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WATER RESEARCH COMMISSION

Integrated Urban Water Modelling for South African Water Services

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Abstract

Water is central to nearly all municipal functions, including potable supply, wastewater collection and treatment, stormwater management, environmental protection, and revenue collection. However, in South Africa, these functions are often managed independently, leading to inefficiencies and fragmented decision-making. This position paper emphasises the importance of Integrated Urban Water Modelling (IUWM), particularly through Integrated Urban Water System (IUWS) models that incorporate sub-models for rainfall-runoff, sewer networks, wastewater treatment plants, and river water quality. Such models enable a holistic understanding of interactions between subsystems, thereby identifying leverage points where interventions can maximise system-wide benefits. IUWM tools serve as powerful decision support systems, providing data essential for long-term planning, sustainable management, and resilience of urban water systems.

Introduction

South Africa is a water scarce country that continues to be faced with challenges related to high water demands with limited supply, deteriorating water quality, and poorly operated, maintained and overloaded water infrastructure, coupled with a lack of personnel skills. As a result, many municipalities are in a state of crisis with respect to urban wastewater management. Improving wastewater management from collection to treatment to effluent discharge and reuse is a critical part of addressing these challenges.

The efficient management of water and wastewater contributes to human health and enhances the quality of life. Modelling and data integration are powerful tools which municipalities can use to identify synergies, optimise wastewater system performance, ensure appropriate operational practices and find more cost-effective solutions to achieve the desired effluent and receiving water quality. Modelling is also a powerful tool for estimating the capacity of existing infrastructure under various scenarios, as well as for designing upgrades, including those which allow for the recovery of water, nutrients and energy from wastewater. Furthermore, the potential for tracking the incidence of diseases like COVID-19 in communities through sewer network monitoring and modelling has recently gained attention (Street et al. 2024).

Over the past four decades, research and practice have increasingly emphasised the importance of integrated urban water management (IUWM). Unlike conventional sectoral approaches, IUWM considers the interconnections between water supply, wastewater, stormwater, and receiving water systems, aiming to optimise system-wide performance. This holistic framework supports more efficient resource use, reduces environmental impacts, and enhances urban resilience. Scholars have highlighted that IUWM not only improves infrastructure planning and management but also facilitates sustainability transitions in cities, ensuring that water, energy, and environmental objectives are met in an integrated manner (Mitchell, 2006; van der Steen & Howe, 2009; Makropoulos & Butler, 2010).

This has necessitated the development of integrated urban water systems (IUWS) modelling tools to support integrated approaches to the assessment and definition of system planning needs, as well as for discharge permit negotiations. This is largely driven by regulatory and economic factors, more especially, the financial and capacity constraints faced by many municipalities in being able to meet multiple regulatory obligations for various components of their urban wastewater and stormwater management systems (Benedetti et.al, 2013). The absence of well-structured training programmes suitably targeted to municipal stakeholders in the integrated urban water management chain is also a constraint that many municipalities are working towards addressing to enhance their capacity, experience and knowledge.

A significant proportion of wastewater treatment plants (WWTPs) in South Africa do not meet their discharge permit requirements and contribute to the degradation of the water environment (GD National Report, 2022). The reasons for this vary from wastewater loads exceeding plant capacity to poor operation due to neglected maintenance. In efforts to address these challenges, the establishment of a process modelling group has been prioritised and the process of setting up a data integration system as a decision support system, which will help prioritise remedial actions, has been considered.

This position paper, therefore, ***inter alia***, proposes the need to focus on the following aspects:

- Modelling and data integration as powerful tools for decision support in addressing current challenges
- The need for an integrated approach to water and wastewater management
- Challenges associated with data quality and gaps. Good models need good data
- Models as providers of a framework for organising data from different sources and identification of critical gaps
- Useful insights from simple water balances to detailed dynamic process models.
- The need for an enabling environment for modellers as specialists within institutions to be effective.
- The need to include decision makers upfront in modelling projects to get buy-in for uptake and utilisation of developed models.

