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Review

Role of Models in the Decision-Making Process in Integrated Urban Water Management: A Review

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Abstract: Managing urban water systems in which stormwater, wastewater, and drinking water sectors affect each other is a difficult task that requires the right modeling tools for decision making. Integrated urban water management models (IUWMs) are tools that allow decision makers to demonstrate the effectiveness of various management, operational and design strategies. Although models are useful tools, the wide range of available models with many different capabilities make it challenging for the users to select an appropriate model for their specific objectives. In this review we investigated the capabilities of popular models in IUWM. We developed a comprehensive list of indicators to compare the capabilities of the models. We also analyzed the application of these models in a comparative way and evaluated their input requirements. Finally, we provided a procedure to select the appropriate model in the management environment based on the user's needs. In summary, the results show that most of the models' applications are focused on supply and demand, wastewater management, and stormwater management. Very few models consider social factors and policy aspects in IUWM. While each model has its own advantages, we found some of them, such as MIKE Urban, Hydro Planner, and Aqua Cycle, to be more comprehensive. Nevertheless, there are still gaps in the models in areas such as water-energy nexus, evaluating ecosystem services, including socioeconomic factors and sustainability analysis.

Keywords: integrated urban water management (IUWM); urban water management models; urban water system; decision support system

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1. Introduction

Water is the most critical component of human activity in urban areas. As global population growth, industrialization and urbanization continue with the nearly inevitable level of water scarcity and insufficiencies in the water systems' resilience, urban water management has become an ever-challenging task [1–6]. It has been found that the cost of investment in the urban water sector is rapidly increasing and the increase is greater than the capital expenditure budget in most cases. [7,8]. In the face of these challenges, the traditional approach to water management, in which the components of the urban water system (i.e., source water, drinking water, wastewater, or stormwater) are considered independently of each other, is no longer viable [3,9]. Integrated urban water management (IUWM), which was first introduced in the late 20th century, is a method to design and manage the different components in municipal water systems holistically (i.e., water supply, wastewater, and stormwater) [6]. IUWM includes several approaches as alternative solutions, such as developing decentralized water and wastewater systems, fit-for-purpose practices, graywater/rainwater reuse, implementing green infrastructure to manage stormwater, and energy recovery [10]. Although the concept of IUWM has been around for a while, the transition to a fully integrated management framework is slow. In addition, well-documented cases of IUWM can barely be found, even in countries that have been practicing IUWM, such as the U.S. and Australia [11–18].

As IUWM is a relatively new concept, decision support tools are one of the most important requirements from both practitioners and academics to assist urban water managers to deal with IUWM complexities holistically. Decision support systems (DSSs) are systems that gather all of the relevant information from a variety of sources needed for the decision-making processes and the end-users [15]. Despite the potential uncertainty associated with DSSs, they can help an individual or group of people to make the best decision regarding water resources management by considering all the elements that play a role in the decision-making process [16]. DSSs in urban water management account for many different factors such as ecology, climate, socioeconomics, etc., and not just water-related data. There are different components of a DSS in urban water management and associated uncertainty that decision makers might need to deal with during the decision process [19,20]. Decision makers have different approaches to select the best alternative when they face multiple objectives that are sometimes conflicting. Among these approaches, scenario analysis, multiobjective programming (MOP) and multicriteria decision analysis (MCDA) are especially helpful. MOP would be useful when there is a conflict between objectives, while MCDA would allow decision makers to select the most appropriate option among various alternatives [17,21].

Alongside management, urban water modeling and simulation have progressed as operational tools for addressing urban water challenges [22]. Models assist decision makers to achieve their goals in planning and policy making for urban water problems [23,24]. Models are needed to study how the components of IUWM connect and how they are altered in order to recognize future opportunities and restrictions in various urban water systems [2]. The transition from the traditional view to the integrated management of urban water system has been reflected in the models as well [25]. However, integrating different components into a single modeling package has its own challenges. Sufficient knowledge of each component is required, as the meaningful output of the model is not simply the sum of each component. IUWM systems are complex and are not just a simple linkage of individual subsystems [10,22,25]. The simulation of quantity and quality of the water and consideration of fit-for-purpose approaches are substantial in such models. In addition, they should be able to represent different components of the urban water system, such as wastewater and stormwater, separately [26]. In integrated systems, some complexities are inevitable. Therefore, complexities such as the introduction of a new subsystem and the interaction by the required subsequent features needs to be considered [20]. Urban water modeling systems are becoming essential for a complete understanding of the underlying water cycle. Over the last two decades, there has been major progress in tools which facilitate modeling and simulation of urban environmental processes [11,20,26,27]. These models provide useful information for decision makers to assist with their decisions in urban water management. Models can be used to demonstrate the effectiveness of various management strategies, design strategies and operational strategies [20,27]. It is critical to understand the structure of models and how they are used, as it will help both local decision makers and external researchers to recognize potential opportunities and restrictions in IUWM. Urban water models vary widely in terms of how they are structured and their capabilities to investigate different aspects of the urban water system. Therefore, adapting an appropriate model to a specific context is crucial for achieving the goals of urban water management.

In recent years, several integrated urban water management models (IUWMMs) have been developed. IUWMMs have been reviewed by many researchers. For instance, Mitchell et al., screened 64 commercial freely available models and looked into seven models to evaluate them, based on their technical capabilities [14]. They provided an overview of those seven models, based on the spatial and temporal scale, and the components of an integrated water system such as drinking water (i.e., water flows, water quality, water demand, and water supply sources), stormwater, wastewater, and groundwater. House-Peters and Chang have looked at the IUWMMs through the lens of coupled human and natural systems. Uncertainty, resilience, interaction within the temporal and spatial scales, and the conversion of the model to dynamic modeling were also evaluated [20]. Bach et al. (2014), investigated some of the IUWMMs and classified them into four groups from the lowest level of integration which is integrated component-based models (ICBMs) to the highest level of integration which is integrated urban water system models (IUWSMs) [20]. The other types are integrated urban drainage models (IUDMs) and integrated water supply models (IWSMs), which integrate either the drainage or the water supply and lastly, the integrated urban water cycle models (IUWCMs) that connect IUDMs to IWSMs. The highly integrated IUWSMs integrate various urban water "infrastructures" and "disciplines". In such systems, social, economic, climatic, and energy factors are included in the model wherever it is relevant. Renouf and Kenway (2016) evaluated urban water models and categorized these approaches into four groups of urban water system modeling, urban metabolism, consumption approaches, and complex systems. In each approach the direct and indirect water flows were evaluated [28]. Peña-Guzmán et al. (2017) reviewed urban water cycle simulation and management models from 1990 to 2015 [27]. They looked at the geographical distribution of the model usage and categorized the model based on popularity. In their review, the authors looked at the applications of the models reported by other researchers. They concluded that most of the models have been used in academia rather than in real decision-making environments.

