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THEMATIC ISSUE

Integrated urban water management: development of an adapted management approach

Case study area: Darkhan, Kharaa catchment, Mongolia

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Abstract The challenge of establishing integrated urban water management (IUWM) lies in the nature of and interaction between various subjects. Following on from integrated water resources management (IWRM), IUWM is structured as a holistic approach. Environmental issues, institutional functions and instruments for planning and management form the basis for integrated urban water management. This paper presents the development of a methodology for identifying, bundling and prioritising measures, taking into account resource orientation and cost-efficiency analysis. The approach is applied to the City of Darkhan, Mongolia's second largest city, which serves as a model area for Central Asia. The model region has to cope with an extreme continental climate, the livestock agriculture of the nomads, nutrient losses in cultivated agricultural areas, trans-boundary impacts on Lake Baikal and the potential for conflicts through mining activities. Settlement structures are heterogeneous, the cultural imprint of post-socialist structures is still present and the technical infrastructure can be described as decrepit. The planning approach presented here consists of the integrated delineation and bundling of measures, along with the creation of an adapted database structure and a decision-making process for prioritisation. The form of the resulting implementation plan will depend on the actual costs and duration.

Keywords Integrated urban water management · Decision-making · Mongolia · Planning approach

Introduction

Sustainable water management will be the next big challenge for mankind. The use of resources must respect the need to keep ecological sustainability and economic feasibility in harmony. Urban areas can be described as nutrient hot spots because of the many valuable resources in waste and wastewater. Rural areas, on the other hand, are often deficient in nutrients. Hence, urban water management needs to be extended to the river basin scale.

Integrated urban water management requires a link between ecological, economical, legal and cultural processes. This gave rise to the following research questions: Which disciplines are important for defining possible measures? What is a suitable way to manage the data? Which methods allow objective and reproducible prioritisation in decision-making?

The expert knowledge generated by the BMBF-funded IWRM MoMo project performed in Mongolia's Kharaa River basin helped supply the answers. This paper proposes subsequent development and implementation of the Toolbox Model in its actual state as a possible urban water planning tool. The focus is on the methods and less on the data used.

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The integrated concept as a decision guide for planning urban water management

Integrated water resources management (IWRM) is often applied to areas facing climatic, economic, ecologic and socioeconomic challenges, with the concept concentrating on issues at the river catchment scale. In the case of urban water management strategies, even those that conform to the guidelines for IWRM still lack a systematic approach for integrated, reuse-oriented sustainable adaptation. Here, the term 'integrated' is used differently. It implies either the consideration of different stakeholders or the combination of all urban water services (Zarghami et al. 2008; Mitchell 2006; Makropoulos et al. 2008; Tjandraatmadja et al. 2012; Guoting and Wardlaw 2013).

In this study, integrated urban water management can be described as "a process which promotes urban water services, viewing water supply, drainage and sanitation as components of an integrated physical system generating nutrient flows and re-use of water resources to maximise the economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP 2012; Mitchell 2006; Rost and Londong 2013)".

The approach presented here focusses on planning and managing the urban water system within the river basin. This calls for data on hydrology, land use, aquatic ecology, water quality and integral urban water management, as well as socioeconomic and political aspects. Integrated concepts on the scale of the river basin have been developed by Borchardt (1996) and Meusel (2008). The ecological and economic impact of the urban water system will be considered with a view to prioritising the need for action.

The integrated concept at the core of our research involves complex decision-making processes. Existing decisions concerning urban water managements are concerned with sanitation or water service solutions (Feng 2009; Gebrie 2012; Zarghami et al. 2008; Loetscher and Keller 2002).

Our management approach is not intended as a decision aid for technical single measures or sanitation systems, but as a guideline for the sustainable planning of urban water management, taking into account the river basin hydrologic system and material flow cycles as well as administrative issues. Different tools will be provided for guiding the planning process. We refer to the overall methodology as the Toolbox Model.

From the integrated concept to the toolbox model

Screening, bundling and prioritisation of suitable measures are the main objectives of the proposed Toolbox Model and are described in the following subsection. The approach will be realised with the help of several tools which will facilitate structural planning. It is vital to incorporate the know-how of all stakeholders and include them in the decision-making process.

