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Review

Urban Water Cycle Simulation/Management Models: A Review

Carlos Andrés Peña-Guzmán [1,2,*], Joaquín Melgarejo [2], Daniel Prats [2], Andrés Torres [3] and Sandra Martínez [4]

1 Environmental Engineering Program, Universidad Santo Tomas, 110231426 Bogotá, Colombia
2 Institute of Water and Environmental Sciences, Universidad de Alicante, San Vicente del Raspeig Route, s/n, 03690 Alicante, Spain; jmelgar@ua.es (J.M.); prats@ua.es (D.P.)
3 Civil Engineering Program, Pontificia Universidad Javeriana, 110231594 Bogotá, Colombia; andres.torres@javeriana.edu.co
4 Matanza Riachuelo Catchment Authority (ACUMAR), Esmeralda 255 PB, C1033AAJ Ciudad Autónoma de Buenos Aires, Argentina; seddam2002@yahoo.com.mx
* Correspondence: carlos.pena@usantotomas.edu.co or carpeguz@gmail.com; Tel.: +571-318-516-5542

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Abstract: Urban water management is increasingly important given the need to maintain water resources that comply with global and local standards of quantity and quality. The effective management of water resources requires the optimization of financial resources without forsaking social requirements. A number of mathematical models have been developed for this task; such models account for all components of the Urban Water Cycle (UWC) and their interactions. The wide range of models entails the need to understand their differences in an effort to identify their applicability, so academic, state, and private sectors can employ them for environmental, economic, and social ends. This article presents a description of the UWC and relevant components, a literature review of different models developed between 1990 and 2015, and an analysis of several case studies (applications). It was found that most applications are focused on new supply sources, mainly rainwater. In brief, this article provides an overview of each model's use (primarily within academia) and potential use as a decision-making tool.

Keywords: urban water cycle; integrated management of urban water; computational models

1. Introduction

The continuous growth of urban areas across the globe is directly tied to rapid economic, population, and infrastructure growth [1,2]. Currently, urban areas account for more than half of the world's population; more than 500 cities already have more than a million inhabitants [3,4]. It is estimated that in 1900, only 9% of the world's population lived in urban areas; by the 1980s, urban population had increased to 40% globally. By 2000, this figure had reached 50%, and it is expected to reach 60% by 2025 [5].

For urban populations, the importance of water cannot be overestimated. Its management is a challenge in terms of sustainability and administration, for cities have short time frames in which to offer the best possible water administration, wastewater collection, rainwater harvesting, and effective water treatment without generating negative environmental, social, sanitary, or health effects [6].

Over the last two decades, computational models have gained recognition as effective tools for addressing the aforementioned challenges. These models allow for the achievement of policy objectives [7], evaluation of the feasibility of different solutions for specific problems [8,9], and proper decision-making for urban water management [10].

Historically, these models have encompassed a number of different approaches, from individual perspectives to more holistic visions, bringing together natural water flows, piping flows, and various subsystems (ecological, environmental, socioeconomic, and political) [11,12]. Initially developed approximately two decades ago, these models were primarily employed to understand the behavior and interactions of urban drainage, treatment systems, and bodies of water. Such models were presented in Denmark in 1992 at the INTERURBA conference *"Interactions between Sewers, Treatment Plants and Receiving Waters in Urban Areas"*, and they were geared toward identifying relations, impacts, and possible controls [13,14]. At INTERURBA II in Portugal (2001), these models were expanded to include rainwater management [15,16]. As the relations between model components and water supply began to be captured and expressed, researchers began to concentrate their efforts on the development of models that were more comprehensive in terms of elements and interactions [17]. In Austria, INTERURBA III took place in 2013. This iteration was titled "*Modeling the urban water cycle as integral part of the city*", and its objective was to study the interactions between models used for management of urban water and socioeconomically feasible urban development [14].

The incorporation of all components of the Urban Water Cycle (UWC) has improved the management of urban water resources and the development of different component systems, including supply, treatment, distribution, consumption, wastewater collection, drainage, and quality and quantity control of surface and groundwater sources [12,15,18–22].

As per Renouf and Kenway [23], UWC modeling was previously based on the quantitative simulation of anthropogenic flows given by water use, along with the simulation of water flows. UWC models factored in balances of mass, energy, and flow [9,20,24–34] until artificial-intelligence models were implemented [35,36]. All UWC models studied in this review, however, have been adapted to different temporal and spatial scales.

As proposed by Mitchell et al. [37], there are more than 65 commercial or free models that rely on partial or total combinations of UWC elements. Bach et al. [15] classified them according to four levels, each of which reflects the degree of integration: Integrated Component-based Models, Integrated Urban Drainage Models (IUDMs) or Integrated Water Supply Models (IWSMs), Integrated Urban Water Cycle Models (IUWCMs), and Integrated Urban Water System Models (IUWSMs).

It is crucial for researchers, academics, administrators of urban water resources, and urban-infrastructure planners and designers to learn about these models and their varied applications because they can be used to devise integrated solutions for the different UWC components. The use of these models may help ensure the feasibility of solid economic investments—and establish technical arguments—for the creation of policies and guidelines geared towards sustainability.

This article presents a review of UWC software and models designed for integrated urban water management. This review was based on two parts: models developed between 1990 and 2015 that included all UWC components (IUWCMs and IUWSMs) and different applications of these models between 1990 and 2016. The paper is divided into three parts: an introduction to UWC, a description of the models reviewed, and case studies (applications) of these models.