2. Integrated Urban Water Management (IUWM)

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 (Furlong et al., 2017). Integrated urban water management (IUWM), which is usually conducted on a river basin scale, can be broadly defined as an approach that integrates water sources, water-use sectors, water services, and water management scales (Global Water Partnership, 2012). It underpins better coordinated, responsive, and sustainable management of water in urban settings by recognising interdependencies across different parts of the water cycle and across stakeholders.

IUWM recognises alternative water sources, differentiates the qualities and potential uses of water sources, views water storage, distribution, treatment, recycling, and disposal as part of the same resource management cycle, seeks to protect, conserve and exploit water at its source, accounts for non-urban users that are dependent on the same water source, aligns formal institutions (organisations, legislation, and policies) and informal practices (norms and conventions) that govern water in and for cities, recognises the relationships among water resources, land use, and energy, simultaneously pursues economic efficiency, social equity, and environmental sustainability, and 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 discover where interventions will have the greatest effect on overall performance. For instance, 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 in illustrated in Figure 1.

Predictive mathematical models can 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 (Mosleh and Negahban-Ansar, 2021). 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.

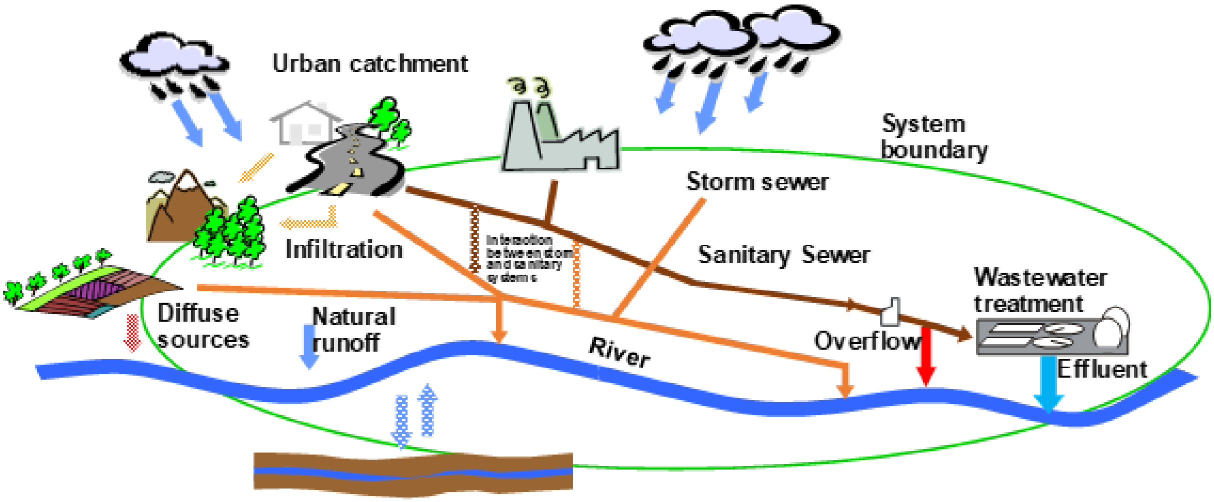

Figure 1. Urban wastewater system with separate sewers. Adapted from Benedetti (2013).

Furthermore, integrated models offer a way for stakeholders in the integrated urban water management chain to explore the new opportunities offered by digitalisation towards promoting efficient, innovative and sustainable solutions to water-related issues.

2.1 The Integrated Urban Water Systems (IUWS) model

Different integrated urban water systems models have been developed by various organisations and are reviewed elsewhere (Mosleh and Negahban-Ansar, 2021). The main focus of this position paper is on the IUWS model as implemented in the WEST (DHI, 2022) modelling platform. WEST is primarily a wastewater treatment modelling software, 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.