Identification of measures

Furthermore, urban water management does not just target issues relevant to water bodies, but aims to achieve adequate hygienic, ecological and economic standards. This must be taken into account in identifying the measures required. Culturally influenced habits play a particularly dominant role when informal settlements are examined. An interdisciplinary assessment of the river basin is carried out to identify relevant measures. The following list outlines the scope of this assessment. The topics need to be studied for screening the river basin. Deficits and derived measures will be the outcome. Measures may be scientifically caused, expert knowledge caused as well as required by law.

Climate prognosis

Climate change causes extreme weather events and changes in the availability of water, which in turn pose difficulties in managing urban water infrastructure. Such a change in the hydrologic system calls for the implementation of sustainable measures.

River discharge

The objective is to balance water availability for the river basin. In evaluating the impact of urban areas on the hydrologic inventory, it is important to understand the processes taking place and the effects of changes in land use. Different users of the hydrologic system must be taken into account, while paying attention to water urban water demand. Changes in river discharge may be caused by systemic changes and call for sustainable measures.

Land cover and land use

Land cover and land use influence the entry of nutrients into the river system. This can have a detrimental effect on water quality. Land use studies help evaluate options for recycling nutrients generated within the urban water cycle. Changing land use also causes changes in the response of the hydrological system and hence changes in water use and availability. This interaction between changes in land cover and in the hydrological system plays a dominant role in identifying appropriate measures.

Water demand and water use

Socioeconomic data are useful in evaluating water availability and water use. Urban settlements, agriculture and industry represent a heavy drain on water resources within a river basin. It is particularly important to evaluate the likelihood of future water scarcity before planning urban water measures for cities that are characterised by demographic change and industrial development.

Nutrient input into rivers

Nutrient input from erosion impacts on water quality and sediment dynamics. Decreasing soil fertility is connected to changes in land use along with the quality and quantity of water. The analysis of nutrient impact points out to hot spots of discharge, which may lead to need for action.

Biological and hydro-morphological parameters

The natural diversity of biological and hydro-morphological parameters is affected by impacts on the river basin. Hot spots such as urban areas or discharge from mining can be pinpointed and their influence evaluated. From this it is possible to derive measures for limiting the negative impact of built-up areas.

Socioeconomic data

Data on urban water infrastructure, payments, acceptance, demographics, conditions and behaviour are essential for determining demand and plans of action. Population and socioeconomic relations have a big influence on the water cycle and especially the river basin. This naturally also has consequences for water management.

Law and institutional data

Data on the institutional organisation of urban water management helps define the general framework. New resource-oriented and integrated concepts for urban and river basin management obviously need changes in the law and institutional responsibilities. Even the monitoring of all components described needs an organisational structure and legal regulation.

Quality and quantity of groundwater resources

The evaluation of groundwater resources in terms of their quantity and quality is an important factor in guaranteeing water supply. The estimated volume of groundwater is important for balancing the urban water cycle and appraising water losses within the urban water cycle. By determining the quality parameters of groundwater, it is possible to identify the impact of material flows other than those from the technical infrastructure, i.e. from infiltration. Both the quality and quantity of groundwater can shed light on the condition of urban water infrastructure and hence on the need for appropriate measures.

Urban water balance

The consumption of water and the resultant wastewater have to be in balance within a working urban water cycle. An imbalance can be caused by several deficits, which in turn call for changes to infrastructure.

Setting objectives

Interdisciplinary analysis identifies the most effective measures for establishing the key elements of IWRM. The next step is to develop goals or planning objectives (compare the section on Application) in conjunction with stakeholders. When it comes to further prioritisation, the weighting of effects may vary depending on screening and measure identification. In that case the identification of measures is separated into the categories ‘scientific based’, ‘expert base’ and ‘required by law’ (Rost and Londong 2013). The decision-making process depends on this aspect and the development target.

Measure bundling and prioritisation

The measures that make up an integrated approach must interrelate, i.e. the planning of technical measures requires the appropriate legal framework as well as qualified human resources.

To prioritise this integrative system of measures, it needs to be fed into a database. Here, it must be said that data dissimilarity and the complexity of the system constitute the main challenges of developing a decision tool.

