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Conceptual Urban Water Balance Model for Water Policy Testing: An Approach for Large Scale Investigation

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Abstract: Urban water management will face various challenges in the future. Growing population in cities, changing climatic conditions and uncertain availability of water resources necessitate forward-looking water policy strategies. In this paper, we introduce a new water balance model to evaluate urban water strategies at a city scale. The aim is to evaluate decentralised water management measures within a large-scale investigation and to reduce external potable water demand. The upscaling process of local information (water demand, areal data) to a conceptual model approach is described. The modelling approach requires simplification of detailed processes to enable the execution with limited computing capacity. The model was applied to Greater Metropolitan Melbourne, Australia, a highly sprawled city with nearly four million inhabitants. Scenario analysis demonstrated the impact of using different water resources of different quality classes, the extensive implementation of water saving appliances and decentralised water storage strategies on the city's water balance. Results indicate a potential reduction of potable water demand of up to 25% with a conservative rainwater reuse and, even 60% with widespread implementation of rain- and greywater recycling. Furthermore, we demonstrate that even small systems implemented at a local level can have noticeable effects when operated as clustered schemes.

Keywords: alternative water resources; water quality; decentralised storages; water recycling and reuse; upscaling local information; potable water demand reduction

1. Introduction

Population growth, changing climatic conditions and water supply security challenge water supply systems today and in the future [1–3]. Recent droughts across the world have caused severe stress on water resource availability and raised political awareness for a transition towards more robust and versatile water supply system [4]. This phenomenon occurs worldwide and large urban agglomerations are forced towards a more careful handling of their water resources [5]. To improve urban water management, it is important to understand the impacts and interrelationships within the urban water cycle. Water balance models can be used to support this understanding [6,7].

The urban water cycle is a complex system with a myriad of influential factors [8–10]. Towards system understanding [11], individual parts of the urban water cycle were examined (e.g., runoff reuse [12], and rainwater harvesting [13]). A scientific modelling approach requires abstraction to gain a comprehensive view of the system. The degree of abstraction is predetermined by the scope of application of a model [14]. The level of detail ranges from a dedicated water balance at household level to a global representation of a city where the spatial resolution is neglected. A wide range of models have been developed in the past, with differing resolution, focus and aims [15]. Previous work was focussed on a very detailed and dedicated representation of the processes within the urban water cycle [16]. This includes decentralised rainwater management measures, water demand estimations at household level (appliances) and approaches to simulate local water balances at a high resolution. Besides the approaches focusing on water cycle, conceptual frameworks discussing a wider spectrum of the urban water management towards water sensitive urban design [17] are available. These integrated frameworks and models deal additionally with energetic, social and socio-economic issues (e.g., Urban Metabolism [18], DAnCE4Water [19], and WaterMet2 [20]).

Graddon et al. [21] presents a modelling environment, where the modelling approaches from UrbanCycle [22] and UrbanNet [23] is coupled. The software tool Urban Developer [24] is also based on the research model UrbanCycle. They have in common, that the modelling scale can range to the allotment and the connections play a major role in the model framework. Networks on multiple layers can be modelled, but they require a deep knowledge of the system and the connections within. Mitchell et al. [25] developed the model Aquacycle, a more conceptual approach with limitations in spatial representation of the data and daily time steps. A further development represents the model UVQ [26], which expands the original volume based model with a contaminant cycle. Furthermore, models interacting with a pipe network (water supply or drainage) and hydro-dynamic simulations require a high temporal resolution [27]. They are made to investigate mainly hydraulic questions but do not contemplate the whole water cycle. Because of their detailed model structure and the required input data, existing models were not designed to be used in a spatially explicit manner and for large scale applications [28]. On the other end of the spectrum, very simplified models on a higher level consider the investigation area without spatial resolution [29]. This approach may give a rough overview of the global water volumes but is not useful for a differentiated view of a city's water balance. The research gap between these opposing approaches is a model framework with a clear delimitation to detailed processes, but with a spatial partitioning to consider local characteristics.

