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The WRC operates in terms of the Water Research Act (Act 34 of 1971) and its mandate is to support water research and development as well as the building of a sustainable water research capacity in South Africa.

Integrated Urban Water Modelling for Sustainable Resource Management

A Water Research Commission (WRC) funded project focused on integrated urban water modelling (IUWM) and considered integrated urban water system (IUWS) model, including the sub-models for rainfall runoff, storm and sanitary sewers, wastewater treatment plants and river water quality to improve the overall efficiency of water management through understanding the interactions between the different subsystems, to identify where interventions will have the greatest effect on overall performance. The project further suggests the role of integrated water system models as important decision support tools that can generate critical data for long-term planning and management of urban water systems.

Background

South Africa is facing a serious crisis in terms of both the quantity and quality of water available for human and economic development, as well as the health of our aquatic ecosystems. A 17% water deficit is projected by 2030 if current trends continue. This, while 3 million people still do not have access to basic water supply, 14.1 million do not have access to safe sanitation, 56% of wastewater treatment plants (WWTPs) are in poor or critical condition and the number of main rivers in the country classified as having poor ecological condition increased by 500% between 1991 and 2011.

Inadequately treated effluent discharges from poorly operated and maintained and/or overloaded municipal WWTPs are a key cause of deteriorating river quality. This threatens the health of vulnerable communities living along river banks and negatively impacts the suitability of the water for downstream use. Overflows from blocked and overloaded sewers also threaten the health of communities, with poorer communities being the most affected. The lack of available wastewater treatment capacity is also a barrier to new housing, commercial and industrial developments in many municipalities.

Better wastewater management is an important part of addressing the country's water shortages. Furthermore, there is a growing global awareness that wastewater treatment needs to move beyond focusing primarily on pollution prevention to maximising resource recovery

(water, energy and nutrients) to reduce waste disposal requirements, better manage scarce resources and also mitigate climate change. The Department of Water and Sanitation's National Strategy for Water Re-use identifies the performance of existing WWTPs in terms of meeting discharge standards and reliability as being critical to the successful implementation of water reuse to reduce stress on existing water supplies. On the other hand, the National Water and Sanitation Master Plan (NW&SMP) focuses, *inter alia*, on the development of technologies, guidelines and implementation of support tools that enable South Africa to use alternative and appropriate sources (including reclaimed wastewater) as part of the water supply mix.

The creation of the necessary enabling environment is therefore essential to the successful implementation of the NW&SMP. Critical aspects include better management of data and information, building skilled capacity in the water sector, ensuring the financial stability of municipalities and enhancing research, development and innovation. To this end, South African researchers have made a substantial and internationally recognised contribution to the advancement of wastewater treatment modelling over the last few decades. However, the uptake of modelling by South African municipalities to improve wastewater management has been limited so far.

Integrated urban water management

Urban water management has traditionally been divided into a number of independent silos: abstraction, potable

water treatment, distribution, wastewater collection, wastewater treatment, and environmental protection. This segregated approach simplifies the operation, monitoring and planning of each water service. However, there is a growing realisation that a more integrated approach is required to address the long-term challenges of climate change and increasing urbanisation.

Integrated urban water management (IUWM) offers a set of principles that underpin better coordinated, responsive, and sustainable resource management practice. It is an approach that integrates water sources, water use sectors, water services, and water management scales. It (1) recognises alternative water sources, (2) differentiates the qualities and potential uses of water sources, (3) views water storage, distribution, treatment, recycling, and disposal as part of the same resource management cycle, (4) seeks to protect, conserve and exploit water at its source, (5) accounts for nonurban users that are dependent on the same

water source, (6) aligns formal institutions (organisations, legislation, and policies) and informal practices (norms and conventions) that govern water in and for cities, (7) recognises the relationships among water resources, land use, and energy, (8) simultaneously pursues economic efficiency, social equity, and environmental sustainability, and (9) encourages participation by all stakeholders.

IUWM seeks to improve the overall efficiency of water management through understanding the interactions between the different subsystems, so as to identify where interventions will have the greatest effect on overall performance. So, for example, improving the efficiency of a wastewater treatment plant will not lead to a significant improvement in receiving water quality if pollution largely arises from other sources. The different components of an urban wastewater system with separate storm and sanitary sewers are illustrated in Figure 1.