The framework for prioritising measures is dictated by the structure of the database. Figure 1 shows a simplified version of the database. This structure derives from the real-world relations between environmental conditions, measures and objectives. The catalogue of measures is situated at the centre. All other database tables stand in relation to the measure catalogue. A table for environmental conditions includes several parameters at the core of identified measures, such as nutrient issues and permissible levels of nutrients. Environmental states are observed and this leads to the bundling of measures. Hence, the concept does not aim at prioritising single measures, but focuses instead on a combination of measure design to raise efficacy. It is impossible to successfully implement a single technical measure when informative

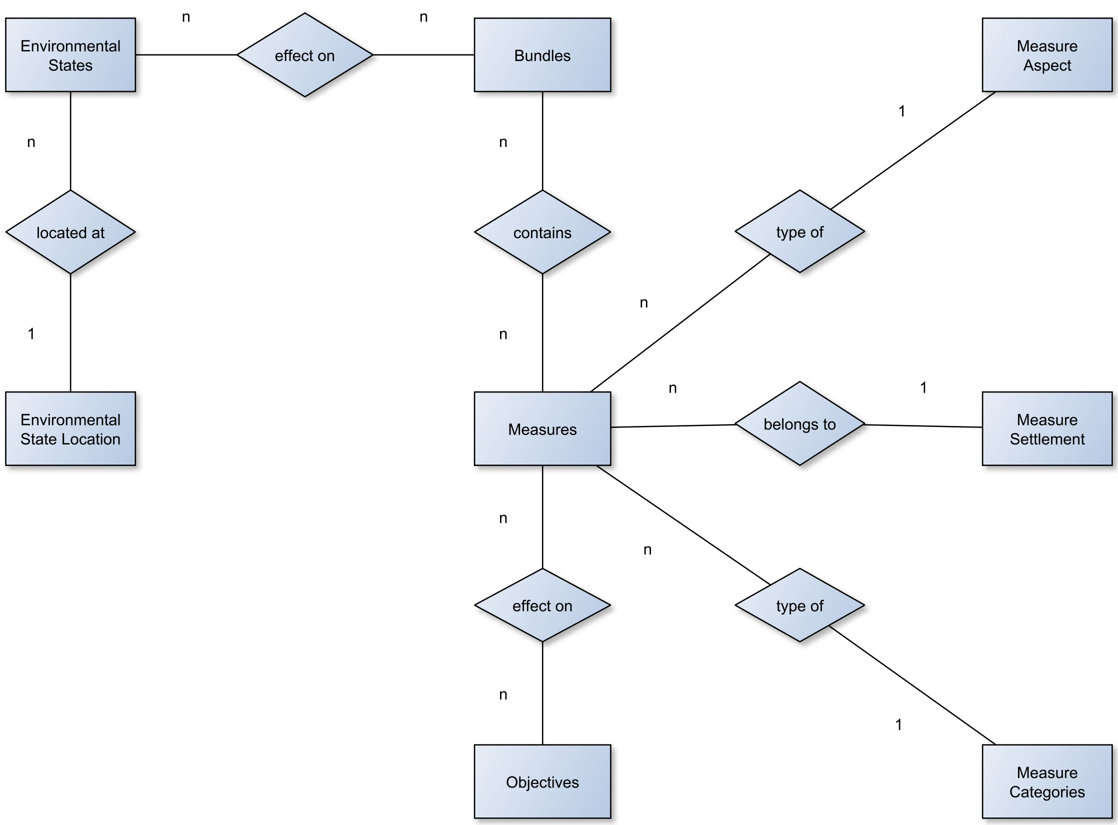

Fig. 1 Simplified database structure for the implementation of the Toolbox Model, showing the main tables and interrelations

and administrative measures are missing (EU 2000). This is illustrated by the measure categories. Each category has a specific justification such as science, law or expert knowledge seen from a technical, informative or administrative perspective.

Several measures can be combined into bundles. These are prioritised by setting development goals and criteria, and via weighting and decision-making. As an example for the decision-making process, Table 1 shows the matrix for the measure bundles and their effects on a specific environmental state as described by a substance concentration monitored at a specific location. In most cases, there will be no effect and, as the data are not stored in a matrix but in a relational database, only existing effects will be stored. When, for instance, the goal is to improve environmental state 1—which means reducing the connected substance concentration—all bundles that have an effect on this concentration will be found. If the goal is to improve environmental states 1 und 3, all measure bundles that have effects on both states will be found. This helps to find the combination of measures with the biggest effect on several environmental states and ultimately the greatest likelihood of achieving the defined goals.