2. Urban Water Cycle

Based on the literature review, a blanket definition of the UWC concept can be articulated as follows: The spatiotemporal interaction between water and hydrological processes, as well as supply, treatment, distribution, consumption, collection, provision, and reuse carried out in urban or partially urban areas.

This cycle has four main inputs: water, contaminants, energy, and chemicals, as can be observed in Figure 1. The first, and most essential, for this cycle is water, which comes from two primary sources: supply sources (e.g., surface water and/or groundwater), and precipitation. These inputs allow for the calculation of balances and hydric consumption within the UWC [26,29,38,39]. The second input refers to contaminants, which are closely linked to water flows, for these flows are the transportation medium and/or input to the cycle. Contaminants enter the cycle via surface water and/or groundwater flows, wastewater water flows from property-related uses, treatment of wastewater flows, and, lastly, rainwater flows associated with atmospheric water, different surfaces, and chemical use associated with these surfaces [40].

The third input, energy, is highly consequential within the UWC because of the costs and environmental effects attributable to greenhouse gases and the use of natural resources [41–46]. Energy use is principally related to the function of treatment systems, water supply, and thermal water heating [47–55]. Moreover, during wastewater treatment, biogas is produced by the digestion of organic compounds [48,56,57].

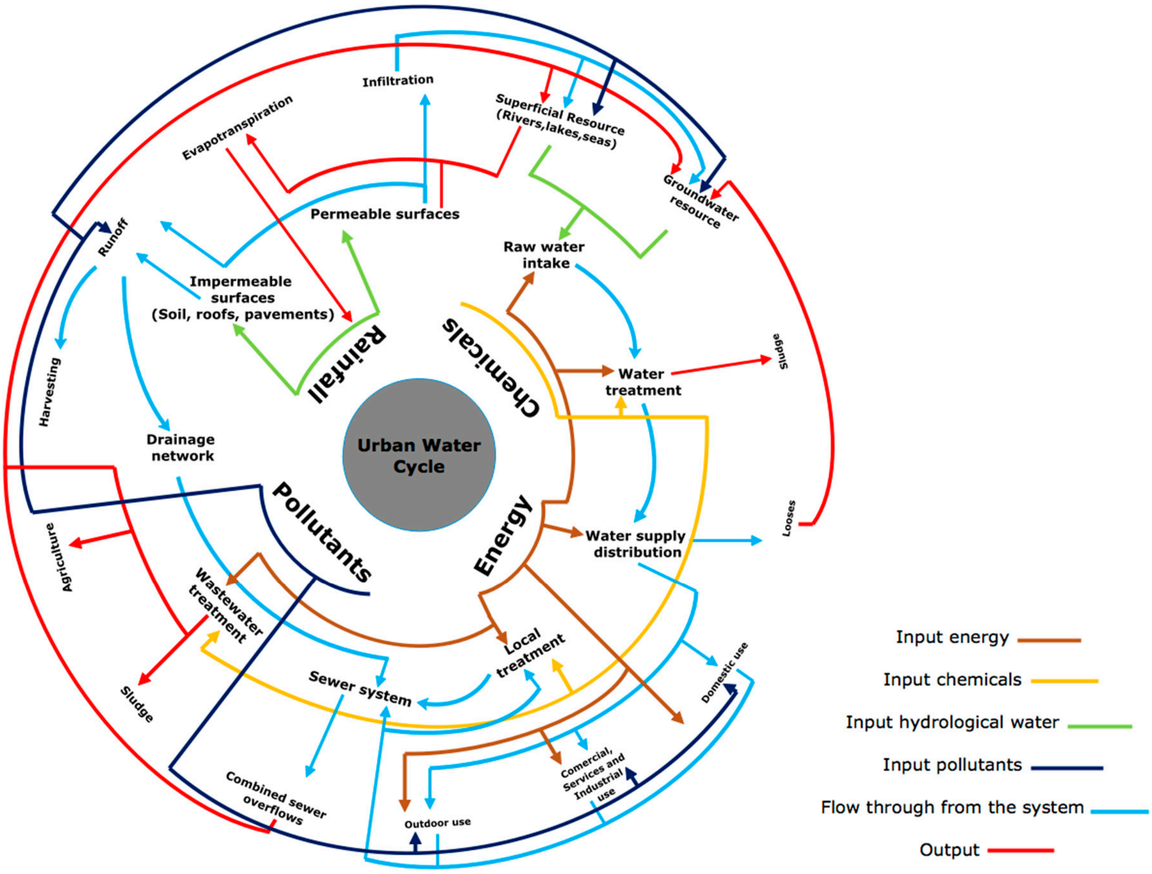

Figure 1. Urban Water Cycle (UWC). Adapted from [58].

The fourth and final input refers to chemicals used to treat wastewater and drinking water; special emphasis is placed on the costs associated with chemicals in terms of the operation of these treatment processes as well as their potential environmental and health impacts [34,59,60].

However, the cycle's behavior, along with that of inputs, is modified by external and internal factors involved in any process. These factors intervene both directly and indirectly within each input, thereby increasing the entire cycle's complexity. See Table 1 for more information on this complexity.

Table 1. Internal and external factors of the UWC.