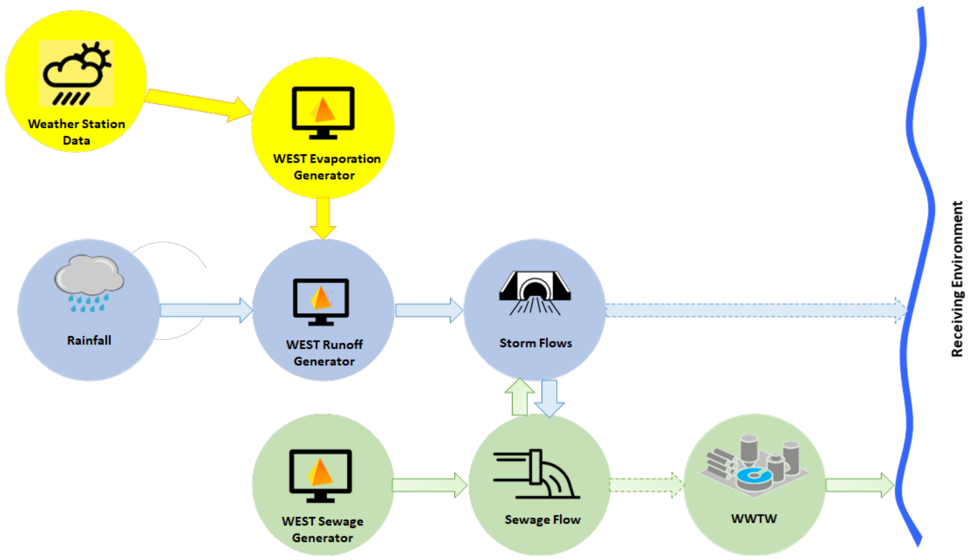

Figure 2. IUWS conceptual elements.

The IUWS model was originally developed at Ghent University in Belgium in the mid-2000s (Solvi, 2007), partly as a response to the EU Water Framework Directive (2000) , 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. Modelling was 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 storm water management to identify the most cost-effective approaches to 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, Canada, etc. However, to the best of our knowledge, this is the first to try to adapt this model to South African conditions.

3. The South African context

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. While 98% of the available freshwater resources are already allocated, a 17% water deficit is projected by 2030 if current trends continue. This is 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 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 (National Water and Sanitation Master Plan, 2018).

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 re-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 therefore an important part of addressing the country's water shortages. Furthermore, there is a growing global awareness that wastewater management 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 mitigate climate change. The Department of Water and Sanitation's National Strategy for Water Re-use (NSWR, 2011) 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.

The National Water and Sanitation Master Plan (NW&SMP, 2018) currently includes key actions relating to wastewater management. However, the creation of the necessary enabling environment is 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. In terms of the allocation of financial and other resources within a municipality, wastewater management has to compete with other critical priorities, including housing, health, environmental protection and economic development. However, many of these actually rely on effective management and treatment of wastewater. The problem of prioritising the allocation of resources is compounded by competing political pressures, which often result in allocations that are objectively non-optimal.

South African researchers, particularly the Water Research Group at the University of Cape Town (UCT), have played a pioneering role in advancing wastewater treatment modelling. Their work has been internationally recognised, especially for developing the Activated Sludge Models (ASMs), which remain the global benchmark for simulating biological wastewater treatment processes. The UCT group has significantly contributed to the refinement of nutrient removal models, parameter calibration methods, and the application of modelling for design, optimisation, and operation of WWTPs (Henze et al., 2000; Ekama, 2009; Ekama & Wentzel, 2008). These contributions have not only strengthened the scientific foundation of wastewater treatment but have also influenced international standards and guidelines adopted by the International Water Association (IWA). However, the uptake of modelling by South African municipalities to improve wastewater management has been very limited so far. In this regard, the establishment of the WISA Modelling and Data Division in 2021 has provided a platform for promoting an integrated approach to water management and the establishment of comprehensive water-related data management systems to ease access to relevant data.

4. 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 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, 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.

4.1 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 given in Table 1.

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

Input Data	
• Geographical o Catchment boundaries o Rivers o Topography o Population distribution o Economic activities • Municipal Infrastructure o Water supply connections o Sanitary sewers o Storm sewers o Pump stations o Wastewater treatment plant configuration o Outfalls	• Climate o Rainfall o Evaporation o Radiation o Wind o Temperature o humidity • Operating data o Water supply o Sewage flow o Wastewater plant operation

Calibration/validation data	
• Sewers o Flows o Contaminant loads • Rivers o Flows or levels o Contaminant loads	• WWTP o Influent flow and composition o Treated water flow and composition o 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 (Brouckaert et al, 2022) 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 stormwater management model (SWMM) model of the catchment (US EPA, 2022).