An implementation plan can be developed with the help of the Toolbox Model for integrated urban water management. This approach for managing urban water resources was applied within the IWRM MoMo2 project (Integrated Water Resources Management in Central Asia: Model Region Mongolia phase 2—founded by the German Ministry of Education and Research) for the City of Darkhan in Mongolia. The project is focusing on sustainable water use based on the key elements of IWRM (Kalbus et al. 2012; Karthe et al. 2014). The following section presents the said case study and the water-related issues of the City of Darkhan.

Case study area—city of Darkhan

The study area, the city of Darkhan, belongs to the Kharaa catchment in northern Mongolia (catchment area is 14,500 km^2). This area accommodates approximately 75,000 inhabitants. It is the second largest city of Mongolia and is situated in the northern forest steppe. Darkhan is subdivided into Old Darkhan, New Darkhan and the industrial zone. A significant number of informal settlements (so-called 'ger' areas or bags) can be found surrounding the Old and New Darkhan districts. "Ger

Table 1 Matrix showing the mapping of the effects of measure bundles on environmental states

	Environmental state 1	Environmental state 2	Environmental state 3	…	Environmental state m
Bundle 1	Effect 1.1	Effect 2.1	Effect 3.1	…	Effect m.1
Bundle 2	Effect 1.2	Effect 2.2	Effect 3.2	…	Effect m.2
Bundle 3	Effect 1.3	Effect 2.3	Effect 3.3	…	Effect m.3
…	…	…	…	…	…
Bundle n	Effect 1.n	Effect 2.n	Effect 3.n	…	Effect m.n

areas are low-income informal settlements on the outskirts of cities, where basic infrastructure services such as piped water, sanitation, proper roads, public transportation etc. are poor or non-existent (Sigel 2010)". Sigel et al. (2012) emphasise the demand for integrated urban water management and strategic planning based on a household survey. About 50 % of Darkhan's inhabitants live in that kind of settlement. Within most of the Mongolian cities, the percentage of informal ger settlements is even higher than 50 %. Differences between water supply, sewage and disposal or treatment depend on people's location. A central water distribution system for drinking water and hot water is available for apartment areas. The only water facilities available to ger settlements are public water kiosks without any sanitation infrastructure (Sigel 2010). Figure 2 shows the distribution of the different districts around Old Darkhan. Apartment areas which are provided with water facilities are marked with blue polygons. The orange-marked areas are those areas which are not connected to the urban infrastructure.

Most towns in Mongolia and central Asia are split into settlements with poor or no access to public infrastructure and those with access. Rehabilitation of the urban water infrastructure is essential to serve all these settlements properly.

The City of Darkhan is also facing challenges related to water resources, and so the IWRM MoMo project has collected and analysed all data available on this aspect. While a holistic monitoring concept independent of German funding still needs to be established, the collected data give a broad overview of the situation to help undertake a