UWC Part	UWC Component	Internal Factor	External Factor	Source
Water supply subsystem	Raw-water intake	Population, availability, techniques	Climate, environment, economy, geography	[61–65]
	Water treatment	Population, techniques, quantity, quality, energy	Climate, economy, regulations, geography	
	Storage	Population, techniques, energy	Climate, environment, economy, geography	
	Water supply distribution	Population, techniques, quantity, quality, energy	Economy, geography, society, culture, environment, regulations	
Water demand	Water consumption	Population, weather, population density, land use, equipment, economy	Education, territory growth, culture, regulations	[66–71]
Wastewater and stormwater subsystem	Collection	Population, weather, population density, land use, equipment geography, hydraulics, regulations, public health, environment, economy	Society, culture, education	[17,72–77]
	Treatment	Land use, equipment, geography, regulations, public health, quality, quantity, environment, economy, energy	Society, culture, education	[52,53,78–81]
	Receiving Water	Equipment, geography, regulations, public health, quality, quantity, ecology, environment, economy	Territory growth, type of water-receiving body	[58,82–86]

3. Description of Models of UWC Processes

To implement models for UWC management, a comprehensive understanding of these models, their characteristics, and users' needs must be established. Therefore, in this section, 17 models encountered in the literature review are presented with a presentation of the spatial and temporal characteristics, other characteristics, and simulated processes, among other aspects.

To complement the information regarding UWC models found in Table 2, important factors and components are described below. The aquacycle sequentially simulates the balances of the UWC processes of drinking-water supply, hydrology (precipitation and evapotranspiration), and wastewater; these balances are established via loops that cover the entire system on a daily timescale. The amount of "imported" water supply is the sum of the entire population's water uses in addition to the water utilized for irrigation and water lost due to leaks in the system. Wastewater refers to all imported water and percolation and runoff flow rates. For its part, rainwater is runoff minus percolation and storage. Urban Volume Quality (UVQ) is an expansion of Aquacycle. UVQ is distinguished by its simulation of contaminants; it also assumes that there is no degradation or conversion of the evaluated contaminants and that the user must specify concentrations, loads, and performance of treatments [29,30]. UVQ and Aquacycle are models with grouped parameters that do not require a large amount of input data, simplifying the use of these models.

Table 2. Description of UWC models.

Model	Type of Model	Development Team or Institution	Country	Spatial Scale	Time Scale	Platform	Support Software	Simulated Processes					Model Emphasis	Software Link	Source
								H	Hd	Hy	C	S			
Aquacycle	**IUWCMs**	CRCCH	Australia	Pr, Ne, GNe.	Daily	Windows		X		X		X	Hydric balance.	www.toolkit.net.au	[29,87]
UVQ	**IUWCMs**	CSIRO	Australia	Pr, Ne, GNe, Cit.	Daily	Windows		X		X	X	X	Hydric and contaminants balance.		[30,88–91]
MIKE URBAN	**IUWCMs**	DHI	Denmark	Ne, GNe, Cit.	Hourly and Daily	Windows	ArcGIS, MOUSE, SWMM5, EPANET2 MIKENET	X	X	X	X	X	Hydrological balance, hydraulic calculations.	www.mikepoweredbydhi.com	[92–98]
UWOT	**IUWCMs**	The urban water management and hydroinformatics team of the School of Civil Engineering, NTUA	Greece	IndD, Pr, Ne, GNe, Cit.	10 min to monthly	Windows, Linux, Matlab (for optimization) and eLearning platform		X		X	X	X	Optimization of the development of strategies for UWC management	www.watershare.eu	[9,32,99–101]
WaterCress	**IUWCMs**	Richard Clark and David Cresswell	Australia	Pr, Cat.	Daily	Windows		X		X	X	X	Hydric and contaminant balance.	www.waterselect.com.au	[25,102–105]
Sobek-Urban	**IUWCMs**	Daltares	The Netherlands	Cat, Ne, GNe Cit.	Minutes and seconds	Windows	GIS	X	X	X	X	X	Hydrological balance, hydraulic calculations, real-time control, water quality.	www.deltares.nl	[106]
Hydro Planner	**IUWCMs**	CSIRO	Australia	Ne, Cit, Cat.	Daily	Windows	REsource ALlocation Model (REALM), E2	X		X	X	X	Hydric balance.		[28,107,108]
WaterMet2	**IUWCMs**	Exeter University and NTUA	Greece and UK	Pr, GNe, Ci.	Daily	Windows		X		X	X	X	Hydric and contaminants balance, energy, greenhouse gases, chemical material balance.	www.emps.exeter.ac.uk	[24,109–112]
UrbanCycle	**IUWCMs**	University of Newcastle	Australia	Pr, GNe, Cit.	Hourly, daily	FORTRAN	DRIP, Probabilistic Demand Model	X		X		X	Hydric balance.		[20,113–115]
Urban Developer	**IUWCMs**	CRCCH	Australia	Pr, GNe, Cit.	Hourly, daily	Windows	MUSIC	X		X		X	Hydric balance.	www.ewater.org.au	[33,116]
Dance4Water	**IUWSMs**	Monash University, University of Innsbruck, Centre for Water Sensitive Cities and Melbourne Water	Australia and Austria	Pr, Ne, GNe, Cit.	Daily	Virtual, Web	SWMM, UrbanSim	X	X	X		X	Hydrological balance, hydraulic calculation, UWC-related social factors	www.dance4water.org	[117–124]