This paper presents a novel water balance model (WBM), which is based on a conceptual approach and aims to provide an overview of an entire city's temporal and spatially variable water balance. End user water demand and individual influencing factors are temporally and spatially highly variable. A conceptual model provides the opportunity to show variations within the water balance of a city without deep knowledge of local conditions, but allows us to improve the results as more data become available. As such, the extensive work required to model precise structures can be avoided and computational costs kept low. A key principle of the model, building upon the principles adopted by Mitchell, Mein and McMahon [25], is the introduction of graded and clearly defined water qualities as the basis for the "fit-for-purpose" utilisation concept [17]. This is part of the water sensitive city concept, which encompass a wide range of sustainable methods to handle water in an urbanised area. According to this concept, water that is already situated in the city is utilized for demand [30]. The model can be used to optimize the allocation of water resources in urban areas such that the use of alternative water supplies is maximized. Consequently, the potable water that needs to be provided and transferred to the city is reduced and the external water supply (storage level of long term reservoirs) is relieved. This second pillar of water supply can help to manage an efficient and sustainable water supply system.

The model does not address the pipe network and hydro-dynamic elements. Its function is to compare water volumes of aggregated units, which are based on regional political borders. To adhere to real urban structures, the model framework enables the combination of results with statistical and social data and facilitates the communication of water policies. The identification of critical areas and scenarios can help decision makers to take appropriate action at an early stage to experiment with water policies that could support the management of an overstrained water supply in the future.

This work was motivated by the recent decade-long drought that significantly affected Melbourne, Australia. The application of the model approach to the case study of Greater Metropolitan Melbourne discusses scenarios of utilising alternative water sources of differing quality, the implementation of water saving appliances (WSA) and decentralised water storage (DWS) strategies. We will run the model for 2015 and show the influences of different scenarios on the potable water demand. Furthermore, we also evaluate how the total water demand is met based on different compositions of individual water qualities and utilisation ratios based on the available resources and storages.

The aim of this work is to explain the modelling approach of a new WBM and to scale local and detailed information to an extent, where it can be used in a conceptual way. The intention is to link the gap between decentralised water management applications and a city scale evaluation of the water balance. The modelling approach is demonstrated on a large case study. An overview of the used abbreviations in this work can be found at the end of the paper.

2. Materials and Methods.

2.1. Model Overview

The simulation aims to represent a large city's water balance from a conceptual point of view. Complex models are data and computationally intensive and require deep knowledge of local conditions, structures, population and user behaviour. They often provide detailed information that may not even effect higher-level decisions. Arising problems such as data availability, accuracy and integrity can be avoided using a conceptual model. This requires harmonising input data from different sources and simplifications of complex structures and system interactions. Our approach is designed for large investigation areas and the simplifications are made for the purpose of providing an overview of the water balance across entire sprawled out metropolitan regions. Within the model boundaries, the urban water infrastructure and surface water hydrology is considered. Not included are receiving water bodies and ground water processes. The urban water cycle is represented in a spatially explicit manner. Based on this principle, the area is discretised to units (denoted as "Blocks") that represent the most detailed elements in the model. Local information is merged or scaled to this extent for use in the model, while details below this level are not considered explicitly. The scale of aggregation of the Blocks is based on the number of inhabitants to receive a sample of various consumers and to compensate for outliers. We define the simulation time step as hourly. The choice was based on a trade-off of wanting to capturing sub-daily variations of the water balance, but avoiding the need to include more complex interactions that occur at finer time steps. Figure 1 provides an overview of the model creation process from the detailed data to the conceptual model.