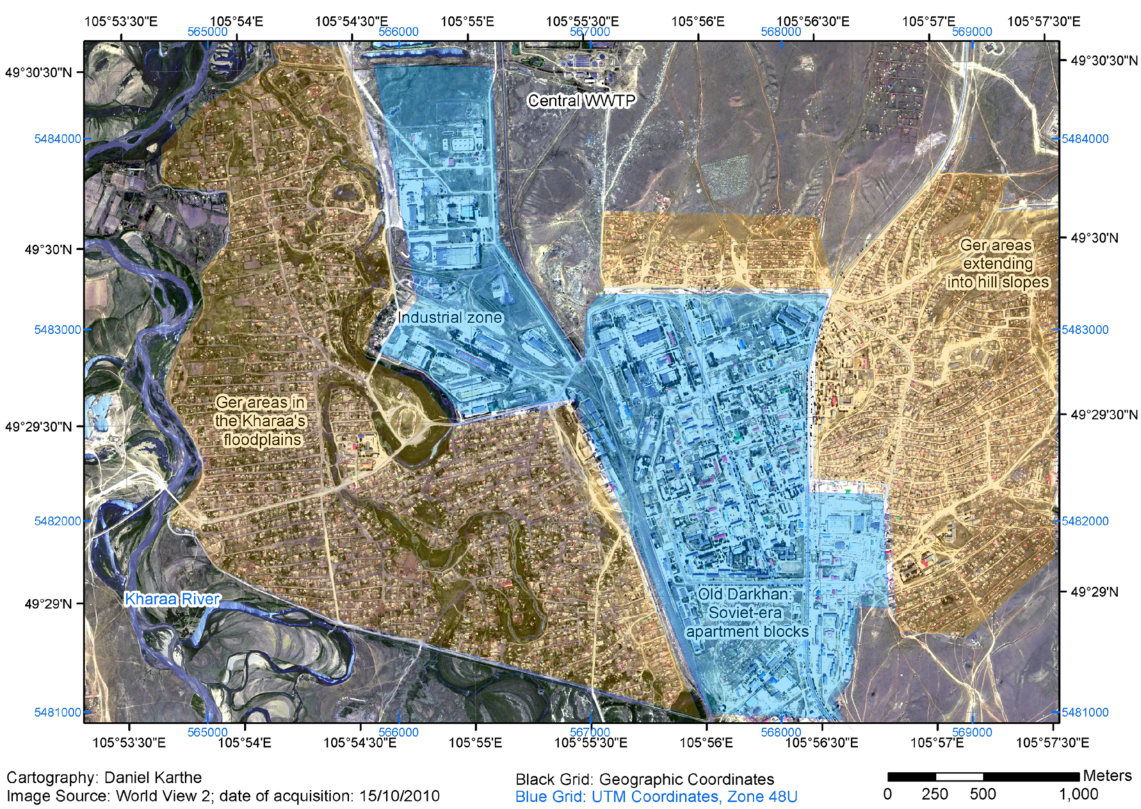

Fig. 2 Overview map of Old Darkhan showing the main settlement structures

deficit analysis and identify measures. Some of the main results are summarised below.

The groundwater aquifer that constitutes the main drinking water source for Darkhan and consists of gravel and sand is deemed to be sufficient. The surrounding geology consists of highly jointed karst, lime rock and dolomite. Reliable groundwater sources are limited to the currently used aquifer (Hofmann et al. 2014).

Due to its location, Darkhan/Mongolia in central Asia has a strong continental climate and can be characterised as semi-arid. The winters are very long, cold and dry. The temperature during the winter can reach a minimum of −40 °C. The mean annual temperature oscillates around 0 °C. The summers are short and hot, with an average temperature of more than 15 °C during July. The maximum day temperature during the summer can rise to 40 °C during the daytime. Precipitation is scarce and is mainly concentrated between June and August, but is subject to high spatial and temporal variability (MoMo-Consortium 2009).

The very cold, long winter and the permafrost present considerable challenges to urban water management and sanitation. The management approach described here considers different ways of implementing effective urban water management. This means resorting to different technologies over and above nutrient cycling strategies. Within the BMBF MoMo II project, pilot plants for sampling the resource-oriented concept adapted to regional characteristics were established and scientifically evaluated.

The ecological state of the Kharaa River close to the city is good and still manifests good nutrient retention. However, forecasts indicate the need for measures against nutrient emission. The highest nutrient emission is caused by urban drainage as well as by inputs from erosion (Hofmann et al. 2010).

Mongolia's politics are still characterised by centralisation. Vertical and horizontal deficits in political structures complicate transparency and responsibility for sustainable management (Houdret et al. 2012).

This political system also causes difficulties in the water management sector and organisational structure in Mongolia. The current law does not obligate informal settlements to remove or treat wastewater. The communal utility provider in charge of drinking water supply, sewage and treatment of wastewater does not bear responsibility for ger settlements. Neither innovative concepts nor new technological solutions can be implemented easily. Furthermore, municipal city planning does not yet include ger settlements in schemes for further development (Baast 2012). Starting in 2013, new funding was provided by the government of Mongolia with the general aim of transforming Mongolian towns into modern, eco-friendly and sustainable cities. The Soum (city) governors are legally obligated to involve the people in the decision-making process. A holistic approach for the integrated planning of urban water measures that take into account cost-efficiency, nutrient flows and re-use options is likely to promote such sustainable development.

The application and adaption of the Toolbox Model was carried out during phase 2 of the MoMo project. The resulting model is now able to point out deficits in water management and derive appropriate measures. The difficulties in creating a management plan result from the need to take into account the boundary condition and the different stakeholder targets in Mongolia.