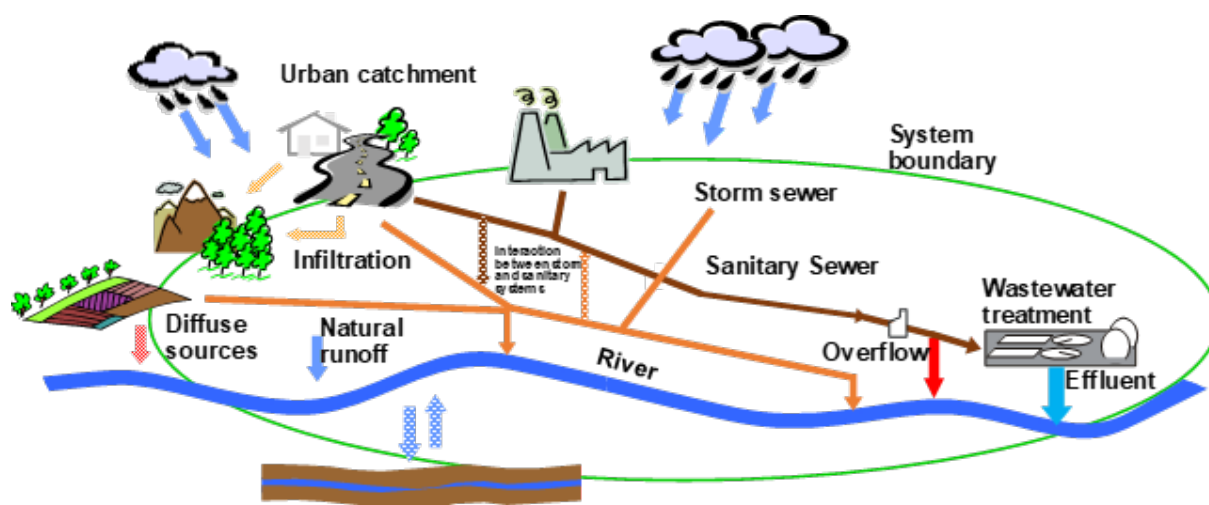


Figure 1. Urban wastewater system with separate sewers.

Predictive mathematical models play a crucial role in the development of integrated practices, to promote environmental and socio-economic sustainability. Models are needed to understand the interconnections between sub-systems and how they may be altered to understand future constraints and opportunities. Integrated water system models can also be important decision support tools, for example, scenario modelling can generate critical data for long term planning and management of urban water systems. Furthermore, integrated models offer a way for stakeholders in the integrated urban water management chain to explore new opportunities offered by digitalisation towards promoting efficient, innovative and sustainable solutions to water related issues.

The Integrated Urban Water Systems model

The integrated urban water system (IUWS) model was originally developed at Ghent University in Belgium in mid 2000s, partly as a response to the EU Water Framework Directive which required member states to adopt measures to ensure “good chemical and ecological status for both surface and ground waters” while allowing some flexibility in determining what these measures should be.

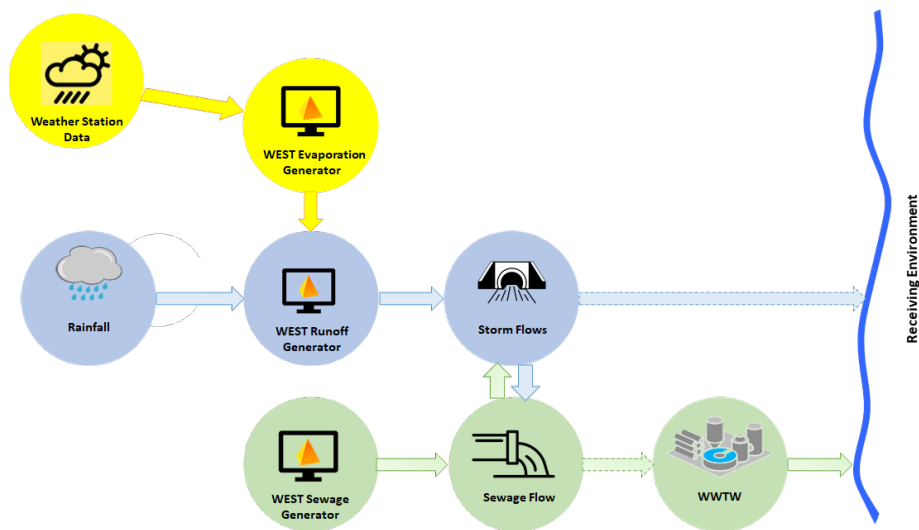


Figure 2. IUWS conceptual elements.