Table 2. *Cont.*

Model	Type of Model	Development Team or Institution	Country	Spatial Scale	Time Scale	Platform	Support Software	Simulated Processes					Model Emphasis	Software Link	Source
								H	Hd	Hy	C	S			
DUWSiM	**IUWCMs**	Lars Willuweit and John J. O'Sullivan University College Dublin	Ireland	Ne, GNe, Cit.	Daily	Microsoft Excel	LARS-WG, MOLAND	X		X	X	X	Hydric and contaminant balance.		[36]
WaND-OT1	**IUWCMs**	University of Exeter	UK	IndD, Pr, Ne.	Daily	Matlab Symulink, Microsoft Excel (VBA)		X		X		X	Hydric balance.		[32]
DMM	**IUWCMs or IUWSMs**	Norwegian University of Science and Technology	Norway	Ne, Cit.	Hourly, daily, monthly, yearly	Microsoft Excel		X		X		X	Hydric balance energy, greenhouse gases.		[34]
Water Balance *	**IUWCMs or IUWSMs**	N/A	N/A	Pr, Ne, GNe, Cit.	Hourly, daily, monthly, yearly	SIMBOX, Matlab, Phyton, R, Microsoft Excel (VBA), ABIMO,		X		X	X	X	Hydric and contaminant balance, energy, greenhouse gases, chemical and material balance.		[26,38,39]
Urban Metabolism *	**IUWCMs or IUWSMs**	N/A	N/A	Pr, Ne, GNe, Cit.	Hourly, daily, monthly, yearly	Excel (VBA), Matlab, Phyton, R.		X		X	X	X	Hydric and contaminant balance, energy, greenhouse gases, chemical and material balance.		[31,125–127]
LCA *	**IUWCMs or IUWSMs**	N/A	N/A	Pr, Ne, GNe, Cit.	Hourly, daily, monthly, yearly	Matlab, Phyton, R, Symulink, Microsoft Excel (VBA), SIMAPRO, GaBi4		X		X	X	X	Hydric and contaminant balance, energy, greenhouse gases, chemical and material balance.		[27,128,129]

Notes: H = hydrological, Hd = hydraulic, Hy = UWC hydric components, C = contaminants, S = strategies for structural management and/or nonstructural action, BMP = best management practices, DRIP = Disaggregated Rectangular Intensity Pulse, VIBe = Virtual Infrastructure Benchmarking, CRCCH = Cooperative Research Centre of Catchment Hydrology, CSIRO = Commonwealth Scientific Industrial and Research Organisation, DHI = Danish Hydraulic Institute, Pr = Property, Ne = neighborhood, GNe = group of neighborhoods, Cit = city, IndD = Individual-dwelling water uses, Cat = catchment, Dance4Water = Dynamic Adaptation for eNabling City Evolution for Water, DUWSiM = Dynamic Urban Water Simulation Model, DMM = Dynamic Metabolism Model, LCA = Life Cycle Assessment, WaterCress = Water-Community Resource Evaluation and Simulation System, UWOT = Urban Water Optioneering Tool, UVQ = Urban Volume and Quality, IUWCM = Integrated Urban Water Cycle Models, IUWSMs = Integrated Urban Water System Models, N/A =Not applicable, VBA = Visual Basic for Applications. *Approach does not refer to specific software.

Originally, the Urban Water Optioneering Tool (UWOT) was proposed to improve WaND-OT1, which simulates the interactions between drinking-water supply, wastewater, and runoff. To create possible scenarios, UWOT has an Excel library with nine applications for microcomponents, two for intermediate levels, and four for the top level. The conditions, operations, and design of each of these applications can be modified [9,100].

WaterCress relies on the concept of nodes. Nodes represent the UWC's functions, operations, processes, and infrastructure. In total, there are 18 basic nodes, with each having a database with quantity and quality variables [105]. In turn, these nodes are linked by flows, such as supply and drainage. For drainage, these nodes are subdivided depending on the type of function. They are assigned a predetermined color: pink for water diversions, blue for catchment runoff, green for runoff from a house or urban node, gray for gray water, and black for wastewater [25,103]. With respect to Hydro Planner, this software works with the model E2, which allows for the integrated simulation of various components such as runoff and nutrient and sediment contamination of a water body [107]. Hydro Planner has seven modules: (1) catchment (simulation of contaminant and runoff processes); (2) water supply; (3) consumption; (4) rainwater (contamination and water flow); (5) wastewater (contamination and water flow); (6) receiving water bodies (contamination and water flow); and (7) integration (networking of modules, input and output calculations, and graphic interface) [28,108]. WaterMet2 quantifies the UWC's metabolism into four main subsystems: (1) water supply (sources, treatment, and supply); (2) water demand (consumption and water uses); (3) wastewater (separated and combined systems and wastewater treatment); and (4) water treatment (in situ or centralized treatment).

UrbanCycle's software is characterized by the creation of precipitation and demand data, which can be entered by the user. The software allows for their creation via stochastic models. For rain, the model has the Disaggregated Rectangular Intensity Pulse (DRIP); for demand, it has the Probabilistic Demand Mode. Urban Developer is based on UrbanCycle, which presents four main characteristics: Adaptive time-stepping allows for the simulation of different timescales, primarily as a function of climate conditions in wet season for short periods, in dry season for an adapted period, and in transition for an intermediary period, leading to a computational benefit in terms of calculation time. Canvas represents the system's graphic interface, for which a number of improvements have been proposed from a structural perspective. Each input node is a component of the UWC, not a system of the UWC. Furthermore, the connections or flow movements are represented by a color that characterizes the type of flow. The configuration of input parameters allows for the modification, copy, and elimination of these parameters (among others) by the user quickly and easily. Finally, it has network nesting, a characteristic that allows for the linking of different spatial scales of the system through subnetworks, which symbolize a node containing all previously established connections.