In the case of Darkhan and the Kharaa River catchment, measures were divided into the following scientifically delineated categories based on the MoMo research results:

- Safe forest use
- Aquatic ecology
- Cattle breeding
- Land use/water use
- Urban areas
- Administrative.

For the urban area of Darkhan, the main measures have been identified and presented in Table 2.

Application of the toolbox model to the city of Darkhan

All the main tools were adapted before applying the Toolbox Model to Darkhan. The task of screening for and identifying measures represents the core of the database. Development targets and criteria were set using participatory methods such as stakeholder workshops and expert interviews. Even if data management and the organisational structure within the water sector of Mongolia prove difficult to handle, the concept for supporting decision-making in urban water management could be adapted at a lower level.

Measures or measure bundles have an effect on the environmental state. But the ultimate choice of measures also depends on how they fulfil the defined objectives, costs, duration and flexibility. The following objectives have been predefined for the City of Darkhan:

- Achieve a good state of surface water
- Make drinking water of a sufficient quality available in sufficient quantities
- Decrease expenditure of energy in water management
- Improve urban drainage and protection from flooding caused by precipitation
- Increase the percentage of renewable energy
- Create jobs

- Provide enough water for agriculture and stockbreeding
- Reduce illness caused by water
- Set socially acceptable operation targets (economic)
- Utilise recyclable material in waste and wastewater.

As the weighting of the different aspects of a measure is a subjective task, the preferred weightings have been defined in a workshop with local stakeholders. The stakeholders consisted of representatives of the local administration, scientists and residents. On this workshop, also the weightings for the predefined objectives have been set. Effect, costs, duration and flexibility can be subdivided into specific minor targets such as fixed costs, operational costs, duration of implementation and duration of operation. The cost and effect of specific development goals have been weighted more highly than flexibility and duration. Flexibility (as the possibility to adapt to changing framework conditions) is weighted similarly to the duration criteria. The resulting weights are shown in Fig. 3.

Based on the weighting and a multi-criteria algorithm such as the Analytic Hierarchy Process (AHT) (Saaty 2001) or Composite Programming (Bárdossy and Duckstein 1985), prioritisation has been calculated and measure bundles have been put forward. Final prioritisation takes place via the database of the toolbox along with the weighting and targeting by local stakeholders.

Implementation method

Informed decision-making for urban water management requires a huge amount of data to be considered. The approach realised here is to store all relevant data inside a relational database. Instead of providing the necessary data for each possible application of the methodology, a data structure with a sample dataset is provided. This approach allows for continuous enhancement of the database, bearing in mind that it will be impossible to provide full data form the beginning. Hence, the whole database structure is developed in a manner that allows automatic incorporation of new data into the decision-making process by regularly updating the database (also see Fig. 1). Furthermore, the database may differ for different countries, different climate and different urban structures. The open database approach permits a database developed for one area to be transferred to another by changing or extending only specific entries. This allows the decision-making toolbox to be applied to specific environments without starting from scratch.

One of the goals for implementing the toolbox software was to exclusively use tools which are open source or at least available at no cost. This may help in the adoption and future extension of the software. Furthermore, installation and maintenance of the toolbox system should be as easy as possible. SQLite (SQLite documentation 2013) was chosen as the relational database engine. The user interface has