While a number of different integrated urban water systems models have been developed by various organisations, the main focus of the study is on the IUWS model as implemented in the WEST modelling platform. WEST is primarily for wastewater treatment modelling, but the IUWS model includes catchment and river sub-models, allowing the integrated modelling of the catchment, sewer network, treatment works and river system. The components of the IUWS model are illustrated schematically in Figure 2 for a catchment with separate storm water and sanitary sewer systems.

Modelling has been identified as an important tool for determining how to best achieve water quality improvements in a given catchment. The IUWS model specifically focuses on pollutant loads from both point and non-point sources, treatment efficiency and water quality while using simplified hydrological models to represent flows in the catchment. It can be used to assess relative impacts of various events such as heavy rainfall and sewer blockages, and interventions such as treatment plant upgrades, sewer maintenance and stormwater management to identify the most cost-effective approaches for improving water quality. It can also be used to evaluate the impacts of rapid urbanisation, changes in land and water use patterns, and climate change. Case studies using this model have been conducted in Europe, the USA, and Canada, among others, and now, for the first time, it is being adapted to South African conditions.

Data requirements for modelling and decision support

The NW&SMP specifies that "...Decision making must be based on sound evidence, supported by rigorous research, innovation and appropriate technology development..." This therefore requires better collection, management and interpretation of data by municipalities to support better decision-making.

A municipality generates large quantities of data associated with its individual operations, such as service delivery and billing, procurement, maintenance, development, community liaison and environmental monitoring, etc. These tend to be focused on the specific needs of individual operations and maintained in separate systems. The problem of optimal allocation of resources requires an integrated view of relevant data from all the sub-systems. This involves consolidating the data on a central system, establishing relevant links between data from different sub-systems, reconciling data conflicts, and interpreting the data for the purposes of managing the organisation, i.e., turning data into information.

In the context of data integration, modelling involves capturing the underlying relationships between disparate data. These can be used in the processes of linking, reconciling and interpreting the data. It can also often be used to estimate unmeasured data that may be required from data that were gathered for a different purpose or related to a different sub-system. Modelling is therefore a key part of turning data into information. Figure 3 and Table 1 illustrate the data requirements of the IUWS model.

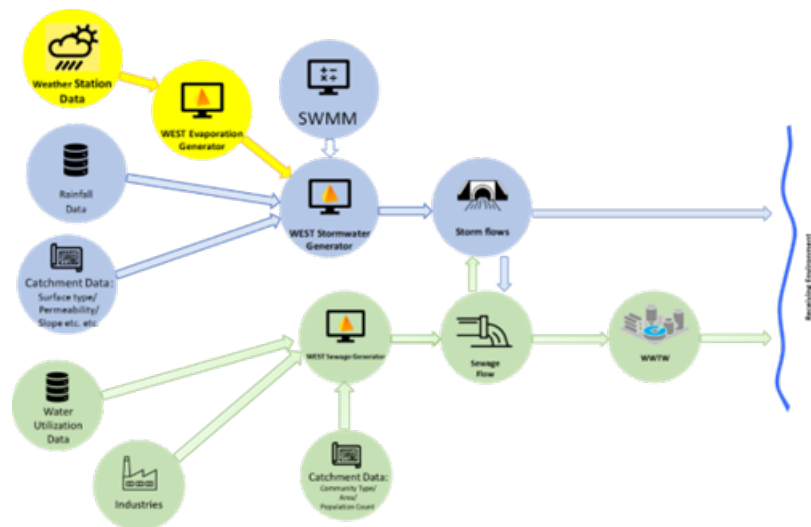


Figure 3. Information flows in the IUWS model.

Data requirements for IUWS modelling

Models require data for two main purposes: **input data** that are absolutely required for a model to run, and **calibration/validation data**, which are compared to model outputs to check the correctness of model outputs and adjust model parameters. A full integrated catchment model, by virtue of its size and complexity, has very extensive data requirements that fall into a number of categories as shown in Table 1.