Over the past two decades, an increasing and varied body of IUWM modeling literature has arisen. The literature has categorized IUWM models, studied their temporal and spatial scales, and analyzed their dynamics. Nevertheless, the slow adoption of these models into practice shows the lack of practical tools for model selection based on the specific needs and application of the models. Although several papers started to look into the application of models [20,27], the level of investigation in those papers was not enough to enable the users to compare and select the most appropriate models. There is still a lack of detailed evaluation of IUWMMs capabilities in a comparative way to provide adequate information on available modeling tools. In addition, the dominant approach that was presented in the previous review papers was to promote developing IUWMMs rather than using the models. As a result, users, particularly decision makers and urban water managers, may find it difficult when investigating into these literatures to select the appropriate modeling tools according to their needs. As such, there is a need to better present IUWMMs capabilities and where they might find value in practice. Moreover, several capabilities of the models were either not emphasized enough or neglected in the literature including cost, energy, governmental policies, and social factors. In addition, the input requirement is not highlighted for the users which we think is an important factor for selecting a model (especially for those not experienced in the field). Knowing the input requirements will help users evaluate data available and what they need to gather for each case as cases have their own unique characteristics and data availability.

To address these challenges, we reviewed and compared the most common IUWMMs and presented an applicable way to select IUWMMs in decision making process. As mentioned before, the most literature centered on IUWMMs, lack the detailed information on the applications, output, and required inputs of the models. The authors also found the need for a practical procedure to assist the practitioners in selecting the appropriate models. Based on the evaluation of selected IUWMMs, this review goes through investigating and comparing detailed models' application, models' input requirement, and a procedure to help users choose the best model according to their goals. This framework is designed for professionals involved in urban water management and aims to promote multi-stakeholder teams working on drinking water, stormwater, and wastewater management under the bigger concept of integrated urban water management. This study aims to assist decision makers to employ IUWMMs, as such models are usually used in academia rather than in decision-making environments. Available literature focuses on the technical part of model usage and, although that is obviously important, it seems to be more beneficial to model developers and not practitioners.

2. Review Approach

2.1. Data Collection

We developed a three-step process to identify the most common IUWMMs (Figure 1). In the first step, we conducted a preliminary search in the two most used research databases including Google Scholar and Web of Science. We searched these two databases for different expressions related to modeling the urban water system to identify the IUWMMs (Table 1).

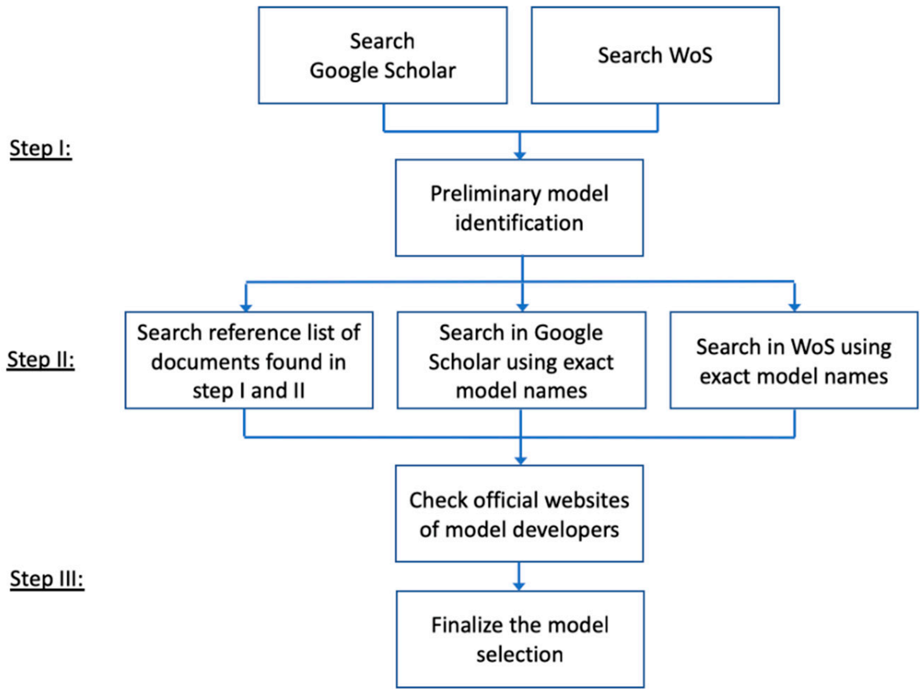

Figure 1. Systematic approach that was implemented to identify and select the IUWMMs.

Table 1. Step I in data collection.

Description	Conditions/Results
Used Databases	Google Scholar and Web of Science
Search Expressions	"urban water management model" or "urban water system model" or "urban water cycle model" or "IUWM model" or "urban water infrastructure model" or "urban water management tool" or "urban water planning tool" or "urban water planning model"
Search Fields	Title and Abstracts
Last Search Date	April 2018

After the preliminary identification of the models in step I, we searched Google Scholar and Web of Science databases again, using the exact name of the models, to collect more documents related to each model. We also constantly searched the reference list of the documents found during steps I and II, to find additional relevant documents that might be available. Of note, during step II, we only included documents that were published in English. In summary, we collected different types of documents including peer-reviewed manuscripts, conference proceedings, case studies, reports and user manuals related to each model. In summary, this effort led to the screening of more than 500 documents and the identification of 32 IUWMMs from those documents.

During step III, after preliminary identification of the IUWMMs, we explored the official websites of the model developers, and contacted the developers directly, if needed. The goal was to see whether the models were still available, to identify the latest version of the models, and to obtain the user manuals. We also explored the official websites of the models to find additional reference documents and case studies. Finally, based on the reference documents that were found, we finalized the model selection. We only included the models that were still accessible and had enough related documents in English. In addition, since the emphasis of this review paper was the integrated models that cover all components of the urban water system (i.e., drinking water, stormwater, and wastewater), we excluded the models with lower levels of integration. In summary, step III resulted in the selection of 13 commonly used IUWMMs, which were analyzed in this research. It should be mentioned that the analysis was based on the latest version of these models that was available. Figure 1 describes the systematic data collection method that was developed and implemented for this research.

2.2. Review Analysis

We employed a five-step process to conduct the critical review. In step 1, models were selected, and a systematic literature review of the model's description, and its characteristics was conducted (Section 3.1). In step 2, ten indicators were selected for model comparison and assessment. After categorizing different sectors in IUWM and investigating the models' descriptions and characteristics, we selected ten indicators that play a crucial role in the process of decision making in IUWM. These indicators include drinking water management (DWM), wastewater management (WWM), stormwater management (SWM), water balance, flood management (FM), quality, energy estimation, cost calculation, social factors, and policy.

In step 3, the models were investigated according to the indicators, and application subcategories of the models were identified. In step 4, the required inputs of the models were categorized. Finally, in step 5, a framework for selecting the models, based on users' needs and objectives was developed. We considered ten key essential indicators based on the challenges faced by cities and under each indicator we listed potential applications of the models to address those challenges.

3. Results and Discussion

3.1. Model Selection

As mentioned in Section 2.1, 13 commonly used IUWMMs, were selected for review in this study. The models that were identified include: Sobek Urban, Aquacycle, Hydro Planner, WaterCress, Water Balance Model (WBM), Urban Cycle, Urban Volume and Quality (UVQ), MIKE URBAN, Urban Water Optioneering Tool (UWOT), City Water Balance (CWB), Dynamic Adaptation for eNabling City Evolution for Water (DAnCE4 Water), Watershed Management Optimization Support Tool (WMOST), and WaterMet2 (Table 2). These models were either the expansion of previously developed models or were developed to introduce new capabilities in urban water management (Table 2). For instance, HydroPlanner addresses the issues with former models such as IQQM, WATHNET, and RELM as they do not include the wastewater component. UVQ is a successor of the Aquacycle model with additional options, such as contaminant simulation and snow modeling capacity. More explanation on the development intention of IUWMMs and other introductory information are presented in Table 2. Additional information on the features and advantages of these models were collected from the literature, including the spatial and temporal scales these models operate. Models such as Sobek Urban consider seconds and minutes as a temporal scale [29]; however, models such as WMOST consider longer intervals of days and months [30]. The spatial scales vary from lot to watershed scale in various models (Table 3). We also included the information about water flow and water demand. In addition, we included whether any of the investigated models consider changes in the system such as morphological change, changes in demand, storage, and climate change, etc. (Table 3). Furthermore, the strengths and advantages of the models in which each model differs from the others were identified (Table 3).

