinking water supply and sewer networks. Besides water quantity, water quality (water supply and wastewater) and energy fluxes are also considered. This “macromodelling” approach, as opposed to the micromodelling approach, attempting to model each single element (e.g. pipe) in minute detail, has been chosen here, in order not to loose the holistic view of the entire metropolitan water system. Detailed modelling of individual elements of the water system takes place as a later step, when detailed planning of infrastructural measures (e.g. construction of a new plant) is to be carried out.

The theoretical foundations of the modelling approach chosen here are based on the principles of resource flux modelling (e.g. Baccini and Bader, 1996; see also Schütze and Robleto, 2010). 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). The present version of the software allows only stationary models for these transformations (algebraic transformations). Different solvers for the system of nonlinear algebraic equations are implemented (Newton-Raphson, Levenberg-Marquardt and a specialised nonlinear iterative solver). From first experiences of the application of the system, a strong need for the option to include dynamical description methods (difference equations, differential equations) was identified. This need results partly from a number of important storage elements in the system (groundwater body, water reservoirs), but more seriously from the need to combine unit modules with tight interactions which can be described better using differential equations (ODEs). The latest version under development includes this option and the related ODE solvers (for stiff systems). 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. Figure 2 illustrates the water fluxes of the Lurin subsystem in 2008 by means of a Sankey diagram. Data and population predictions have been obtained from SEDAPAL.

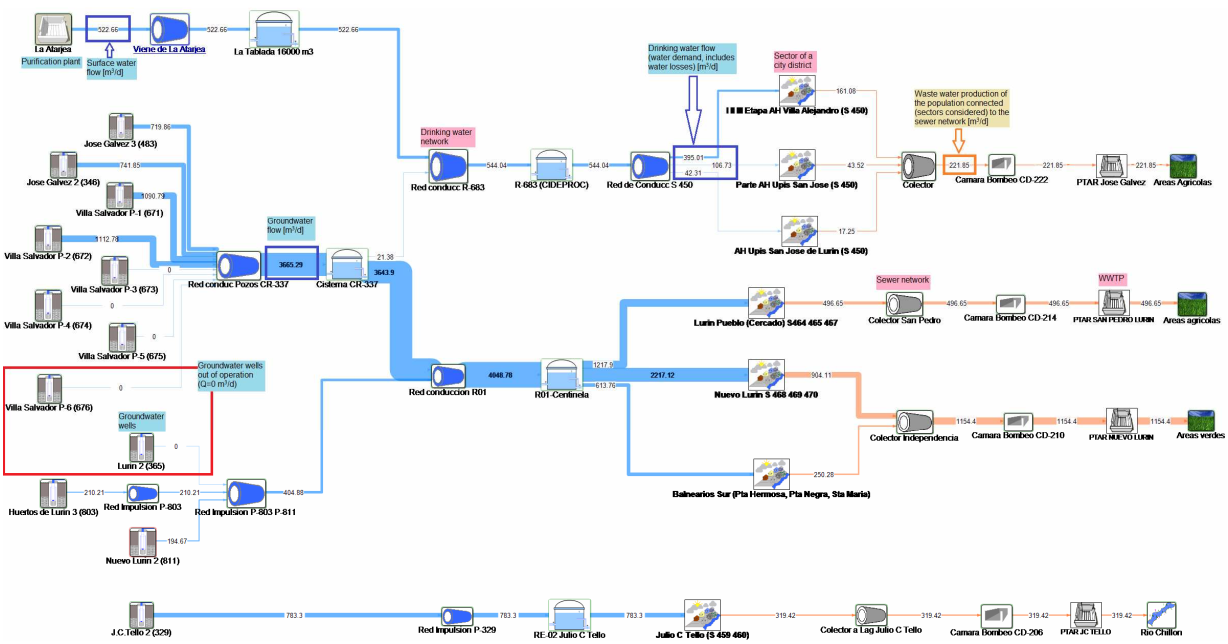

Figure 2. Sankey diagram: Water fluxes in the Lurín subsystem

In order to meet the requirements of flexibility and of application in a developing country context, 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. This features distinguishes this simulator from other, existing tools. Modification and extensions of the modelling system does not require any programming knowledge and can be done easily by the user himself. 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 and easily 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.