Table 1. Categories of data required for a comprehensive IUWS Model

Input Data	
- Geographical - Catchment boundaries - Rivers - Topography - Population distribution - Economic activities - Municipal Infrastructure - Water supply connections - Sanitary sewers - Storm sewers - Pump stations - Wastewater treatment plant configuration - Outfalls	- Climate - Rainfall - Evaporation - Radiation - Wind - Temperature - humidity - Operating data - Water supply - Sewage flow - Wastewater plant operation
Calibration/validation data	
- Sewers - Flows - Contaminant loads - Rivers - Flows or levels - Contaminant loads	- WWTP - Influent flow and composition - Treated water flow and composition - Sludge production

Data used in models can be directly measured, for example, weather station and effluent monitoring data, data estimated from measurements, e.g. COD fractions in wastewater and data generated by more detailed models of the various sub-systems. For example, in Figure 3, calibration data for the storm water flows is generated using a Storm Water Management Model (SWMM, USEPA) of the catchment.

In practice, complete data sets are never available, and the scope and extent of the model have to be matched to the available data. This is a complex adaptive process, and the model will progressively grow and improve as data gaps are identified and addressed. Furthermore, the process of engaging critically with the data yields insights and can be useful for water management in unexpected ways.

IUWM software and tools

The wide range of issues involved in an integrated urban water model and the diverse sets of data available require a range of software tools. The choice of specific packages is influenced by factors other than their intrinsic capabilities, such as cost, institutional IT policy, and the modeller's familiarity. The following software was used in this study:

- **WEST (DHI, 2022)**

WEST is a wastewater treatment modelling package from

the Danish Hydraulic Institute (DHI) that includes a suite of IUWM modules. This was obviously an important reason for its selection, but it was also relevant because various stakeholders were already familiar with its use for modelling of WWTPs. Furthermore, it includes very detailed models related to water quality, but very simplified models on hydraulic aspects.

- **Storm Water Management Model**

The storm water management model (SWMM), in its basic form, is a free package from the United States Environmental Protection Agency (USEPA). It complements WEST in that it provides detailed hydraulic modelling, but only a rudimentary treatment of water quality. An extended version of SWMM is used by the case study municipality for flood warning, and this provided a ready-made model to the current study, which could be run on the basic version of the software. This was used for modelling runoff and river flows, which could be used to prepare input to the WEST model.

- **ArcGIS**

ArcGIS is a Geographic Information System from ESRI. This is used by the case study municipality for many purposes, including asset management, and was therefore available to the study. It is a key tool for many purposes, as it can hold information on the sewer network, the rivers, water supply connections, etc. It also interfaced directly with SWMM so that items of municipal infrastructure could be accurately located in the hydraulic model, as shown in Figure 4.



Figure 4. GIS map showing the distribution of rivers and sewers in relation to a WWTP catchment for the case study.

Case study examples

Catchment water balances

Simple catchment water balances constructed in Excel can highlight anomalies in the available data and yield important insights. Figure 5 compares monthly wastewater flows and billed water consumption for water connections served by a specific WWTP. As is expected, wastewater flow fluctuates with rainfall; however, in this case, the wastewater flow was more than double the billed water consumption for the driest months. There were no bulk water meter readings for this catchment to check these results against. However, Figure 5 suggests that either the excess wastewater is due to non-revenue (unbilled) water or there is some error in the data or model assumptions, for example, sewer connections have not been assigned to the correct WWTP. In fact, the discrepancy between billed water and wastewater flow decreased when the municipality switched to a different billing system.