Of note is that many other models were identified during the first step of the review process (e.g., DUWSim, WaND-OT1, DMM, Urban Metabolism, Urban Developer, City Drain3, MUSIC, Re-Visions, and VIBE). However, there was not enough available information to discuss indicators for these models. In addition, some of these models were the engine (or foundation) of the models that we included in the review. As a result, we did not include these models in the review.

Figure 2 represents the trend in development and application of the reviewed IUWMMs. Initially, the focus of the models (e.g., Urban Cycle) was to address the basic needs such as water supply and demand and only a few strategies were available in such models for water management that included rainwater harvesting and wastewater recycling strategies. Then, models such as Aquacycle started to include more water management strategies (i.e., rain tanks, subsurface direct graywater irrigation, aquifer storage [31]). They also included larger spatial scales such as catchment level (Table 2). Further in the development, models were able to consider water quality analysis (i.e., UVQ, Sobek Urban, DAnCE4Water) [32–34]. Models in this category considered more contaminants such as waterborne pathogens. A wider range of indicators such as cost, and energy estimation were added later to the models. One example of this category is CWB. In addition, these models have better representation of natural systems [31]. Social factors (i.e., considering change in end-user behavior, technological, and demographic change) are added in the latest steps of this trend development (Figure 2).

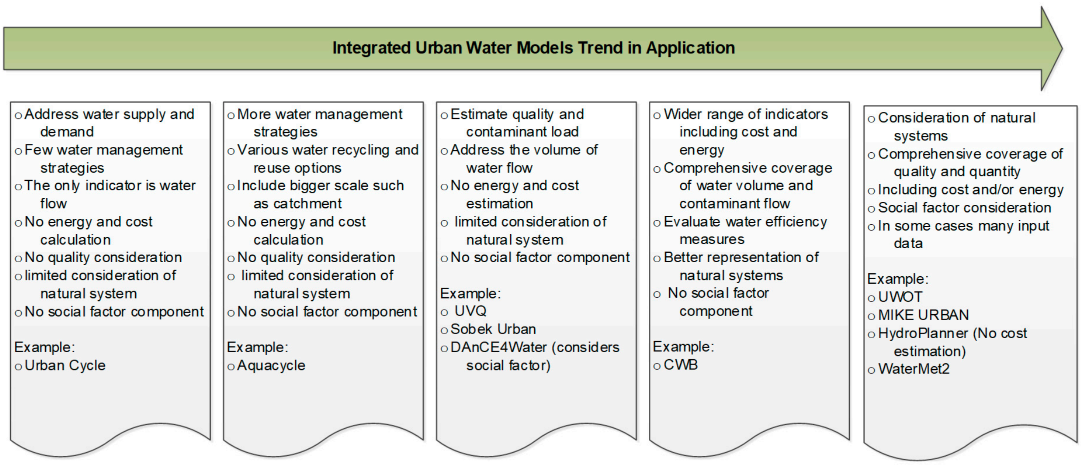

Figure 2. Category of development and application of IUWMMs.

Table 2. Selected Models.

Model	Type	Year	First Developed by	Development Intention	References
Sobek Urban	IUWCMs	1999	Deltares	Model explores irrigation and drainage system, sewerage, flooding simulation, water quality, canal and waterway control system design and optimization.	[29,34–38]
Aquacycle	IUWCMs	2001	Cooperative Research Center for Catchment Hydrology (CRCCH)	Expanded previous models. Integrated water cycle, water reuse, include strategies such as rain tanks, stormwater system and wastewater collections, aquifer storage, and graywater irrigation.	[27,39–49]
Hydro Planner	IUWCMs	2001	Commonwealth Scientific and Research Organization (CSIRO)	Address the issue with former tools such as IQQM, WATHNET, and RELM that do not include the wastewater recycling in calculating the demand. Comprised of seven modules that can link the models in different areas. Simulate the whole urban water cycle, water flow, and constituent modeling, to familiarize urban water managers with the water cycle components and their interactions.	[10,26,27,50–53]
WaterCress	IUWCMs	2002	Clark and Cresswell	Answers the problem with the feasibility of selected alternative system layout. Simulate water flow through the natural and built environment.	[27,54–59]
Water Balance Model (WBM)	IUWCMs	2004	Quality/Quantity Simulation model (QUALHYMO)	Aid governments to reach acceptable urban water health and environmental security outcomes. A decision support tool that connects engineering and planning to reach the sustainability goals such as economic sustainability, decreasing environmental value, increasing social value, and creating recreational prospects.	[11,27,28,39,55,60–67]
Urban Cycle	IUWCMs	2005	Hardy et al.	An object-oriented model aiming to address the growing and changing requirements of water division in Australia. It is aimed for "adoption of continuous simulation, hierarchical network modelling, and the careful management of computational complexity."	[10,26,27,39,68–72]
Urban Volume and Quality (UVQ)	IUWCMs	2005	Mitchel et al.	Aquacycle's successor with extra options such as contaminant simulation and snow modeling capacity, simulating constituent load and water flow volume from source to discharge, and water management alternative evaluation.	[10,26,27,33,39,73–83]
MIKE URBAN	IUWCMs	2007	Danish Hydrological Institute (DHI)	This model overcame one dimensional SWWM limits in flood simulation by combining 1D sewer modeling with 2D overland flow modeling and incorporates current resources, demand, distribution, and runoff models.	[10,26,27,39,84–90]

Table 2. *Cont.*

Model	Type	Year	First Developed by	Development Intention	References
Urban Water Optioneering Tool (UWOT)	IUWCMs	2008	Water Cycle Management for New Developments WaND	"Provide guidelines and decision support tools for the implementation and assessment of efficient and sustainable water management interventions in new urban developments with due consideration to social, environmental and health associated factors."	[2,27,91–98]
City Water Balance (CWB)	IUWCMs	2010	Sustainable Urban Water Management Improves Tomorrow's City's Health (SWITCH) Last	Better representation of natural system, access to broader range of alternatives comprising sustainable urban drainage system, calculate life cycle energy use and whole life cost analysis. Designed for decentralized system.	[22,31,99,100]
Dynamic Adaptation for eNabling City Evolution for Water (DAnCE4 Water)	IUWSMs	2011	Monash University, University of Innsbruck, Centre for Water Sensitive Cities and Melbourne Water	Simulate dynamics of both urban system and societal features, considers both urban planning factors and demographic data.	[32,101–107]
Watershed Management Optimization Support Tool (WMOST)	IUWCMs	2013 V3-2018	United States Environmental Protection Agency	Decision support tool at local and small watershed. Includes hydro-processor, screens a wide range of potential water resources management options considering environmental and economic sustainability.	[30,108–112]
WaterMet2	IUWCMs	2014	Exeter University and NTUA	Metabolism based modeling, quantify resource flow (water and energy), water energy nexus, environmental impact on IUWM. Conceptual and mass-balance-based, quantify metabolism, focus on sustainability issue.	[113–115]

Table 3. Model characteristics and strengths.