Table 2 Measures identified based on previous work of the MoMo project

Measure	Justification
Building a new industrial wastewater treatment plant in the industrial area of Darkhan	To eliminate chrome from tanneries and arsenic from power plant
Implementing a cost-covering fee schedule for water supply and sewerage. In particular, significant industrial user surcharge	To fund measures
Creating retention ponds with nutrient filter for collecting and releasing storm water	Storm water released directly onto alluvial flats via roads and drainage channels
Constructing a sewage plant without a biological stage, with addition of iron and phosphorous recovery (based on the Norwegian model)	TN and TP emission levels downstream of Darkhan do not necessitate a biological stage
Monitoring of water quality and flowthrough velocity in Deed Guur (upstream of Darkhan) and Buren Tolgoi (downstream of Darkhan) (IWRM monitoring concept)	Raised nitrogen levels in the water would necessitate denitrification and nitrification in the sewage plant. The goal is to maintain a constant water quality (non-deterioration)
Installing external animal watering places up to 20 km downstream of Darkhan	Hygiene problems stem from water withdrawn straight from the river downstream of Darkhan
Installing a system for the continuous monitoring and evaluation of existing infrastructure	For coordinated redevelopment planning
Retrofitting/upgrading of existing systems for water supply and sewage disposal	Need to improve quality and minimise costs of water supply and sewage disposal
After redevelopment, continuous maintenance of water supply and wastewater discharge/treatment facilities (drainage system, wastewater treatment plant)	Need to improve quality and minimise costs of water supply and sewage disposal
Measures to overcome adverse living conditions in the ger settlements, particularly hygiene conditions, by installing a regulated water supply system and wastewater/waste disposal plant that safeguards the dignity of the population	Absence of a water supply system and a wastewater/waste disposal plant that safeguards the dignity of the population
Implementing international standards for the collection and depositing of waste	No clear regulation of wastewater disposal and inputs via surface runoff and leaching
Developing suitable organisational structures to safeguard ongoing management (operation, repair, maintenance) of storm water sewers	Storm water sewers are currently used for waste disposal and cause inputs into surface waters and groundwater

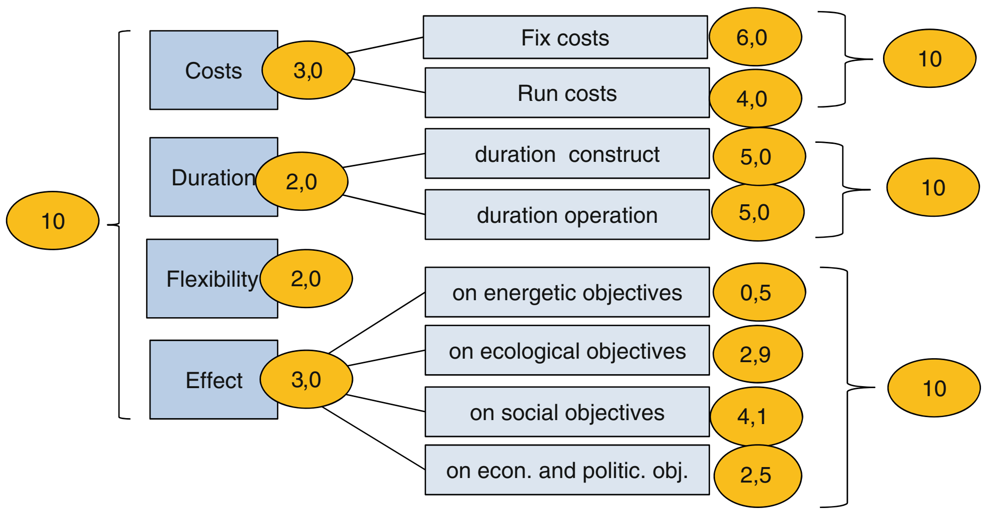

Fig. 3 Weightings for different aspects of measures, e.g. the effect of a measure is more important than its flexibility and the effect on social objectives is much more important than energy objectives. The sum weight for each major measure aspect and for all objectives has been set to 10 in this example

been developed using the Java programming language (Oracle 2013). References such as national standards can be stored as PDF files directly inside the database. Hardware requirements for using the toolbox are low.

Another goal for the toolbox implementation was to not only store textual descriptions and relations between environmental states, objectives and measures, but also numerical values describing these states and measures. Each state can have several levels describing the urgency for action. Each level has numerical boundaries. The measurements are characterised by classified fix costs, running costs, construction time and average operation time, all supported by numbers. Having all data supported by numbers makes it possible to do calculations based on these numbers by running database queries. This allows for the calculation of total costs for measure bundles and comparing different bundles or effectiveness.

If simple numbers prove insufficient for describing economic relations, a more powerful means of representation is provided. More complex mathematical descriptions can also be stored inside the database. These descriptions will be described using the Modelica language (Modelica Association 2012) and the Open Modelica system. In Modelica, all models are described using an object-oriented modelling language which allows automatic composition of the model by combining the partial models into a single overall model depending on the selected combination of measures. The partial models are stored inside the database together with all other data. The resulting models containing several connected partial models will be generated automatically using their connectors. At the time of writing, the automatic connection of sub-models is still at the experimental stage.