Several simplifications are introduced to convert water resources, demand and runoff to consistent and manageable objects (Figure 1). The water quality classes (QC) define the functional range [31] and the basic structure of the model as well as each water resource and flow in the model is classified within this structure. The classification is oriented towards the rate of pollution of the water and its boundaries for further utilisation and reuse. The applied water qualities in the paper are potable water (po), rainwater (ra), light greywater (lg), stormwater (st) and black water (bl). Rainwater is defined as roof runoff, whereas stormwater constitutes the more polluted runoff from ground level impervious areas. Light greywater is defined as household wastewater with a low level of pollution (pathogens, chemicals, fats, oils or biological) [32,33]. The classification can be adjusted to different modelling aims easily (different classification, additional or less classes).

Water storage tanks serve as a cache between demand, reuse, rainfall and runoff and represent the merged storage capacity in a Block. The change of the storage volume during one time step (defined as one hour) is calculated with the storage equation (Equation (1)). It represents the basic relationship between the volume flows of the WBM. The same equation is valid for each QC.

$$\Delta V_{storage,QC} = V_{inflow,QC} - V_{demand,QC} - V_{outflow,QC} \ [L/h] \quad (1)$$

Essential input data include: hydrological data, spatial information to generate surface runoff, census data and water demand on an hourly basis. Necessary model operating parameters are the storage tank sizes as well as the definition of the QCs and the assignment to the demands.

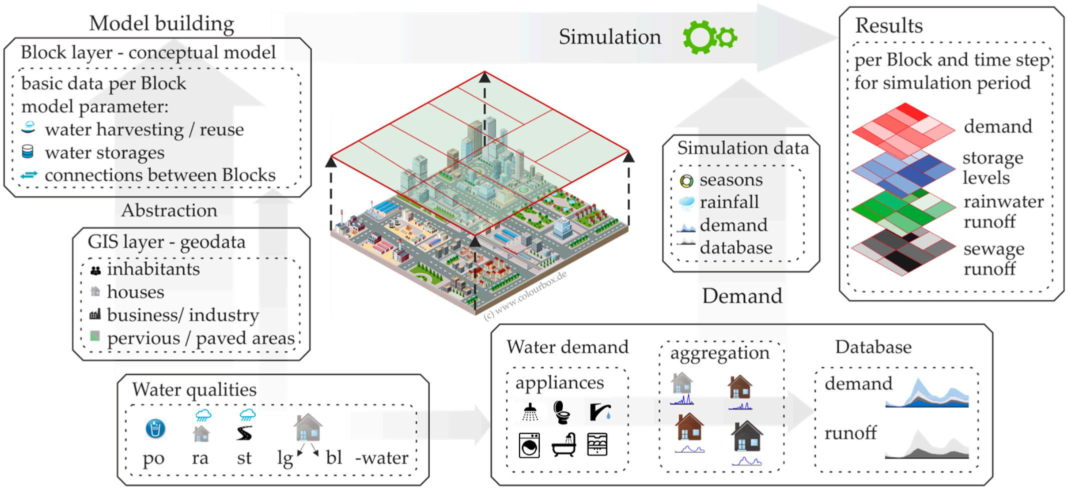

Figure 1. Scheme of the model development: abstraction of detailed data to a conceptual model (assignment of water qualities—potable (po), rain (ra), storm (st), light grey (lg), and black (bl)—water—end-user water demand to Block demand curves, areal data to Block parameters and implementation of decentralised measures), simulation (with statistical data) and spatially presentation of the results.

2.2. Water Demand

Water demand origins from a myriad of individual water consumers. For the model, the end user-based water demand data are converted to a quality-based system. In this context, the defined QCs represent the minimum quality requirements of the demand. This allows aggregation to simplify the complexity of various consumers on different scales in a Block into simply the defined QCs. The merged quality-based water demand of a Block can be defined as a 24-h demand curve (DC) (schematic data in Figure 2).