Model	Spatial Scale	Temporal Scale	Water Flows	Water Demand	Change Consideration	Strengths/Advantages	References
Sobek Urban	River catchment, neighborhood, region, city	Minutes-seconds	Quantify both water flows and other main fluxes related issues consider desired specified flow.	Coupled demand with network of nodes	Morphological changes	Real-time control, very user-friendly interface, schematize problem and organize needed data.	[29,35,37]
Aquacycle	Unit block, cluster (suburb), catchment	Daily	Temporal distribution of water flow	Daily variation	Change in storage within the system	Strong model to introduce the substitute for imported water, estimation of daily, monthly, and annual water demand, simplicity, rapid run time.	[27,39–49]
Hydro Planner	Town, region	Daily	WS, SW, WW, receiving water module	Projection of water demand and changing scenarios	Examines water demand, climate change, population growth, and technological change	The end-use model software such as REALM is linked to this model for supply−demand stability. Integrates climate change, demographic variation, and land use alteration in predicting supply and demand. Inclusive coverage of urban water volume and constituents.	[10,26,27,50–53]
WaterCress	Lot, neighborhood, region	Daily	The model simulates daily flows and volume within a boundary	Diurnal variation	Error adjustment factor can be applied in case of rapid changes.	Contains all the available sources such as stormwater, groundwater, water from desalination sources, imported water, and traditional catchment sources. Effect on environment and natural system. Reliability of water supply, water quality, and average cost. Bigger scale than Aquacycle and better representation of a city.	[27,54–59]
WBM	Subdivision, catchment	Hourly or sub-hourly	No flow rate		In new version, the model adds an infiltration system	Widely used, especially for stormwater management. Assess the efficiency of site planning on stormwater management to achieve stormwater control under various conditions such as different land use, land cover, and climate scenarios. Four situations are considered by WBM: site surface alteration, site controls on base flow discharge, detention pond storage, and stream erosion.	[11,27,28,39,55,60–67]

Table 3. *Cont.*

Model	Spatial Scale	Temporal Scale	Water Flows	Water Demand	Change Consideration	Strengths/Advantages	References
Urban Cycle	Lot, neighborhood, suburb	Sub-hourly (sub-daily)	Model detailed SW peak flows but not base flows	Diurnal variation	NA	Alternative selection by hierarchical network modeling, compared with traditional strategies. Simulating very detailed run off, demand, and wastewater. Able to predict the peak flow.	[10,26,27,39,68–72]
UVQ	Lot, neighborhood, suburb, town, region	Daily	Temporal distribution of water flow	Diurnal variation	Non-structural changes to the system	It provides performance necessities for treatment processes to enhance reuse options and reduce environmental impacts, simplicity, rapid run time, and exploring 50 different scenarios.	[10,26,27,33,39,73–83]
MIKE URBAN	Neighborhood, suburb, town, region	Sub-hourly	Detailed flow rate of SW, WW, and WS	Diurnal variation	Considers urbanization, socioeconomic trends and climate change	Commercially used, it is a complex model, detailing flow rates in water supply, stormwater and wastewater. Very comprehensive algorithm for water quality. High detail but little run-time feedback between distinct water streams.	[10,26,27,39,40,84–90]
UWOT	Lot, neighborhood, region, city	10-min to monthly	Instead of simulating flow, the generation, aggregation and transmission of a demand signal simulated.	Demand signal including the quantity of the demand and quality of the water supply	Simulation of changes in behavior by frequency of use (demand oriented approach)	Incorporates Simulink/ MATLAB and Microsoft Excel into a decision support tool. Include sustainability factors such as environmental, economic, social and technical; includes indoor water efficiency usage and sustainable urban drainage options.	[2,27,91–98]
CWB	Neighborhood, city scale	Daily	Assessing sustainability in water flow	Demand input is based on per-unit area demand	Based on IPCC, the worst case scenario is used so the more extreme climate could be modeled.	Combines water efficiency options of UWOT and reuse options of Aquacycle but in much greater details. Best operation in larger scales.	[20,31,99,100]

Table 3. *Cont.*

Model	Spatial Scale	Temporal Scale	Water Flows	Water Demand	Change Consideration	Strengths/Advantages	References
DAnCE4 Water	Lot, neighborhood, region, city	Daily		Diurnal variation	Change in different urban planning rules in future scenarios, climate and demographic change	Support SWWM, consider social, economics, urban form, ecology, energy and a number of sustainability indicators. Include "what if" scenarios for dynamic evaluation	[101,105,116]
WMOST	Watershed with the flexibility in the number of HRU *	Daily- monthly	Water flow of SW, WW, potable water, and combined sewer system	Demand time series for both potable and nonpotable. Demand management	Future climate and growth scenario	WMOST models the environmental impacts and costs of management decisions in a watershed scale, including the impacts of decisions. Includes combined sewer overflow simulation and minimization.	[30,112]
WaterMet2	Neighborhood, region, subcatchment, catchment	Daily	Daily water flow rate, include graywater inflow.	Diurnal variation	GHG flux as a dominant factor in climate change	The main advantage is the evaluation of metabolism-based performance of water system.	[113,115]

* HRU: Hydrologic response unit.

3.2. Models' Application

In the third phase of the research, which was the major part of this review, models were investigated according to the assessment indicators. After the screening phase, the potential users need to know more details under each indicator. Thus, in this stage we provided the application's subcategories to better help the user to select the most appropriate model according to the detail needs (Table 4).

3.2.1. Drinking Water Management

Drinking water management was covered by all of the models as it is one of the main components of IUWM. However, when looked at more carefully, the detail in which the models consider this component are very different. While all the models cover water supply and demand, their approaches are sometimes different. For instance, Aquacycle estimates monthly or annual water demand, yield, and consumption [46] while, Hydro Planner is capable of developing the regional water allocation and water availability analysis. Hydro Planner also considers the growing effect of urban development, land use change, and climate change and takes into account water supply management strategies [51]. Utilizing these strategies assist with maximizing the supply reliability and minimizing the negative effects on receiving water bodies [117]. UVQ provides water demand scenarios and management and is capable of considering supply and demand at different spatial scales [73,78]. UWOT is also able to manage the optimal distribution of demand to available resources [60]. WaterCress evaluates a range of conventional and unconventional alternatives as well as the stability of water supply [31]. Leakage reduction is an important issue in the water industry and water-distribution systems. It can cause a notable loss in water resources [118]. Annually, more than 32 billion m3 is lost during the delivery of water supply. Of note is a number of models, such as MIKE URBAN [84], UVQ [80], WBM [60], WMOST [112] and CWB [78,81,119], take into account water losses and provide leakage analysis and reduction. Efficient water distribution design can mitigate the challenges with such systems. Efficient design and quality management is one of the capabilities of MIKE URBAN [88,120]. CWB simplifies city water systems temporally and spatially in distribution systems [31] and UWOT also covers transmission and distribution of water in the urban water balance [93]. Other models partially cover the distribution system or do not include it at all. For instance, Urban Cycle is not able to evaluate systems with transferred back water to upstream nodes or complex distribution systems with multifaceted functioning rules, linking to the accessibility and use of water, or dictate how flows are controlled [121]. There is only one model (WaterCress) that allows the users, such as farmers, to model their own water supply capacity, planners to develop water allocation plans, and designers to link any source of water to various demands [54,122]. Other capabilities of the models such as water treatment options, abstraction from hydro-systems, and alternative water infrastructure options, are described in Table 4.