In practice, complete data sets are never available, and the scope and extent of the model has 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 that can be useful for water management in unexpected ways.

4.1.1 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 will be influenced by factors other than their intrinsic capabilities, such as cost, institutional IT policy, and the modeller's familiarity.

4.1.2 WEST (DHI, 2022)

WEST is a wastewater treatment modelling package from the Danish Hydraulic Institute (DHI) that includes a suite of IUWM modules. It includes very detailed models related to water quality, but very simplified models of hydraulic aspects. Although this is expensive software, it is already readily with most stakeholders familiar with using it for modelling of WWTPs.

4.1.3 SWMM (Storm Water Management Model)

SWMM, in its basic form, is a free package from the US EPA (2022). It complements WEST in that it provides detailed hydraulic modelling, but only a rudimentary treatment of water quality. An extended version of SWMM is useful for flood warning, and this can be used for modelling runoff and river flows, which could be used to prepare input to the WEST model.

4.1.4 ArcGIS

ArcGIS is a Geographic Information System from ESRI (2017). This is an expensive package, but is useful for many purposes, including asset management. It was a key tool for many purposes, as it can hold information on the sewer network, the rivers, water supply connections, etc. It can also be interfaced directly with SWMM so that items of municipal infrastructure can be accurately located in the hydraulic model (Figure 4).

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

4.1.5 EXCEL and R

Apart from the specialised software packages, these general packages are extensively used for data preparation and manipulation, and for manipulating model outputs for presentation. In some cases, they were even used for simple water balance sub-models of parts of the system.

5. Examples from case studies

5.1 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. Even though there were no bulk water meter readings for this catchment to check these results against, 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, sewered connections have not been assigned to the correct WWTP. In fact, the discrepancy between billed water and wastewater flow decreased when the case study municipality switched to a different billing system.

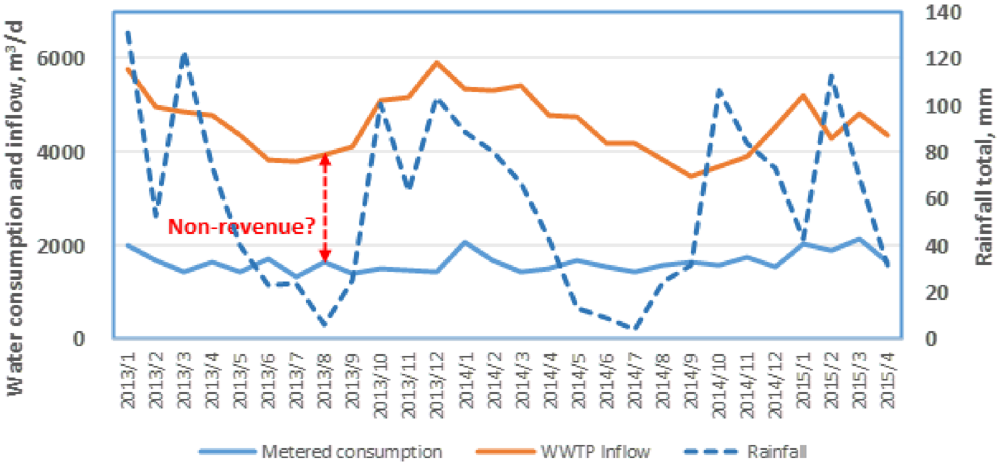

Figure 5. Monthly average billed water consumption for sewered connections vs WWTP inflow.

Figure 6 shows the ratio of WWTP inflow to metered flow for sewered customers for 12 case study WWTP catchments. 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 was 0.86 in 2019, but the values for individual plants varied from about 0.5 to 2. Ratios >> 1 suggest a high proportion of unbilled water consumption, or errors in the model assumptions or data, as discussed above. On the other hand, ratios << 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.