Dance4Water is based on the Virtual Infrastructure Benchmarking (VIBe) model presented by Sitzenfrei et al. [118,119]. This model creates virtual urban environments that include digital models, water bodies, land use, and urban infrastructure (e.g., sewage and drinking-water distribution systems) [123,124,130,131]. This model follows a stochastic approach, using multiple layers of cellular automata [118]. This software presents three linked modules to simulate the entire UWC. The first module, the Urban Development Module (UDM), encompasses actions that create territorial development resulting from population increase or urban-development plans at an annual scale. For this purpose, UrbanSim software was created [35]. The second is the biophysical module (BMP) [122], which represents UWC-infrastructure components and performance. Two submodules—city and water-system generator (infrastructure) and performance assessment (performance)—were created as part of the second module. The performance submodule uses SWMM (Storm Water Management Model) software for hydraulic and hydrodynamic calculations that are subsequently included in the model [117]. The third and final module is the Societal Transition Module (STM) designed for simulating the extent and impact of society on the UWC; the STM also serves as a tool for strategic planning [117,120,132].

DUWSiM integrates multiple models, namely climate (LARS-WG stochastic weather generator), land use (MOLAND—Monitoring Land Use/Cover Dynamics), and water balance in urban areas (DUWSiM WB—Dynamic Urban Water Simulation Model Water Balance). This integration is done via a database consisting of different input data, such as socioeconomic, geographical, physical-infrastructure, demand, and climate factors. This database provides data for the water-balance model, which simulates the daily flow of movement of UWC processes (drinking-water supply, rainwater, wastewater, evapotranspiration, percolation, etc.). DMM was developed using the MS-Excel platform, which facilitates user adaptation of the interface. Excel lets the user enter different input values and create scenarios by modifying sustainability indicators; in Excel, calculations are performed in intermediary files. The program has four files: (1) notes, assumptions, and guidelines; (2) user control via an input data file (entered or calculated), for which values display particular characteristics of the study area and concomitant consumption; (3) annual files (annual-scale calculations), which are input data consisting of nine independent spreadsheets that are components of the UWC; and (4) comparison of final results (this spreadsheet presents absolute or relative indicators of the performance of economic, social, environmental, and functional factors).

MIKE URBAN independently (in parallel) simulates water supply, drainage, and wastewater sewage; this software couples 1-D sewer modeling with 2-D overland-flow modeling. It is integrated with the ESRI ArcGIS platform using the "geo-database" concept [95]. This assembly uses valuable aspects of GIS, such as network topologies, global-reference coordinates, labels, spatial analysis, and graphical functions, resulting in layers and the ability to connect layers for optimal management [98]. Sobek-Urban is an integrated software package consisting of 1DFLOW Rural-Urban-River, Overland flow-2D, Rainfall-runoff (RR), 1DWAQ Water quality and Real-time-Control (RTC). The 1-D flow solves the Saint-Venant equations by means of a finite difference, and the 2-D flow uses a rectangular grid and finite difference framework [133].

4. Application of UWC Models

The application of these models has led to mixed results, perhaps a result of these models' use for myriad purposes including: resource administration, management, and decision-making in the development of cities to manage and control hydric resources in terms of quality and quantity, contamination control with relation to natural resources, infrastructure planning, public-policy evaluation, financial management, and evaluation of socioeconomic development [134]. Case studies are discussed below.

Table 3. Case studies involving UWC software or approaches.

Model	Case Study	Country	Type of Application														
			WHB	C	SDDW	EISW	EIGW	RC	WWT	BMP	H	F	RT	RR	RGW	EGG	SF
Aquacycle	[135]	USA	X							X							
	[136]	Egypt	X		X	X			X								
	[137]	Israel	X		X					X				X	X		
	[138]	Australia	X		X									X	X		
	[139]	Australia	X														
	[140]	South Korea	X														
	[141]	South Korea	X		X									X	X		
	[142]	Australia	X		X									X	X		
	[143]	Germany	X		X									X	X		
	[144]	France	X		X					X					X		
	[145]	Ghana	X	X	X									X	X		
	[146]	Australia	X										X				
	[147]	Greece	X		X	X				X				X	X		
	[39]	Australia	X							X							
	[148]	Spain	X	X					X								
	[149]	South Korea	X		X									X	X		
	[150,151]	Australia	X														
	[29]	Australia	X		X					X				X			
Urban Volume Quality (UVQ)	[152]	Australia	X	X	X			X						X	X		
	[153]	Australia	X	X	X					X				X			
	[154]	Australia	X	X	X					X				X		X	
	[155]	Vanuatu	X	X	X		X	X	X				X	X			
	[156]	Australia	X	X	X					X			X	X			
	[157]	Austria	X	X													
	[158]	Australia	X	X					X								
	[159]	Mexico	X	X	X		X							X			
	[160]	South Korea	X	X		X			X								
	[161]	Australia	X		X					X				X			
	[162]	Australia	X	X		X			X								

Table 3. *Cont.*

Model	Case Study	Country	Type of Application														
			WHB	C	SDDW	EISW	EIGW	RC	WWT	BMP	H	F	RT	RR	RGW	EGG	SF
Urban Volume Quality (UVQ)	[163]	UK	X	X			X										
	[164]	Australia	X							X							
	[142]	Australia	X	X	X				X	X				X	X		
	[165]	Slovenia	X	X			X										
	[166]	Australia	X	X	X									X	X		
	[167]	UK	X	X			X										
	[168]	Germany	X	X			X										
	[169]	Slovenia	X	X			X										
	[170]	UK	X	X	X	X	X	X		X							
	[171]	Germany	X	X	X				X					X	X		
MIKE URBAN	[172]	Denmark	X								X						
	[173]	India									X	X					
	[174]	Denmark	X								X	X					
	[175]	Denmark									X	X					
	[176]	Denmark									X	X					
	[177]	India										X					
	[178]	Denmark									X	X					
	[179]	Denmark									X	X					
	[96]	Lithuania										X					
	[180]	Denmark									X	X					
	[181]	Germany								X		X					
	[182]	Denmark									X	X					
	[183]	Sweden									X						
	[184,185]	Denmark								X	X						
	[185]	Denmark									X						
	[186,187]	Bangladesh									X	X					
	[188]	USA	X														
	[189]	Denmark									X	X					
	[190]	Denmark	X								X						
	[191]	Australia						X			X						
	[192]	Japan										X					