3.2.2. Wastewater Management

Wastewater management including collection, treatment and reuse is another important capability of IUWMMs. More than half of the reviewed models include these wastewater management capabilities (Table 4). Some of the reviewed models also consider additional components in wastewater management. For instance, WaterCress considers the wastewater treatment plant extension design [123]. Hydro Planner is capable of simulating wastewater, associated constituent generation, and routing processes via wastewater modules [52]. Hydro Planner considers wastewater and supply water, their interactions, and how they affect the environment [51]. Aquacycle is capable of storage analysis, and characterization of wastewater quantity and temporal and spatial distribution [40,124]. UVQ has the ability to specify different water systems within neighborhoods and the order in which stormwater and wastewater flows from one neighborhood to another [75]. UVQ compares wastewater management alternatives against the traditional approaches and considers the nutrient loads and treatment removal efficiency [78].

Leakage analysis and reduction is crucial due to its substantial impact on groundwater and soil pollution prevention. A leaky sewage system has been identified as one of the main sources that contaminate groundwater [125,126]. Sulfide gas formation is another issue that must be managed in a wastewater system as it causes toxicity to sewer workers and concrete corrosion [127,128]. Among the models, MIKE URBAN covers the wastewater leakage analysis and reduction and sulfide gas formation analysis [84]. MIKE URBAN is capable of supporting the city's water and wastewater master plan and enabling the user to make future simulations for a cost-effective and resilience wastewater collection system, capacity management and operational maintenance. MIKE URBAN does the geocoding of catchment networks, wastewater loads, and demand distribution. It optimizes system performance to decrease the problem with combined sewer overflow and estimates the effect of river flooding on the sewer system. MIKE RBAN combines 1D sewer modeling with 2D overland-flow modeling [84].

It is also important to consider whether the model considers centralized versus decentralized wastewater management technologies. For example, CWB simulates the water flow but it is designed only for decentralized technology and does not estimate the cost and energy usage of centralized systems [31]. Urban cycle, for instance, is capable of very detailed water demand and wastewater simulation at sub-daily time scales [121].

Graywater reuse is a great alternative for conserving water [129]. Among the models reviewed in this study, Aquacycle reflects subsurface irrigation with graywater [42], WBM is capable of using graywater for nonpotable [60] uses, and UWOT has the integration through recycling scheme including graywater, treated water, and rainwater [130]. Table 4 represents other capabilities of models in wastewater management.

3.2.3. Stormwater Management

It is now well known that stormwater management involves more than just drainage design and flood risk reduction, which have been practiced traditionally. The traditional practice is changing into more sustainable stormwater management, and it is evident not only in flood reduction, but also in pollution mitigation, urban landscape improvement, and drainage investment reduction [131]. Almost all of the models include the drainage design (Table 4). However, as models consider sustainability more, they look at stormwater as a resource that can be captured and reused (i.e., aquifer recharge) [44]. For example, Aquacycle has the capability to cover alternative strategies such as rainwater harvesting, cluster stormwater systems, catchment stormwater systems, subsurface direct greywater irrigation, aquifer storage, and wastewater recycling at unit, cluster and catchment level. Furthermore, the Aquacycle basic model works similarly to Urban Cycle; however, Urban Cycle includes fewer alternative strategies [31]. All of the reviewed IUWMMs are able to design and evaluate at least some of the stormwater best management practices (BMPs). Rainwater harvesting, an important aspect of stormwater management and reuse, is also covered by most of the models (Table 4). Models like UVQ [78] and Hydro Planner are able to simulate the constituent generation and routing process in stormwater management system [46]. Aquacycle is among the models that not only focuses on hard engineering, but also considers the impact of green infrastructure on the water balance [41].

WaterCress [123], Aquacycle [42], UVQ [74,75], and WBM [123] consider stormwater harvesting, water storage, and its size optimization. WBM allows users to assess the efficiency of site planning with stormwater management strategies (e.g., absorbent landscaping, infiltration facilities, green roofs, and rainwater harvesting) and to attain expansion goals for rainwater detention and runoff control under different land uses, soil, and climate conditions [132]. UVQ explores the influence of shifting the urban system and grade of drainage connectivity on the features of stormwater runoff [74]. This model emphasizes the interconnections of the water supply, stormwater and wastewater system, the direction in which stormwater moves from one neighborhood to the other, and the capability to identify different water systems within the neighborhood [75].

3.2.4. Water Balance

One of the initial applications of water-cycle models is to assess the water balance in the system. This application enables users to identify the different flows (water, wastewater, and stormwater). Water balance is the movement of water in the hydrological cycle—in our case, the urban cycle. The basic water balances in all of the models is the changing in storage, which is sum of input minus sum of outputs [133] (Equation (1)).

$$(P + I) = (E + D) + \Delta S \tag{1}$$

where, ΔS is change in storage, P is precipitation, E is evapotranspiration, and D is drainage. In places with an unconnected drain system, D consists of Dw as wastewater and Ds as stormwater [134]. Models included in this review can perform the water balance, a primary need in urban water cycle. Aside from performing the daily water balance, Aquacycle considers the various water recycling options and their influences on the water cycle as they may increase the water supply and decrease wastewater and stormwater [133]. Aquacycle's outputs consist of water balance, with daily values for precipitation, evapotranspiration, piped water supply, stormwater, drainage and wastewater collection [133]. Several models developed after Aquacycle, such as UVQ, consider contaminant loads at each receiving point under different scenarios in the total water cycle [75].

3.2.5. Water Quality

Eleven models can perform water-quality analysis at different levels. In MIKE URBAN, the user can track the age of water, dissolved contaminants, growth of microorganisms, and decay of substances. Users can consider mass inflow rate and concentration level to analyze the water quality. MIKE URBAN models the bulk flow reactions by nth order kinetics and pipeline reactions by zero or first order kinetics. The critical water quality features in MIKE URBAN are water age analysis, chlorine concentration and path, and concentration of pollutant analysis [88,135]. Sediment, dissolved substances, transport modeling, water quality risk analysis [90], and the efficient design and quality management of the water distribution system operation are among the capabilities of this model [88]. MIKE URBAN uses the EPANET engine for water quality in pipe systems [135]. The catchment module in Hydro Planner supports the linking of models that can simulate contaminant and run-off generation [51,52]. Hydro Planner is capable of constituent balance analysis, including sediment, nutrients, pathogens, and contaminants [52]. In addition to the quality of supply water [54,123], WaterCress can track salinity changes from source to sink as well as other general water quality parameters [55] (Table 4). UVQ shows the application needs of treatment procedures and tools to accomplish user-indicated water quality discharge attributes as well as the specifics of water flow and quality from land block areas [75]. WBM also tracks and simulates the water quality and contaminant load [64]. CWB explores water-borne contaminants using a basic image of city water systems [31]. UVQ predicts and track the contaminant load and its primary sources [73–75]. In this model, stormwater, wastewater, water supply, and groundwater are represented at the same time. In addition, it covers the impact of different water management strategies on contaminant flow in the urban environment and its effect on subsurface discharge and surface water [75]. It also looks at contaminant load and imported water contaminant concentration [78,81,136]. Water Met2 considers the quantification of nutrients and waste in urban regions [113].