The storage of all data (including environmental states, objectives, measures and the relations between these

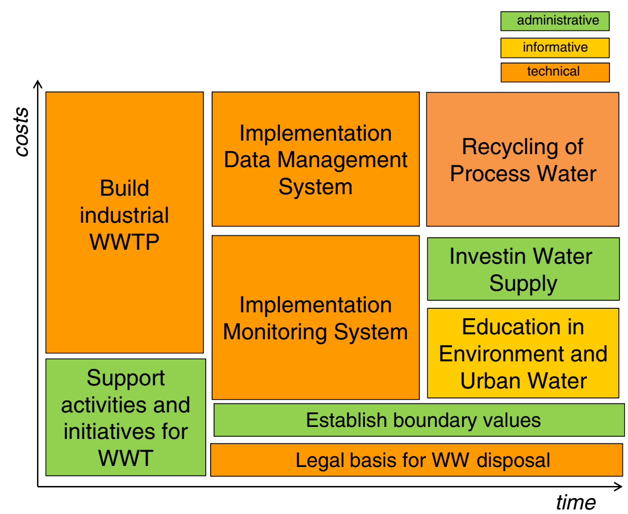

Fig. 4 Example of a bundle of related measures ordered by cost and time efficiency

entries as well as the necessary mathematical formulae) in a single database makes it possible to implement different methods for multi-criteria decision-making. The most effective measure bundle is described as the one fulfilling the objectives within the shortest implementation time at the lowest cost. A measure bundle contains several measures covering different aspects and ordered by cost and time efficiency. Figure 4 gives an example of how different measures which depend on each other and need to be implemented together can be ordered to achieve a given objective in the shortest time with minimal costs. Different bundles that achieve the same goals may have different costs and timescales.

Currently, a Composite Programming algorithm is being implemented and used to find the most effective measure bundles based on the environmental state and the defined objectives. More complex and effective algorithms are planned for the future.

The overall objective was to provide a decision-making tool based on mathematical calculations, which examines the effectiveness of different combinations of distinct measures. Here, we mean effectiveness in terms of costs, impact, duration and preconditions for the individual measures as well as the benefits of combining different measures. Different combinations of measures will be automatically compared to find the most effective option.

The toolbox can be not only used for estimating the effectiveness of measure combinations, but also be deployed as a compendium for all information in the field of water management for the case study area. Most of the relevant higher-level data are available in structured form, including references to its origins.

To test the usefulness of the database structure, it has been filled with all the available data. This process revealed difficulties in acquiring all the data necessary for describing the costs of measures for the case study area. Especially, the costs for water infrastructure-related construction work were nearly unavailable. As a result, the toolbox method has only been methodically tested, but not its full application for real decision-making processes. As this paper is mostly about the methods, the work necessary to bring the toolbox into real application by decision makers should be considered. This will mean filling the gaps in the database as well as keeping the database up to date. This paper can only provide a starting point for this work.

Conclusion and discussion

This paper has outlined the details of a database, the relations between the different data sets and mathematical descriptions of cost functions and objectives as well as the decision-making methods. All these together form the Toolbox Model. The decision-making process itself results in a sub-model describing the concrete combination of measures necessary to reach the goal.

The resulting sub-model describes the time-depending costs required to reach a specific goal determined from the deficit analysis by implementing a combination of measures. It allows a good estimation of the real measures in terms of outcome and necessary input. The quality of this model naturally depends on the quality of the data put into the database.

The methods for identifying and prioritising measures have been tested. Only the measure-identifying methods have been practically applied at the stakeholder workshop in Darkhan. Only the prioritisation methods have been tested for the functionality of the algorithms. The database has initially been filled with comprehensive data, but is still far from complete. Especially, local costs for education and construction measures need to be filled in by the user. As it is already too large to be presented in this paper, it can, however, be acquired from the authors.

Thanks to the calculations involved in the decision-making process, it is possible to find the most effective combinations of measures to attain a goal if the costs of all required measures are already known and put in the database. On this basis, a concrete implementation plan can then be developed. The search algorithms still need to be improved.

The developed tools are aimed at local decision makers. They will be responsible for the correctness of the data stored in the database, as the presented work can only be seen as a starting point. The calculations lead to objective results based on the available data. But erroneous data may lead to non-objective results in the end.

The SQLite database and the related Java classes developed during the research project will be released as open source and are available from the authors.

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