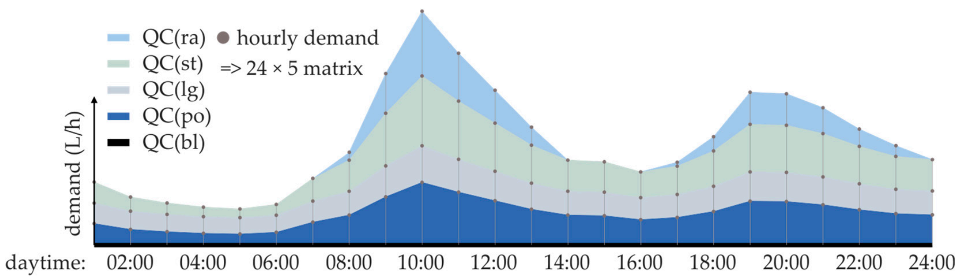

Figure 2. Schematic example for a quality-based daily demand curve (DC) containing five Quality Classes (QC; QC(bl) = 0) over 24 h.

To create a Block DC from end user-based raw demand data, we classify water demand into four main types, each with unique end-use categories (see Figure 3): (1) residential (indoor and outdoor) demand; (2) commercial demand; (3) industrial demand; and (4) irrigation (public and agriculture). The demand (D) for each type is assembled based on local attributes and prevailing conditions. Total Block demand is calculated as the sum of these four types and results in a 24-h time series for each QC (Equation (2)). This process is performed separately for every simulation day and each Block.

$$D_{QC,24} = D_{Residential} + D_{Commercial} + D_{Industrial} + D_{Irrigation} \quad (2)$$

Residential indoor and commercial demand have an exceptional position because they are provided and itemised in detail at the household level. The data originate from regional measurements or can be calculated using stochastic demand models [34–36]. The transition from small-scale household level demand to an individual block demand in the model is performed in two steps (Figure 4).

	Residential		Commercial	Industrial	Irrigation	
	Indoor	Outdoor	Indoor	Statistic	Public	Agriculture
Base demand	end use (app)	flow rate	end use (app)	dem. patterns	demand / m²	demand / m²
Scaling factors	residents res. / house season wsa	veg. factor user behaviour weather season	employees wsa weekday		park size weather season user behaviour	field size weather season user behaviour

Figure 3. Demand types (residential, commercial, industrial, and irrigation). The base demand originates from statistical data; scaling factors are Block-dependent parameters to assemble the individual Block demand.

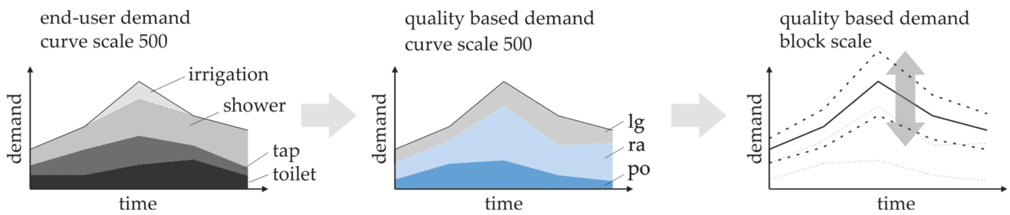

Figure 4. From end-use demand to standard DC (curve scale of 500 people, schematic diagram) and scaled Block demand.

2.2.1. End Use Analysis

The first step is executed prior to the simulation. The end-uses (e.g., household appliances) are assigned to QCs based on their minimum water quality requirements (Table 1). This pattern is applied to the raw demand data. We distinguish between households with a different number of residents and merge equally sized households (1–6 persons) to standard sized DCs of 500 people. These curves represent a random sample of the consumers demand under defined conditions [37].

Table 1. Example for water quality assignment to end-uses (in: demand/inflow; out: outflow after use).