3.2.6. Flood Management

Urban water managers have a great interest in flood management and estimating flood damage in order to evaluate the adaptation measures and to address flood risks [137,138]. Flood management has been included in five models studied in this research. Of note, is that some of the models were initially developed to perform flood management modeling and simulation as one of their main capabilities. For instance, flood management is the main use of MIKE URBAN and Sobek Urban. Assessment, monitoring, and optimization of drainage systems are among the important functions of these two models [27]. MIKE URBAN is able to simulate flood extension and inundation [89]. The MIKE URBAN model simulates 2D overland flow and Geographical Information System (GIS) integration. It provides emergency response planning for urban flooding and solutions for local urban flooding through the design of mitigation measures such as efficient drainage systems [85,86,89,139]. Since MIKE URBAN is a two-dimensional model, it can also be used to determine the impact of boundary walls on flooding [89]. In addition, MIKE URBAN evaluates the effects of river floods on sewers and estimates maximum water depth for flood assessments [138,139]. WaterCress is likewise capable of flood modeling, but it links the model with hydrological databases. It also provides the capacity to run real-time resource and flood assessments [54]. DAnCE4Water considers indicators for performance of urban water infrastructure. These indicators are rates of sewer overflows and flooding [28]. The WMOST model has a flood damage module which calculates the damage caused by flood and the cost for its management.

3.2.7. Energy

Energy is becoming a crucial factor for decision makers due to its strong interconnection to water sectors, especially in urban water management. Until recently, analysis of energy implications in water- and wastewater-related strategies has been very limited, despite many challenges such as the growth of energy consumption and prices [92]. For urban water services, energy is linked with water in different stages such as bulk water harvesting and transport, water treatment, water distribution, wastewater collection and treatment, and finally effluent discharge. The energy associated with stormwater and decentralized supplies has been less considered in urban water management, since it is relatively small compared to water supply or wastewater management systems. For instance, the energy use linked with rainwater tanks is not comparable to energy use in the drinking water system. There are three areas for energy considerations in models either directly through estimation of energy consumption and lifecycle energy use, or indirectly through greenhouse gas (GHG) emission because of energy use. Hydro Planner has the capability to quantify system-wide energy usage and GHG emissions at various scales and under different management scenarios [51]. MIKE URBAN can model the cost of energy use for operating pumps. Within the "Pump Energy Editor", the user can define a method for cost calculation. UWOT is capable of modeling water-energy interaction in the whole urban water system [92]. This model takes into account the energy used in pumping the potable water and groundwater, the energy used for seawater desalination, and the energy required for pumping, treating, and discharging water (both potable and reclaimed) in the distribution system [93]. The simplified life cycle energy is used in the form of spread-sheet models and used for both water supply and treatment using published values for energy consumption per cubic meter. It calculates lifetime energy use as the addition of embodied energy of all the parts, energy consumption of fuels for construction, maintenance, and operation. It also takes into account the electricity needed for pumps and the energy needed for chemical treatments [99]. CWB considers life cycle energy and costs. It calculates a simplified life cycle inventory of energy. This can be listed as construction, operation and decommissioning [31].

3.2.8. Cost

Cost is one of the important indicators especially when decision makers are evaluating and comparing multiple scenarios. There are different levels of calculating cost in urban water systems. Whole life costing, capital and operating cost, and operation and maintenance cost are the different cost levels that have been included in the reviewed models. Of note is some of the reviewed models consider more than one level of cost. For instance, UWOT considers both whole life cost and capital and operating cost. In addition, it considers other qualitative indicators, such as life cycle cost, willingness to pay, affordability, and associated financial-risk exposure [2,31]. In addition, UWOT provides information concerning water demand and investment costs for the substitute local water technology configuration [94]. WMOST considers operational and maintenance cost and cost-benefit analysis [31,112]. WaterCress enables users to estimate capital, operating, and unit cost of functioning urban water system components [71,122,123]. CWB calculates the whole life cost, including the costs of capital, construction, maintenance and operation. In CWB, costs occurred during the lifetime of the asset are adjusted to net present value [99]. Water Met2 considers operational and maintenance costs which are dependent on the electricity and fuel per cubic meter of amount of water consumption [114] (Table 4).

3.2.9. Social Factors

Integrated urban water systems are multifaceted and understanding the dynamics of such systems, from supply sources to end users, is complex (Ewater 2018). In addition to changes in hydrology and precipitation rate, behavioral changes also affect the urban water system. Behavioral changes can be linked with climate change and changes in water demand [140]. End user behaviors are variable due to the introduction of alternative water resources, such as water management options and direct and indirect drivers for water consumption [52,140–142]. In addition, researchers have found that social awareness and exposure to water deficiency in various parts of the world have caused people to value water and consume it more efficiently [141,143,144]. Demographics (e.g., age, income level, education level, and family size) and household characteristics (e.g., house size and type, outdoor facilities, and water technologies) also affect environmental behavior [94]. Very few models have considered social factors as one of their components. Hydro Planner can simulate the effect of end user behavior alteration on the performance of the supply system and the water quality. The user can use Hydro Planner to evaluate the supply system. This model takes into account the probable changes in climate, population, technological change and variations in future demand and management [51]. UWOT considers changes in behavior, including the time series of frequency-of-use and technological change [91]. UWOT includes other social indicators such as risk to human health, acceptability, participation/responsibility, public awareness, and social inclusion. These indicators are qualitative, so they are rated in five rates [2]. In addition, one of the functions of UVQ is to consider water usage behavior and changes in household occupancy [74]. End-use data can be used in Urban Cycle for various demand-reduction scenarios to evaluate their effect on design indicators. Six end-use categories (toilet, shower, dishwasher, washing machine, tap water, and outdoor use) can be considered at household level [69].

Although some of the studied models include social factors to some extent, there is still a lack of proper tools to evaluate socio-technical features in urban water management. DAnCE4Water is one of the IUWMMs aimed at addressing the societal dynamics issues. This model deals with social and institutional implications of urban water systems rather than biophysical implications. It considers different scenarios of urban water servicing explanations in meeting water-related societal needs [104].

3.2.10. Policy

Governmental policies influence land use and growth boundaries, which can be important in the decision-making process of managers. There are only two models considering this indicator. DAnCE4Water covers the governmental policy assumptions and assesses policy influences by showing market reactions [116]. WMOST permits water resources managers to assess policy management option within a watershed. Managers can specify the limits of land area under each management situation in case the physical limitations are associated with policy requirements [30].