Table 3. *Cont.*

Model	Case Study	Country	Type of Application														
			WHB	C	SDDW	EISW	EIGW	RC	WWT	BMP	H	F	RT	RR	RGW	EGG	SF
Urban Water Optioneering Tool (UWOT)	[193]	Greece	X														
	[194]	Spain	X		X					X					X	X	
	[195]	Greece			X											X	
	[196]	Greece	X						X						X	X	
	[197]	Hypothetical	X		X				X	X			X	X	X		
	[198]	Greece	X		X				X					X	X		
	[199,200]	Greece	X														
	[201]	Hypothetical	X		X				X	X				X	X	X	
	[202]	Hypothetical	X		X				X	X				X	X		
WaterCress	[203]	Australia	X		X												
	[204]	Australia	X		X												
	[205]	Australia	X														
	[105]	Australia	X		X					X				X			
	[206]	Australia	X														
	[104]	Australia	X		X									X			
	[207]	Australia	X											X	X		
	[208]	Australia	X														
Sobek-Urban	[209]	Singapore								X				X			
	[210]	The Netherlands									X						
	[211]	The Netherlands		X			X										
	[212]	The Netherlands										X					
	[213]	The Netherlands								X							
	[214]	Singapore	X														
	[215]	The Netherlands	X														
Hydro Planner	[216]	Australia	X	X	X	X			X	X			X	X	X		
	[217]	Australia	X		X									X	X		
	[108]	Australia	X		X												

Table 3. *Cont.*

Model	Case Study	Country	Type of Application														
			WHB	**C**	**SDDW**	**EISW**	**EIGW**	**RC**	**WWT**	**BMP**	**H**	**F**	**RT**	**RR**	**RGW**	**EGG**	**SF**
WaterMet2	[218]	Iran	X	X	X					X				X	X		
	[219]	Italia	X		X												
	[220]	Norway														X	
	[221]	Unspecified	X		X												
	[222]	Unspecified	X	X	X	X			X	X				X	X		
	[112]	Norway	X														
	[223]	Iran	X		X												
	[24]	Norway	X		X					X		X		X	X	X	
UrbanCycle	[113]	Hypothetical	X		X					X				X	X		
	[224]	Australia	X												X		
	[225]	Australia	X							X					X		
	[226]	Australia	X							X							
	[227]	Australia	X														
Urban Developer	[228]	Hypothetical	X														
Dance4Water	[229]	Austria	X							X		X					
	[230]	Australia	X							X							X
	[121]	Australia															X
	[122]	Australia	X							X							
	[231]	Australia	X							X							
WaND-OT1	[32]	UK	X		X	X							X	X			
Dynamic Metabolism Model (DMM)	[220]	Norway														X	
	[34,232]	Norway	X		X											X	
DUWSiM	[233,234]	Ireland	X														
	[235]	Australia	X		X									X	X	X	
Water Balance	[236]	Portugal	X		X									X	X		
	[237]	Switzerland		X					X								
	[238]	USA	X														
	[239]	Cyprus	X		X					X							
	[240]	Switzerland		X					X								

Table 3. *Cont.*

Model	Case Study	Country	Type of Application														
			WHB	**C**	**SDDW**	**EISW**	**EIGW**	**RC**	**WWT**	**BMP**	**H**	**F**	**RT**	**RR**	**RGW**	**EGG**	**SF**
Water Balance	[241]	USA and Canada	X													X	
	[26]	Australia	X														
	[10]	UK	X	X					X	X							
	[242]	Germany	X														
	[243]	India	X		X												
	[244]	Colombia	X	X		X	X		X								
Urban Metabolism	[245]	Colombia	X														
	[246]	UK	X							X							
	[247]	China	X														
	[248]	Canada	X														
	[249]	China	X														
	[250]	Canada	X														
	[251]	China	X														
	[252]	USA	X												X		
Life Cycle Assessment (LCA)	[253]	Hypothetical				X										X	
	[254]	Spain	X		X	X									X	X	
	[255]	Spain	X													X	
	[256]	Norway				X										X	
	[59]	Norway														X	
	[257]	Australia	X						X					X	X	X	
	[258]	Egypt														X	
	[259]	Australia				X										X	
	[260]	Sweden		X												X	

Notes: WHB = Water or hydrology balance of UWC for managing rainwater or wastewater, C = UWC contaminants, SDDW = Supply and demand of drinking water, EISW = Environmental impact on surface hydric resources, EIGW = Environmental impact on groundwater resources, RC = Rainwater contamination, WWT = Wastewater treatment, BMP = Best management practices, H = Hydraulic, F = Flooding, RT = Rainwater treatment, RR = Rainwater reuse, RGW = Reuse of gray water and sewage, EGG = Energy and greenhouse gases, SF = Social factors.

Firstly, as can be seen in Table 3, the primary use of these tools is for calculating hydric balances because such balances allow researchers to determine flows and/or volumes of different types of water in the UWC. These flows are crucial insofar as they represent the cycle's main inputs and outputs [38]. In turn, this facilitates an understanding of water dynamics in urban areas and facilitates the identification of the degree of interrelation during different UWC processes. In addition, the aforementioned balances are an essential source when determining modifications of the hydrological cycle, for the is the most disruptive force with respect to the cycle's equilibrium [261]. In light of the realities of disruption, balances let decision-makers create scenarios for adequate hydric resource management. Mass balances, for their part, are used to estimate contaminant loads because of the direct relationship between water flows and contaminants [171].