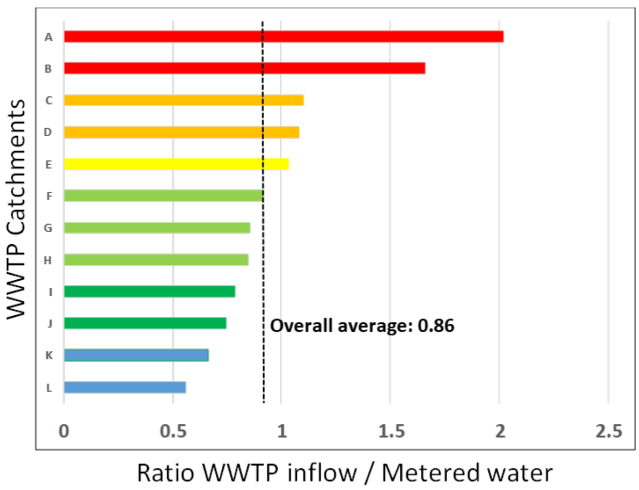

Figure 6. Ratio of WWTP inflow to metered water consumption for sewered customers for twelve case study catchments (2019 data).

5.2 Impact of water conservation on sewers and treatment works

This case study was undertaken within the framework of the South African Sanitation Technology Enterprise Programme (SASTEP), under the Water Research Commission (WRC) project titled ***"Scanning, Testing and Development of a Quality Assurance Protocol for Low Flush Toilet Pedestals."*** The project aimed to evaluate sanitation innovations, focusing on the performance and reliability of low flush pedestals, in line with WRC's broader mandate of promoting water conservation and sustainable sanitation technologies in South Africa (WRC, 2020). A relatively simple spreadsheet model of sewer flows to one of the case study's 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 and used 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:

- 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 storm water 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 wastewater treatment plant capacity in terms of population served. However, urine diversion toilets reduce per capita oxygen demand by diverting most of the nutrients away from the wastewater treatment plant.

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.

5.3 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 has been undertaken. The three criteria that have been used to divide the catchment into sub-catchments are 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. From Figure 7, 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, while 2, 7 and 8 contain lower income townships.

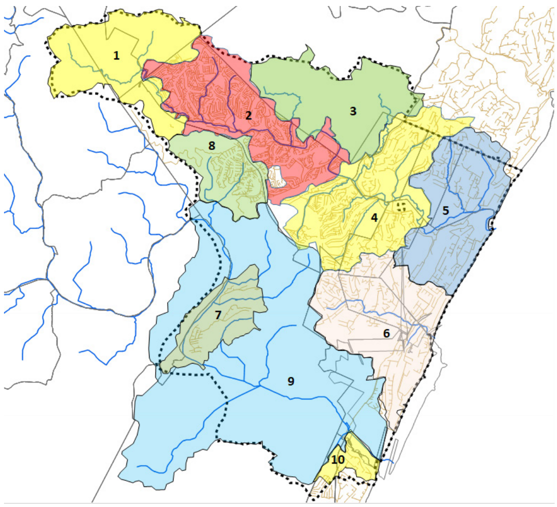

Figure 7. Division of WWTP catchment into sub-catchments.

Figure 8 shows a partial WEST model of the catchment given in Figure 7, which includes the WWTP, sub-catchments 1 to 4 and the sections of river which run through them.