Application	Assignment 1		Assignment 2	
	in	out	in	out
Toilet	potable water	Black water	rainwater	Black water
Shower	potable water	Black water	potable water	light greywater
Irrigation	rainwater	-	stormwater	-

This approach allows a large scale analysis, but keeps the connection to the detailed raw data and the ability to adapt it to evaluate effects of change. This can be, for example, changing consumer habits, seasonal variations of demand or the implementation of water saving appliances (WSA). These factors are expressed by an adaption ration, which is calculated as ratio of the difference between statistical [38] or guideline (e.g., for water efficiency products AS/NZS6400 [39]) values (demand frequency and flow rates). The adaption ration is applied to the raw data during the aggregation process. Each modification is performed separately and saved as a stand-alone DC. With this approach, a wide range of standardised DCs is generated (Table 2).

Table 2. Example for a water demand database of 1 specific water quality assignment, with curve scale of 500 people.

Scale		Residents/Households		Demand		Outflow		Number of DC's
500		1–6		5 QCs 2 seasons 1 + 7 WSA		2 QCs 2 seasons 1 + 7 WSA		
1	×	6	×	(80	+	32)	=	672

2.2.2. Water Demand Aggregation

Step 2 is performed during the simulation. The model samples DCs from the database dependent on the Block conditions and proportionally weights them based on the real combination of household sizes and distribution of water saving appliances. This combination is scaled to the real number of inhabitants and results in one individual DC's for each Block (Figure 5). It must be considered that the spatial and temporal scaling of water demand is a non-trivial process [40]. The described method is a simplified way to be able to implement it in the simulation.

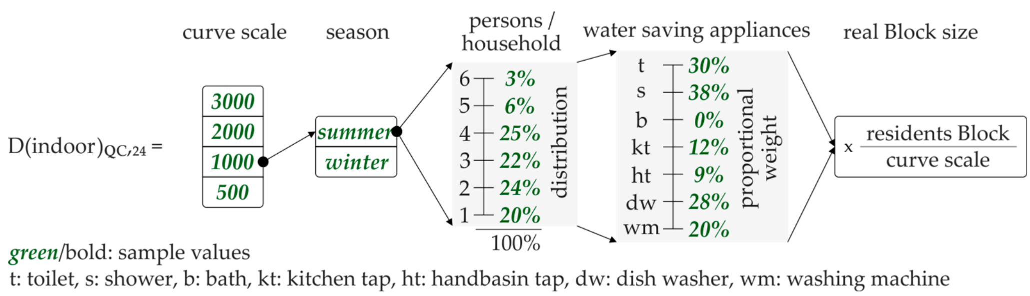

Figure 5. Example for DC sampling (Curve scale: 1000 residents, summer, distribution of household size and water saving appliances).

This process is performed simultaneously for inflow and outflow. Quantitative changes between the quality classes of the input and the output hydrographs represent the quality shift during usage (e.g., from potable water to greywater).

Commercial demand follows the same principle as residential indoor demand, but is driven by the number of employees in a Block instead. Residential outdoor, industrial and irrigation demand is handled differently and is calculated directly during the simulation. Residential outdoor demand ($D_{outdoor}$) is determined by areal distribution of statistical end-user habits. These are the flow rate, duration and frequency of outdoor water use in private gardens [41]. Decisive parameters are the number of households and the ratio of vegetation within the urbanised area. To obtain the vegetation index, satellite data (Landsat 8 [42], pixel size 30 m) was used to calculate the Normalised Difference Vegetation Index (NDVI) [43]. Every pixel within the urbanised area of a Block (not containing of public green space) that exceeds the NDVI threshold of 0.3 is considered as "green". The rate between total and green pixels is used to evaluate the relevant number of households.

$$D_{outdoor} = \text{flow rate} \times \text{duration} \times \text{households} \times \text{vegetation index}/\text{frequency}/\text{hours per day} \quad (3)$$

$$\text{Example: } D_{outdoor}(L/h) = 6.3\ L/min \times 15\ min \times 136 \times 0.4/3.5\ d/16\ h = 91.8\ L/h$$

Irrigation for public green space and agriculture is based on statistical site-related water demand (L/m^2, duration, frequency). To scale the base demand value, the actual area size is obtained from zoning plans. To keep continuity and avoid unrealistic peaks, the outdoor and irrigation demand is spread over the day and frequency period. During rainfall the outdoor demands are not added to the Block demand. Industrial demand refers to unique urban facilities for which typical demand can neither be represented by any of the aforementioned demand categories nor estimated from statistical water demand patterns (e.g., hospitals, airports, factories, universities, of golf courses). For such facilities, a direct provision of DCs is necessary.