Secondly, Table 3 demonstrates multiple model applications for the management, calculation, and determination of drinking-water supply and water demand. This is attributable to the effort to decentralize water supply and establish alternate or unconventional sources to meet populations' water needs without ignoring environmental constraints [12]. Research has found that urban areas face problems related to inequality, in-home contamination, economy, and infrastructure [262]. Consequently, within the most commonly employed practices, new sources include: rainwater, reuse of gray water and wastewater, desalinization, and groundwater. To address the aforementioned aspects, many scenarios proposed in the literature include the harvesting of rainwater and the reuse of gray water. This allows for the conservation of hydric resources, the reduction of runoff volume, and the reduction of wastewater and corresponding contaminant loads [263–267].

Thirdly, there is the selection and evaluation of best management practices, which are structural and nonstructural actions aimed at minimizing the impact of urbanization on the natural hydrological cycle [268]. These practices offer significant potential for UWC management insofar as they can be applied to any part of the UWC, such as reduction of water demand, management of rainwater, reduction of flooding, control of contamination, mitigation of environmental damage, evaluation of ecological possibilities, and reduction of infrastructure investment [269]. Many other applications are affected by the kind of software and the needs proposed by the authors (e.g., hydraulic and flooding applications).

Finally, the software MIKE URBAN and Sobek Urban are primarily used for flooding control, evaluation, monitoring, and optimization of drainage/sewage systems—which is a function of their inclusion of hydraulic and hydrological calculations. It is important to add that both software programs (notably the former) have been heavily employed around the world, although a few applications have involved all UWC components.

Of the more infrequent approaches, social factors are salient. The primary reason for the infrequent inclusion of social factors stems from the fact that most software programs and approaches are focused on technical solutions. Additionally, the inclusion of social factors can be quite complex, a reflection of social dynamics, practices, behaviors, and expectations with regard to water use [270]. This complexity may serve as a barrier to the determination of effective water-management strategies [271]. That said, to some extent, failing to include social factors generates a disconnect, for there is an undeniable relationship between society and the UWC's technical elements (*Sociotechnical*, see Sofoulis [272]). Thus, there is a glaring need to develop tools that encompass social and economic factors (i.e., a more comprehensive engagement with these factors would improve UWC planning). As posited by Koutiva and Makropoulos [273], the use of artificial intelligence has produced tools that can be used for social and economic factors as well as water management. According to the two authors, the most frequently employed artificial-intelligence tools include agent-based modeling, artificial neural networks, Bayesian belief networks, and systems dynamics modeling.

The most frequently used models are Urban Volume and Quality (UVQ), Aquacycle, and MIKE URBAN; each accounted for more than 15 experiments in the literature. In fact, these models were used in more than the 50% of all experiments. After these three, water-balance and life-cycle analyses are next, with each accounting for 10 to 14 experiments (22% of all experiments). UWOT, WaterCress, Urban Metabolism, UrbanCycle, Sobek-Urban and Dance4Water accounted for 5 to 9 experiments each (18% of all experiments). Finally, the remaining models accounted for 1 to 4 experiments each (10% of all experiments).

In terms of year ranges, 60% of reported experiments were conducted between 2012 and 2016. Between 2009 and 2011, this percentage was 20%. Between 2006 and 2008, the percentage was 11%, and between 2003 and 2005, the percentage was 9%. This progressive increase can be attributed to the advent of the concept of Integrated Urban Water Management (IUWM) in the mid-1990s, though IUWM was not widely discussed and adopted until 2000 [268].

Looking at the geographical distribution of these experiments (see Figure 2; darker shading represents more experiments and lighter shading less experiments), the applications of these tools or methodologies have been carried out in a variety of countries. However, Australia has the most applications (41 revealed in the literature review). In that country, Aquacycle, UVQ, WaterCress, Hydro Planner, Urban Cycle, and Dance4Water were the most commonly used software programs. These programs were developed by public and private entities. After Australia, the country with the most frequent use of relevant experiments was Denmark, which conducted experiments using MIKE URBAN, a tool developed and evaluated in the Scandinavian country. The United Kingdom (most commonly using UVQ) and Greece (using Aquacycle and, above all, UWOT, which was developed in Greece) each had six experiments. Other countries, such as South Korea and the United States, had four and five experiments, respectively. There were also 24 countries with less than three recorded experiments each (including countries from continents such as Africa, Latin America, Asia, and Europe).