3.3. Models' Inputs

Identifying the required inputs for the models can help the users to see what type of data is needed as an input for each IUWMMs. Obviously, depending on the outcome a user is looking for, the input requirements are different. The primary inputs for IUMMs in general include climate data, water flow rate (including streamflow), land use and land cover, population, and water quality parameters. Precipitation and evapotranspiration are the most important climatic inputs that are required by all the reviewed models. Temperature, rainfall intensities, and antecedent dry days are also needed in some of the models. Water flow, including drinking water, wastewater, and stormwater input data, is another primary input. Water volume, drinking water leakage, imported water, maximum water depth for flood assessment, daily demand time series, water availability for supply and demand, water consumption (indoor, such as kitchen water use, bathroom, toilet, and laundry and outdoor, such as garden irrigation) are among water flow data. Wastewater flow, run off (roof, pavement, garden, road, and public open spaces), stormwater volume, stormwater (effective area, soil store capacity, and drainage factor) are other data requirements for water flow. Land use/ land cover is another main input (pervious and impervious areas) that is required in some of the models. Population data and household occupancy are important inputs to estimate per capita water demand. Contaminant loads are the inputs for models with the capability of water quality simulation. Other inputs of these models are capacity and estimation of needed storage, maximum storage volume, and tank size. Secondary inputs are not common among models. For example, MIKE URBAN, due to its capability, needs inputs such as catchment characteristics, node and link input, location and physical characteristics of manholes, pipe, canals, and GIS data. Furthermore, knowing the spatial and temporal scale of the models (Table 3) can also help the user to see the data intervals and resolution needed as the model input.

4. Model Selection

Decisionsupport tools based on IUWMMs have become progressively popular in coupled human−natural systems. In the last phase of this review, we provide a procedure to assist with selection of the most appropriate model based on specific needs and available data. The iterative procedure is presented in Figure 3. The proposed procedure includes (1) determination of the goals, (2) selection of the indicator(s), (3) studying the capabilities of available models, (4) identifying the input requirements, and (5) selecting the best option.

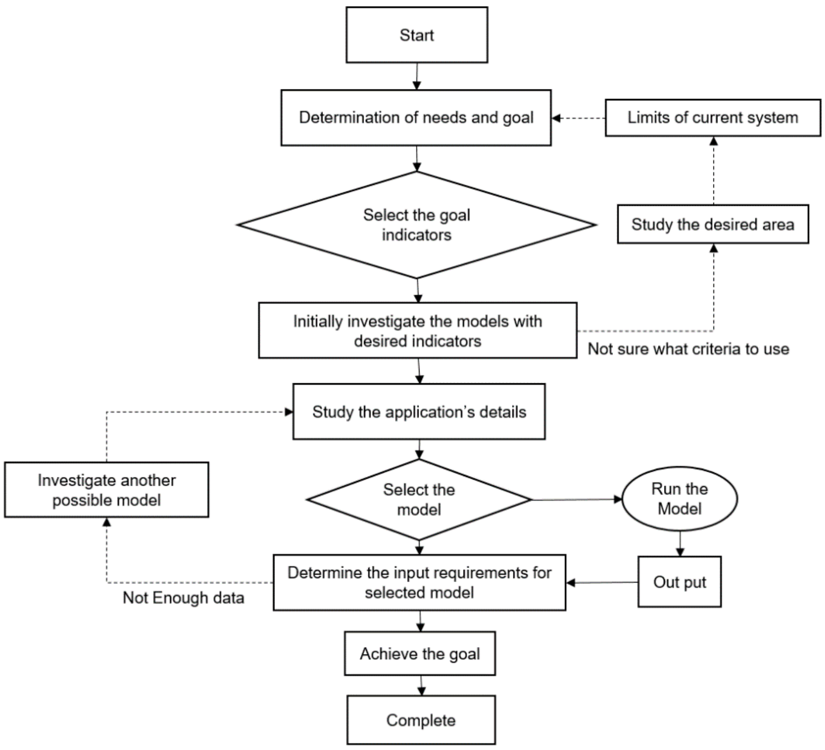

Figure 3. Decision-making procedure for selecting IUWMMs.

The starting point is to specify the overall goal and the needs of the urban water system. Problem identification is the first step that is usually incorporated into the urban water framework [143–145]. The purpose here is to evaluate the limits of the current urban water system and identify the objectives to move forward with decision making in different spatial and temporal scales. Defining the system boundaries and specifying the scale is a crucial step in determination of the goal and could be helpful to ultimately select a model (Table 3). Attempts to define the needs of the system are an important prerequisite for selecting the goal indicators.

The next step is to select the goal indicators. Table 4 represents the preliminary information for the users. Through screening, the user can initially select the models that could be useful for reaching the goal. This step is useful for eliminating the models that are not addressing the goal and paves the path for better analyzing the models with the capability of achieving the objectives. For instance, if one of the main goals for an urban water manager is flood management, a user can screen the Table 4 and initially select Sobek Urban, WaterCress, MIKE URBAN, DAnCE4Water, and WMOST. In an iterative process, it is important to evaluate the current knowledge of the user and take steps back to modify the intention and problem definition (if needed). If the user is not sure what indicator to select in this step, more study within the boundary on the limitations of the system is needed. After gaining new insight from studying the current system, users can continue selecting the model.

The next step is to evaluate the models and finally select the best available model. Comparing models with the desired indicators is not always enough for selecting the models. To better decide which model fits the user's specific needs, more details on how the models are applied is required (Table 4). For example, in the case of flood management, if the user is interested in estimating potential risks beside flood simulation, then Sobek Urban and MIKE URBAN are the two models that can be used.

Following the model selection, the next step is determination of input requirement. The inputs are totally depending on the spatial and temporal scale of the urban water system and the specific goals of the user. Sections 3 and 4 of this paper introduced the primary and secondary inputs needed for such models; however, this step requires more specific data based on the users' objectives. For instance, if the user is interested in tracking water quality, then obviously, the input data in the case of salinity as the targeted pollution is different from the case of waterborne pathogen input. As mentioned earlier, determination of the input is also dependent on temporal and spatial scales (Table 3). If the user reaches a point that two or more models are appropriate and there is not enough data available, the user can use the model that needs less input requirement. For instance, CWB needs hourly or sub-hourly data, while Aquacycle only requires daily data. Thus, if graywater reuse is the purpose, Aquacycle can be used, which needs less data than CWB.

After determination of the input requirements, the user can collect information for the specific case studies he/she is planning for. The user can use the collected data to run the model and finally get the output (Figure 3). The final step is to evaluate the output in order to achieve the desired goal. If the user gains insufficient output, the gathered input data can be checked to improve the results.

Table 4. Details of model's applications according to evaluation indicators.