The process of demand aggregation draws the outline to a detailed modelling approach and ensures that local demand fluctuations, which arise in reality and cannot be reproduced by the model, are compensated and thus negligible [37].

2.3. Water Balance at Block Level

The Block level is the common scaling level of the simplifications during the model creation. Blocks can be shaped in any way and based on any pre-defined geographic delineation, where data are available. We use census districts as this is the unit where demographic data are available, and no further modification is needed.

The model is implemented in CityDrain3, a conceptual and dynamic urban drainage software [44]. The software, with its modular and temporal discrete scheme, is very well suited to be used for the WBM and, as it is open source software, the implementation is easy to handle. The Block module is written in Python 2.7 and contains the Block specific parameters, the storage facilities, the internal processes for demand generation and input and output ports to be embedded in the model framework. The underlying data (e.g., inhabitants, storages, areal data, etc.) are prepared and stored with a geographic information system (GIS). Figure 6 shows the scheme of a Block module. The internal connections symbolise the direction in which the water flow is handled in the Block. For better visibility, connections to and from the storages are bundled.

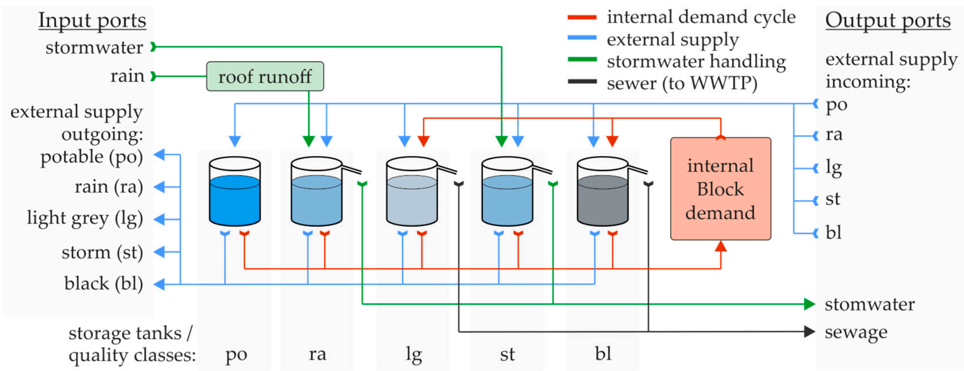

Figure 6. Scheme of a WBM-Block; storage facilities for every QC as core of the Block, demand inside the Block, internal flow pathways and connections to the model environment.

The whole internal demand process, as explained in Section 2.2, is represented by the red box in Figure 6. It is based on the fit-for-purpose (ffp) principle, which means that the lowest possible quality class is used first for satisfying each water demand. If a resource is insufficient or not available, the remaining demand is sent to the demand output port (if connected) or the next available and incrementally better water quality class is used. This cascading process can be performed until the potable water class is reached. The potable water demand is always met by an external supply and consequently needs a connection to an external reservoir. An alternative operating mode of the module is to insist on the defined water quality and allow negative storage volumes to identify shortages of water resources.

An important aspect of the module is to harvest the occurring water of the current time step. The runoff after usage is divided into grey and black water, whereas stormwater (generated by a separate module) and rainwater depend on rainfall and surface conditions of the Block. They are collected in storage facilities and the overflow is discharged as sewage and stormwater, respectively (Figure 2). It has to be considered that greywater cannot be stored indefinitely [33]. To avoid hygienic problems, the total lg-storage volume is replaced at least within five days.