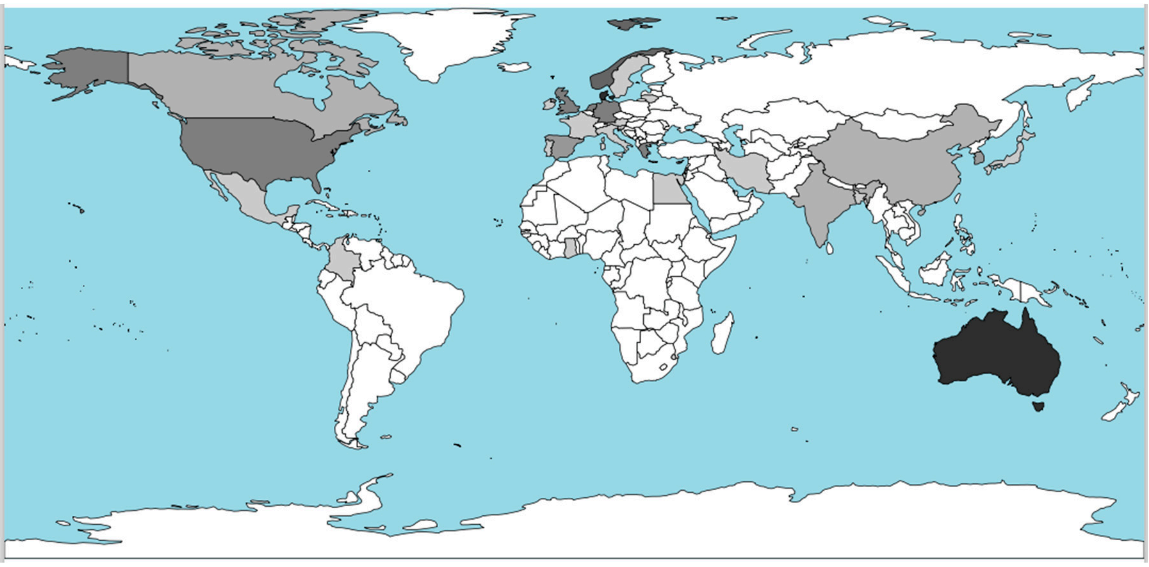

Figure 2. Experiments reported by country.

Despite the potential for the management and administration of UWC, it is important to mention that, by and large, the use of these tools has been concentrated in academia rather than in decision-making environments. This is explained by a number of different factors—related to institutions, politics, society, economics, laws, and organizations—as well as the absence of institutionality, lack of knowledge regarding relevant tasks, and lack of long-term vision, among others [274,275]. However, academics' role in this situation cannot be overlooked: Most projects related to these models are focused on obtaining data rather than constructing bridges between investigation and social application. For instance, there is scant direct application of these models in industrial sectors. As per Abbott [276], this is because the needs within academia and within industrial sectors do not always coalesce. That said, the failure to implement the solutions proposed by UWC models hinders possible determination of the level of population acceptance, which is crucial for establishing the success (or lack thereof) of strategies because many of the experiments discussed herein are based on the decentralization of services and applications in situ [277].

5. Conclusions

Urban water management is a globally urgent problem and entails a host of pertinent issues related to supplying drinking water, handling wastewater and rainwater, reducing environmental impact and waterborne diseases, and mitigating operational and infrastructure costs. Together, these issues pose a challenge to public administration. A deeper understanding would allow for a holistic view of the UWC as well as the development of appropriate management strategies for water in urban areas. In addition, this deeper understanding would help explain the dynamics and interactions of different processes in the UWC.

The use of innovative software and approaches has gained recognition as an effective means for meeting the aforementioned challenges. Combining software and other approaches allows one to create a decision-making tool that integrates technical, environmental, economic, and social concepts to quickly visualize different trends or possible scenarios. The reliance on these tools has increased notably over the last 15 years, with examples ranging from hydric balances to artificial intelligence, with spatial scales from individual properties to entire regions, and timescales from daily to annual. These advances have helped incorporate as many UWC processes as possible.

These software programs or models have facilitated different applications' employment as a vehicle for determining new sources of supply, contamination control, reduction of the effects of urbanization on the hydrological cycle, and efficient water use, among others. In so doing, these tools have greatly enhanced the capacity for sustainable alternatives and boosted the ability to efficiently manage financial and hydric resources.

The vast majority of the experiments revealed by the literature review touched on technical solutions or regulations, for the models/approaches studied were shown to be geared towards calculating water balances and the concentration or contaminant loads as water passes through the cycle. Nevertheless, social and ecological factors should not be forsaken if models and their responses are to be more comprehensive, especially in light of the close link between these factors and the UWC [5,278].

Even though most of these tools are available online or by request from the authors, their application has been centered in Australia and Europe, which is primarily explained by two facts. First, model development, which is only done in these two regions, leads to their application in different fields within these regions. Second, research and policies in these regions related to water management in urban areas have gained traction due to the need to conserve water resources or due to the lack of such resources.

The results described in the articles and academic theses reviewed herein demonstrate a high potential for management of the UWC, though its greatest contribution currently is academic; the approaches have not been applied as a decision-making tool by public or governmental entities. This confinement to academia is a serious obstacle to the implementation of the models for economic, social, and environmental means.

Although there are direct relationships between energy systems and different UWC processes, several models and software programs do not include these systems, for the primary objective of these tools is to determine strategies for managing water volume. Yet, many of these tools, when not designed from a holistic perspective, may directly impact infrastructure-investment costs [50] and/or lead to deleterious environmental effects in the form of greenhouse gases or high energy consumption [52,279,280].

Moreover, it is crucial to reinforce the usefulness of these models to evaluate the acceptance of the results obtained and thereby solidify social appropriation of this knowledge by means of strategies that promote implementation in decision-making contexts.

Lastly, this review allows different public and private entities to identify opportunities to use the software and models discussed herein for the management of urban water resources. Doing so would pave the way for the optimization of cities' economic investments and ensure efficiency of the systems comprising the UWC as well as an environmentally conscious urban development that is future-oriented.

Author Contributions: This article provides a foundation for identifying components and interactions within the Urban Water Cycle (UWC). Furthermore, this article explains the types of models and development approaches for managing urban hydric resources. To this end, the authors describe the potential use and requisite operating conditions of UWC models. In addition, all authors analyze case studies (model applications) to determine model contribution (as well as place and date of implementation). Taken together, this information allows readers to determine each model's benefits and uses.

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