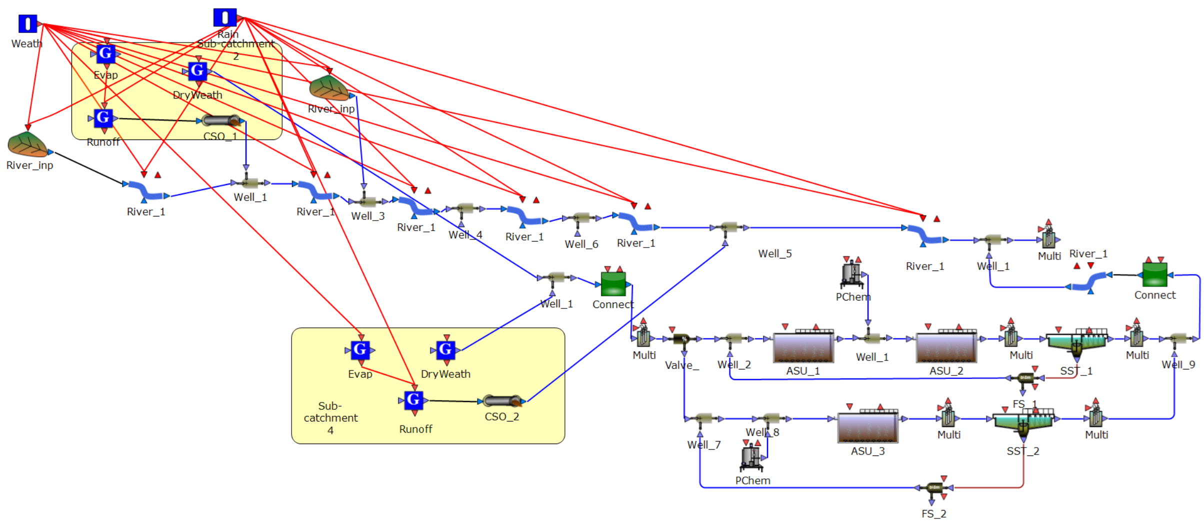

Figure 8. WEST layout for integrated model including the river in sub-catchments 1-4. Sub-catchments 2 and 4 are populated and have associated dry weather and run-off generators, while sub-catchments 1 and 3 are unpopulated and represented by river inputs only.

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 is to identify important gaps in the data available, with the most critical gaps related to the temporal and spatial resolution of the available flow data. Higher resolution flow data is required to 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.

For the case study, weather and rainfall measurements were available at 5-minute increments, but the only measurement of the sewer flow was the inflow to the WWTP provided as a daily total. There was also no pump station operating data, which could have been used to estimate the flow in some of the sub-catchments. This is a fairly typical situation for most catchments in most municipalities since detailed high-resolution flow data is not required for regulatory compliance purposes, and constitutes a significant barrier to the proper calibration of IUWS models. However, the modelling exercise itself can help to identify the critical points in the network where additional flow measurements are required. On the other hand, the SWMM models set up by the case study municipality's Coastal Stormwater & Catchment Management division could be used to generate calibration data for the stormwater runoff and river models, illustrating the importance of different departments and organisations in the water sector working together to share data, tools and expertise in order to build integrated models.

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.

6. Integrating modelling and data into planning and decision making

The primary purpose of IUWS modelling is to provide scientific and technical support for water 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. 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 maker will need to be involved in setting the scope and objectives, and specifying which scenarios need to be investigated. The decision maker also needs to monitor the progress of the investigation to make sure that it is providing the information needed for the decision, and suggest modifications where it is not. By the time it is decision-ready, the decision maker needs to have a thorough understanding of its outcomes and their associated uncertainties and limitations. There is a well-known aphorism by the renowned statistician George Box that "all models are wrong, but some are useful." Therefore, making a model useful is an extensive, iterative process involving the entire modelling team, including the decision-maker(s).

7. Conclusions

Although it has been applied in Europe and North America, integrated urban water modelling is entirely new to South Africa. 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, our experiences have shown that even partial realisations can provide valuable information for water management decisions. Furthermore, these partial models identify the crucial gaps in the data which limit their scope and usefulness. Consequently, a long-term commitment to IUWS modelling will provide a framework for progressively improving a city's data acquisition and data management systems and water management decision-making.

Since water plays a role in almost all municipal activities, its management is typically distributed across various municipal functions, such as potable water supply and distribution, wastewater collection, wastewater treatment, stormwater management, environmental protection and revenue collection. Typically, these tend to operate independently of each other throughout the world, and not just in South Africa. Therefore, integrated water management requires integrated data management, which together imply high levels of communication and cooperation between municipal departments. Furthermore, having an integrated modelling framework in place will be useful for identifying gaps in the necessary institutional linkages so that the poor state of water management and infrastructure in a large proportion of South African municipalities is urgently addressed.

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