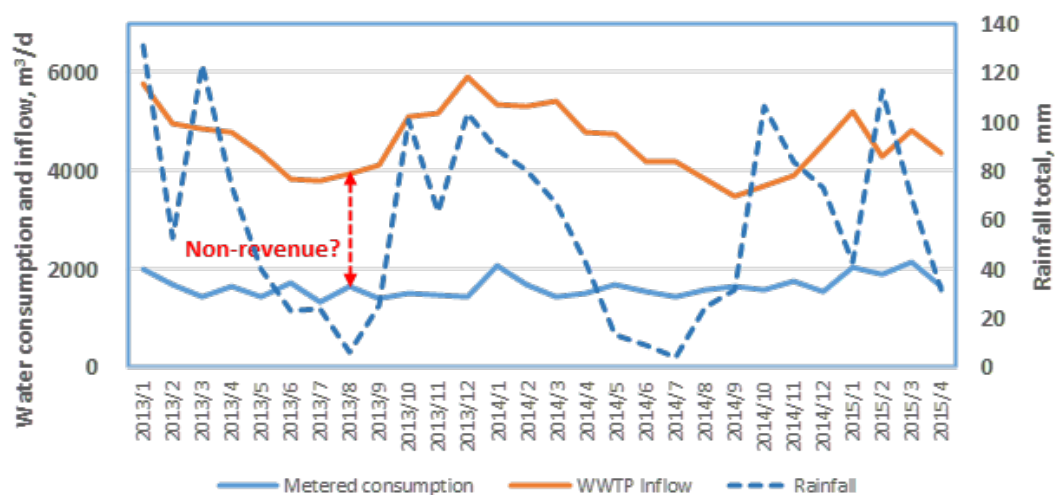


Figure 5. Monthly average billed water consumption for sewer connections vs WWTP inflow.

Figure 6 shows the ratio of WWTP inflow to metered flow for sewer customers representing 12 WWTPs within the various catchments of the case study municipality. Rainfall infiltration will increase the ratio; however, outdoor water use, for example, swimming pools and irrigation, will tend to decrease it, with the two effects tending to cancel each other. The average ratio for the case study municipality was 0.86 in 2019, but the values for individual plants varied from ~0.5 to 2. Ratios $\gg 1$ suggest a high proportion of unbilled water consumption, errors in the model assumptions or data. On the other hand, ratios $\ll 1$ could indicate significant sewage spills. This very simple analysis and ranking of sewer catchments can help decision makers to determine which systems to prioritise for further investigation and intervention.

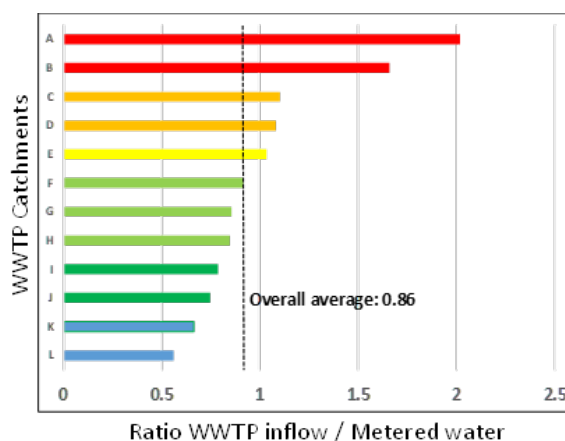


Figure 6. Ratio of WWTP inflow to metered water consumption for sewer customers representing 12 WWTP within case study catchments (2019 data).

Impact of water conservation on sewers and treatment works

This case study was conducted as part of the WRC South African Sanitation Technology Enterprise Programme (SASTEP) project on scanning, testing and development of a quality assurance protocol for low flush toilet pedestals. A relatively simple spreadsheet model of sewer flows to one of the case study WWTPs was constructed to estimate the impact that low flush toilets would have on the sewer system, and an Excel-based capacity estimation tool was developed to assess the impact of reduced flows on the WWTP. It was found that low flush toilets could reduce water demand by up to 28%, for toilets with flush volumes as low as 0.4 L. However, the following was noted:

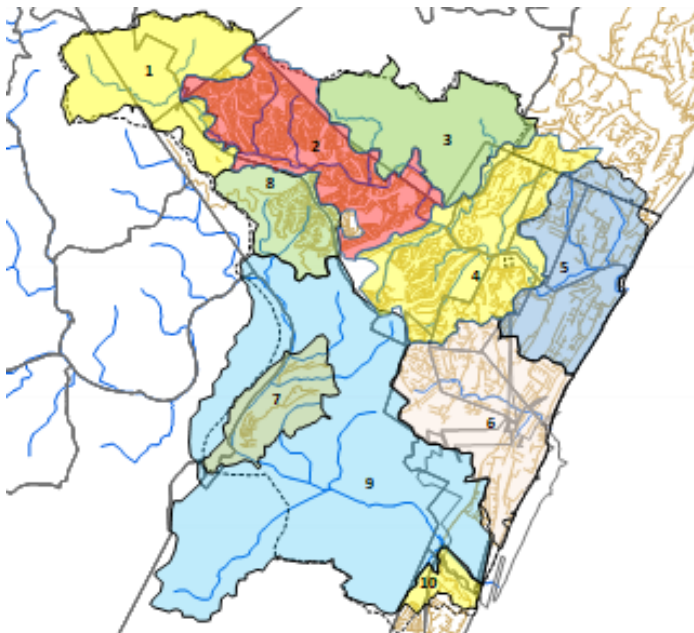
- Reductions in dry weather flow can lead to increased solids deposition, clogging, salinity and corrosion problems.
- There would be a limited impact on peak wet weather flow (< 13% in this case study). Since sewer pipes have to be sized to accommodate the peak wet weather flow, reducing the dry weather flow alone and not the volume of stormwater ingress does not substantially increase the number of connections a sewer can accept.