APPLICATION CASE: THE LURIN DISTRICT OF LIMA

Lurin is one of the districts in the south of the city. It has around 100000 inhabitants and is characterised by a large number of groundwater wells. Signficant urban development is expected for the coming years. Therefore, an example model of the Lurin subsystem has been set up. Scenarios considered so far for this example include, for example, population growth over 18 years as anticipated by Sedapal (SEDAPAL, no year); and information on climate developments obtained by Institute of Hydraulic Engineering of Stuttgart University from regionalised global climate models (in this case, from the model ECHAM 5 with Scenario A2 for the next 30 years). Using, for this illustrative example, a set of exemplary assessment criteria (including water availability for the population; energy consumption of groundwater pumps, distribution network and treatment plants; pollution discharges to the Ocean; revenues from water tariffs), the water system simulator allowed the effect of various acting options, here as operational strategies (e.g. leakage reduction and operational regimes of groundwater pumps), to be simulated, visualised (this proved to be very important) and discussed. According to an evaluation of various operational strategies, it could be concluded that a more uniform use of groundwater sources and a reduction of the energy consumption of the wells has been largely achieved (see Table 2). For this example, it results that prudent operation of the groundwater wells can maintain water supply for some time, however, the need to activate additional water sources will also arise in any case soon in coming years, with only the exact date being dependent on the assumptions made.

Table 2: Some results of management strategies in Lurin district

Scenario	BOD annual average discharge into Lurín river (kg/year)[2]	Annual average energy consumption of the entire system [kWh/year]	Annual average waste water flow (m^3/year)	Annual revenues from tariffs (PEN/year)
Base case (year 2006)	**14.780**	**20.937.250 (year 2006)**	**800.200**	**1543530**
Strategy 0[3]	**74.649**	**96.064.188**	**4.042.153**	**6.931.916**
Strategy 1[4]	**74.649**	**93.400.143**	**4.042.153**	**6.976.758**
Strategy 2[5]	**74.649**	**93.378.608[*]**	**4.042.153**	**6.976.758**

[2] BOD load of the sectors considered in the example
[3] Strategy 0: Considers, amon others, but not limited, population growth (according to the population projection of SEDAPAL), water flow forecast (data from IWS) in the Rimac river, constant water losses (40%) during the period of analysis, etc.
[4] Strategy 1: Considers, among, others, population growth (according to the population projection of SEDAPAL), water flow forecast (data from IWS) in the Rimac river, water losses reduction of one annual percent and modification of the flows extracted from the wells
[5] Strategy 2: The same data of Strategy 1 but with others flows rates from the wells
[*] Reduction of the energy consumption due to the implemented operational strategies in the groundwater pumps

OUTLOOK

At present, implementation of the entire water system of Lima is nearing completion. By time of the conference presentation, the model of entire Lima will be presented. In parallel, preparations for Round Table discussions are at hand. Relevant stakeholders have been identified and integrated in the project by a series of stakeholder workshops, which also provided useful input to model development (Figure 3).

Figure 3: Stakeholder Seminar held at Comunidad Andina de Naciones on 11.03.2010

In future Round Table meetings, impacts of climate change on the metropolitan water system and the resulting challenges will be discussed, using the modelling results as a sound base of information for informed discussions. Also, various acting options (e.g. infrastructural measures, water saving campaigns, changes to the tariff structure, increased wastewater reuse, …) will be considered and discussed in detail, using modelling results, which, therefore, contribute to decision processes with significant stakeholder involvement and support. As the simulation tool has been set up in a rather generic way, it can also be applied to other urban regions and contribute to sustainable urban water management throughout the world.

ACKNOWLEDGEMENTS

Funding of this work by the German Ministry of Education and Research (BMBF) within its "Future Megacities" research programme is gratefully acknowledged (Grant Reference: 01LG0512). Further information on this research programme can be obtained from http://www.future-megacities.org.

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