Indicators	Application	Sobek Urban	Aqua Cycle	Hydro Planner	Water Cress	WBM	Urban Cycle	UVQ	MIKE URBAN	UWOT	CWB	DAnCE4-Water	WMOST	Water Met2	References
DWM	Supply and demand	√	√	√	√	√	√	√	√	√	√	√	√	√	[20,30,31,51,52,54,57,59,60,69,71,73–76,78,88,92,114,123,124,133]
	Water availability analysis			√											[51]
	Water distribution								√	√	√	√	√	√	[31,88,93,107,112,114,121,124]
	Regional water allocation			√											[51]
	Leakage analysis							√	√		√		√		[30,42,78,80,81,133,133,146,147]
	Hydro system abstraction									√					[92]
	Allows farmer, designer, and planner to model their own need				√										[54]
	Alternative water infrastructure option				√										[75]
	Treatment option						√	√		√				√	[74,93,121]
WWM	Wastewater and graywater reuse		√	√		√	√			√	√		√	√	[30,42,53,75,115,133]
	Wastewater treatment options		√	√						√				√	[42,50,93,115]
	Wastewater storage/capacity		√						√				√		[30,42,124,136,148]
	Neighborhood WW flow							√							[75]
	Simulation of sewer flow	√	√					√	√		√	√	√		[28,31,34,49,73,111,120,124,133,134]
	Leakage reduction							√	√						[84,147]
	Sulfide gas formation analysis								√						[84]
	Extension design				√										[123]
	Effect of river flood on sewer								√						[139]
SWM	BMPs	√	√	√	√	√	√	√	√	√	√	√	√		[30–32,41,42,44,50,52,69,76,77,86,99,102,149,150]
	Drainage design	√	√	√	√	√	√	√	√	√	√		√	√	[2,30,31,34,43,51,54,72,74,78,89,114,151]
	Rainwater treatment/ reuse		√	√	√	√	√	√		√					[43,44,50,89,93,94,115,121,122,130,152]
	Optimizing storage size		√		√			√			√			√	[31,42,48,74,122,123,153]
	Runoff management			√		√	√			√		√	√		[2,52,102,112,115,121,123,132]
	Impact of GI on water balance		√												[41]
	Average run off assessment				√								√	√	[112,123]
	Rainfall inflows and infiltration mitigation								√				√		[89,112]
	Planning for measures considering overland flow								√						[139]
Water balance	Entire water cycle modeling/water balances	√	√	√	√	√	√	√	√	√	√	√	√	√	[30,34,46,50,57,60,69,71,74,75,92,93,95,102,113,146]
	Climate change			√					√			√	√		[30,51,52,85,102]
	Different water servicing/demand		√					√				√	√		[74,75,112,116]
Energy	Energy production and consumption estimation	√		√					√	√	√				[31,35,50,135]
	Life cycle energy use										√				[31]
	Energy and GHG emission linkage			√										√	[50,115]

Table 4. *Cont.*

Indicators	Application	Sobek Urban	Aqua Cycle	Hydro Planner	Water Cress	WBM	Urban Cycle	UVQ	MIKE URBAN	UWOT	CWB	DAnCE4-Water	WMOST	Water Met2	References
Quality	General contaminants	√		√	√	√		√		√	√	√	√	√	[2,30,31,34,44,51,55,64,73–75,78,103,113]
	Waterborne pathogens			√							√				[31,51]
	Nutrient			√										√	[51,113]
	Salinity				√										[55,122]
	Sediment and dissolved substances			√					√						[51,90]
Cost	Whole life costing									√	√				[31,99]
	Cost benefit analysis								√				√		[30,135]
	Capital and operating cost				√					√					[71,94,122,123]
	Operational and maintenance cost												√	√	[30,114]
Social factors	Changing end user behavior			√			√	√		√					[51,69,74,91]
	Technological change			√						√		√			[51,116,130]
	Demography and urbanization			√					√			√			[51,84,102]
FM	Flood simulation/ assessment	√			√				√			√	√		[34,38,54,89,106,112]
	Design of mitigation measures								√						[139]
	Emergency response planning								√						[139]
	Estimation of potential risks	√							√						[34,139]
	Damage costs												√		[112]
Policy												√	√		[30,116]

5. Conclusions

Managing an urban water system in which drinking water, wastewater, and stormwater interact with each other is not an easy task. A holistic view of an urban water system under different circumstances can be better achieved if the users select the right tool for decision making. IUWMMs provide decision makers with a tool to address the urban water system, considering the system dynamics and interactions among different components. Although models are great tools in the decision-making process, the specific needs of each system are different and without knowing the details about the model's applications, selecting a model is a challenging task. This review paper was conducted to assess commonly used IUWMMs, and their characteristics and strengths, and to compare their capabilities. We identified 10 evaluating indicators to analyze and compare IUWMMs and their capabilities. We also reviewed the literature to identify which indicators were relevant for IUWMM, and how they should be measured. For each model, we analyzed its performance across a range of these indicators. In addition, we identified the primary and secondary input requirements for IUWMMs that were investigated. Finally, we presented a procedure for decision makers and practitioners to select the best IUWMM that meets their goals.

All of the investigated models claimed to have an integrated framework for modeling the urban water system. However, the level of integration in these models was found to vary significantly and was derived mainly by the specific output of the models. For instance, it was found that for the drinking water component, all the investigated IUWMMs had water supply and demand analysis to some extent. However, other drinking water components such as leakage analysis in the water distribution systems were only considered by a few of the IUWMMs. The majority of IUWMMs that we investigated have a wastewater and graywater reuse capability. However, as with the drinking water component, not all wastewater elements have been included in these models. For instance, the extension design of the wastewater network was only covered by one of the models. In stormwater management the focus of these models was largely on drainage management and hard engineering, and other important considerations such as the impact of green infrastructures on water balance were less reflected. In addition, it was found that few models considered other aspects of the urban water system, such as social and policy aspects, although those factors are very influential on the decision-making process.

In the final phase of this review, a model selection procedure was introduced. As a result of this review, we found that in order to select the most appropriate model, users should put equal emphasis on the output of the models as they do on their main objectives. To facilitate this process, a flowchart for model selection was provided. In addition, breaking down the major objectives for using the models into several evaluating indicators and paying attention to the input requirements of the models would make the model-selection process more efficient. We also provide a Flowchart in Supporting Information for the selection of models which are most appropriate for municipal water management.

The investigated models varied in terms of their capability and functionality. Under the drinking water management category, all the studied models were able to model the water supply and demand analysis to some extent. However, for more specific model functionalities, the models were very different. For instance, only UVQ, MIKE Urban, CWB and WMOST could consider leakage analysis in the simulation. For wastewater management, the models varied significantly. For example, only a few of the models considered wastewater treatment options (Aqua Cycle, Hydro Planner, UWOT and WaterMet2). In addition, Sobek, Aqua Cycle, UVQ, MIKE Urban, CWB, DAnCE 4Water and WMOST were the only models that could simulate the sewer flow. For stormwater management, almost all the models were capable of considering BMPs and drainage design. However, for more specific functions they varied significantly. All the studied models could simulate water balance, but only a few of them considered climate change (Hydro Planner, MIKE Urban, Dance 4Water, WMOST). In terms of energy analysis, models varied significantly and they usually had limited functionality. For instance, only CWB considered life cycle energy use. Furthermore, only Hydro Planner and WaterMet2 could analyze the GHG emission. Under the water quality category, almost all the models were able to model common water quality parameters to some extent. However only two of them could model pathogens (Hydro Planner and CWB). Only a few of the models considered social factors. For instance, Hydro Planner, MIKE Urban and DAnCE 4Water consider demographics and urbanization. Furthermore, only Hydro Planner, Urban Cycle, UVQ and UWOT considered end-user behavioral changes. Finally, in terms of flood management, MIKE Urban was the most comprehensive model and all the other models lacked detailed functionality for flood management analysis.

Even though these models have been around for a couple of decades, the application of many of these models has been limited mainly to academic research projects and not to real-world practice. These modeling tools have the potential to enhance the sustainable management of the urban water system in various ways, such as exploring supply alternatives, integrating water quality and quantity management, and water use efficiency to name a few. More involvement from the decision makers and practitioners in model development would enable the developers to improve the models' capabilities and enhance the adoption of these models in practice. It is suggested that a multidisciplinary approach to the analysis and fitting process of IUWM tools should be encouraged. This approach will improve the usefulness of models by creating more realistic and implementable models for decision makers and practitioners. In addition, incorporation of other areas such as water and energy interconnection, ecosystem services, nutrient recovery, and socioeconomics into the IUWMMs will improve the adoption of these models into the decision-making process.

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