The storage tanks represent the hypothetical total amount of storage volume within a Block, with a separate tank for each QC. Consequently, the storage size parameter can be interpreted as a combination of the actual tank size and the implementation rate of the QC-storage in the Block. For further analyses, we define the technology implementation rate (TIR) as the rate at which new decentralised systems (e.g., storages) are being established for operation in urban areas. The local distribution of storages within a Block cannot be described by the model. Based on this, the simulations will be undertaken with the assumption that every consumer has access to the available resources in a block.

The ports are the connections to the model environment. The input ports receive information from upstream modules, whereas the output ports send model outputs from the current time step to the connected modules (Table 3). The output supply ports are the only active connections, which means the Block has the power to send requests. The other connections are passive and can only react on processes. The input supply ports are intended to supply other Blocks with water and allows the current Block to serve as a cluster reservoir (Figure 3). The connections are constrained by a limiting flow rate to avoid the effect of unrealistic transportation rates.

Table 3. Input and output ports of a WB-Block.

Input Ports	Description	Output Ports	Description
Stormwater:	stormwater from rainfall/runoff module plus stormwater from the upstream Blocks	Stormwater:	combined stormwater and rainwater overflow
Rain:	rainfall of the current time step	Sewage:	combined grey and black water overflow
External supply:	claims from upstream Blocks	External supply:	required water to cover the storages

2.4. Water Balance at City Level

At the city level, Blocks are connected to each other, external reservoirs and, from a modelling point of view, to the rainfall and surface runoff input (Figure 7). The network structure can be parallel without interaction between the blocks or in a linear way to define an upstream/downstream order or cluster structures.

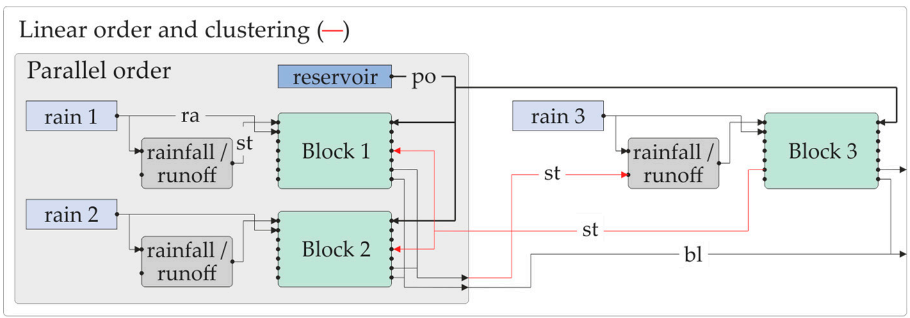

Figure 7. Block connections in linear and parallel order, rain 1 to 3 is the regional precipitation for each Block, Block 1 and 2 are connected to the reservoir without connection to each other (parallel order), Block 3 serves as stormwater cluster; the input and output ports are ordered like shown in Figure 6.

The output of the model is saved every time step and for every Block. For this study, we investigate results of the current storage volumes, internal demand, external connection flows (input and output ports), the upgraded fraction of the water demand for every QC, the storage overflow (equates to stormwater and sewage runoff) and the greywater generation. The subsequent analysis is done separately and significant findings can be transferred to GIS to gain spatial insight in the simulation outputs.

This model structure shows the benefits of the census district Block structure. Limitations from grid-based models are removed as the model is spatially adapted to real urban structures. The exchange of information between neighbouring Blocks follows the direction of realistic network structure. The representation of the results facilitates the communication with decision makers as water policies can differ across political borders. Furthermore, it enables the integration of model results with demographic data to gain additional insights for the implementation of water policy measures.