- Reducing flow but not solids, organics and nutrients load does not increase WWTP capacity in terms of population served. However, urine diversion toilets reduce per capita oxygen demand by diverting most of the nutrients away from the WWTP.

This case study illustrates the importance of understanding the interactions between the different components of the urban water system and how changes in one will impact the others.

The IUWS model in WEST

The IUWS model uses simplified models of both sewers and river catchments with parameters that represent average conditions. To capture the diversity of the overall catchment, it can be divided into a number of sub-catchments with appropriate parameter values to represent the different areas. Figure 7 shows the sub-division of a WWTP catchment straddling two river basins, which was undertaken as a training exercise during the study. The three criteria that were used to divide the catchment into sub-catchments were sewers, drainage and settlement type, i.e. whether the area has sewers, which river its runoff drains to, and what kind of community occupies it.



Sub-catchments 1 to 6 drain to the smaller northern river catchment

7 to 10 drain to the larger southern river catchment

1, 3 and 9 are un-sewered areas

5, 6 and 10 are commercial areas;

4 contains affluent suburbs;

2, 7 and 8 contain lower income townships

Figure 7. Division of WWTP catchment into sub-catchments.

With no history of this kind of modelling in the municipality, much of the data required to calibrate the IUWS model has never been recorded, and one of the objectives of the study was to identify important gaps in the data available. The most critical gaps are related to the temporal and spatial resolution of the available flow data. Higher resolution flow data is required to, for example, determine where storm water enters the sewer system and when and where sewer overflows occur. Ideally, there should be at least one flow measurement point for each of the sub-catchments in the model.

On the other hand, in this study, the SWMM models set up by the case study Coastal Stormwater & Catchment

Other challenges relate to data which are much more difficult to measure, for example, pollutant loads in runoff from informal settlements and sewage spills due to blocked and damaged sewer pipes. The municipality's sewer fault reporting system can provide valuable data on the cause, frequency and general location of sewage spills but provides no information on the volume or duration of spills. Incorporating these effects into an IUWS model calibrated for South African conditions will likely require the development of new sub-models for wastewater loads from unsewered settlements and stochastic models for sewer blockages.

Generally, the primary purpose of IUWS modelling is to provide scientific and technical support for water and wastewater management decisions. However, decisions cannot be taken on the basis of the models alone; they are also subject to non-technical considerations, such as political

priorities, financial constraints, institutional capacity, human resources etc. In this regard, a decision maker must exercise judgment to strike a balance between all these technical and non-technical considerations. This means that decision makers must also become members of the modelling team.

An ideal modelling project will need to be commissioned in order to support a particular decision. The decision makers will need to be involved in setting its scope and objectives, and specifying which scenarios need to be investigated. They will have to monitor the progress of the investigation to make sure that it provides the information needed for the decision, and suggest modifications where it does not. By the time it is decision-ready, decision makers will have a thorough understanding of its outcomes and their associated uncertainties and limitations. Overall, making a model useful is an extensive, iterative process involving the entire modelling team, including the decision-maker(s).

Conclusions

Integrated urban water modelling is entirely new to South

Africa, although it has been applied elsewhere. In its fullest realisation, it requires an enormous amount of data from disparate sources, which makes it appear to be a daunting prospect for a municipality to implement. However, experiences have shown that even partial realisations can provide valuable information for water and wastewater management decisions. Furthermore, these partial models can be used to identify the crucial gaps in the data which limit their scope and usefulness.

Integrated water management requires integrated data management, which together imply high levels of communication and cooperation between municipal departments. Once again, having an integrated modelling framework in place will be useful for identifying gaps in the necessary institutional linkages. Consequently, a long-term commitment to IUWS modelling will provide a framework for progressively improving a municipality's data acquisition and data management systems, and ultimately its water management decision-making.

For more information,

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