3. Model Application

3.1. Case Study Description

We demonstrate the developed WBM on the case study of Metropolitan Melbourne, Australia, which has over four million inhabitants within an area of over 9000 km^2. Melbourne's water supply struggles with irregular precipitation and periodic droughts and it is necessary to make their supply system more resilient against not only future climatic but also demographic uncertainties [45]. In response to the last extreme drought, a desalination plant was constructed in Melbourne. In the model, it is not considered as a dedicated QC as it is a central source and contributes to the potable water QC.

Modelling the water balance of Melbourne is a vast challenge and uncertainties with respect to demand data and spatial accuracy are inevitable. Nevertheless, simplifications in the model setting allow the simulation to illustrate the opportunities of decentralised storages and reuse of water resources as well as the effects of water efficient appliances. The simulation period covers the year 2015.

3.2. Data and Model Setup

The WBM for Melbourne comprises of 9509 Blocks, which represent the administrative districts of the national census (an average of 420 residents per Block). Besides the number of inhabitants, the census data provided the number of households per Block. This was used to specify the water demand data from the database. The spatial input data are pre-processed and incorporated into this spatial structure. We characterised the urban environment (e.g., buildings, streets, lots, defined green space such as parks and golf courses, agricultural land) using the Melbourne zoning plan and a building dataset. This results in 12% impervious area, which is the combined area of streets, lots and rooftops. Rooftops are handled separately for ra-harvesting and contribute with 4% to the impervious area. We intersected these data with census data to obtain Block specific information of drainage effective (for ra and st) areas. Defined green space like parks and golf courses represent 3% of the whole area. Agricultural land is classified as cultivated and potentially irrigated areas and accounts for more than 16% of the area. Furthermore, to obtain urban vegetation information as basis for the residential outdoor demand, we calculated the NDVI from Landsat 8 [42] imagery taken on 14 January 2014 and 9 February 2015. The remaining area, which is not classified, has no influence to the model and is neglected.

Residential demand is responsible for 64% of the entire potable water demand in Melbourne [46]. Data pertaining to this, especially individual end use volumes, was obtained from a stochastic demand model based on local measurements in Yarra Valley Water utility district during summer 2012 [35]. The seasonal adaption and the demand values for irrigation stem from the statistical analysis of Melbourne's residential water end uses [38,47]. Commercial and industrial demand data were not available for this investigation. To substitute the missing demand information, population equivalents were used instead. For validation and to adjust the population equivalents, total demand data from water retailers and inflow measurements from the wastewater treatment plants were used.

The rain input is given by 10 rainfall measurements distributed throughout the city area [48] (Figure 8). Compared to long-term evaluation, the year 2015 was in the range of average precipitation volume with values between 358 mm/year in the western and 1122 mm/year in the eastern part of Melbourne (616 mm/year mean value).

Demographic and geographic parameters were kept constant throughout the scenarios. The variables in this investigation were storage size and the water demand. Initial dimensions of storage tanks were defined as follows: virtual potable water storages are installed for functional reasons of the model and for an easier evaluation of the demand. They serve as daily storages; hence, they should be able to store the average daily demand of 120 L/resident [38]. Considering the installed rainwater systems in Melbourne, the average rainwater tank size is 4115 L/household [47]. The size of stormwater storages strongly depends on the characteristics of the catchment area, the intended rate of retention and the main aim of the measures, namely reuse or environmental protection. A detailed dimensioning of stormwater detention facilities is usually based on design rainfall events and the corresponding hydrograph [49]. For simplification purposes and to be able to apply a universal pattern to the Blocks, a simple relationship between storage tank and catchment size was defined. We chose an initial value of 10 L/m^2, which lies within the range of on-site stormwater detention systems and below the guide value for stormwater detention basins [50,51]. Greywater reuse as a permanent system is not yet widespread [47]. According to manufacturer specification, the average dimension is about 50 L/resident. As the storage tanks are hypothetical, the initial dimensions are just the starting point for the parameter variation. Scenarios are focused on availability of local water resources. Therefore, centralised black water treatment, distribution and reuse is not considered. Nevertheless, it could be implemented if this question becomes of widespread interest for water management.

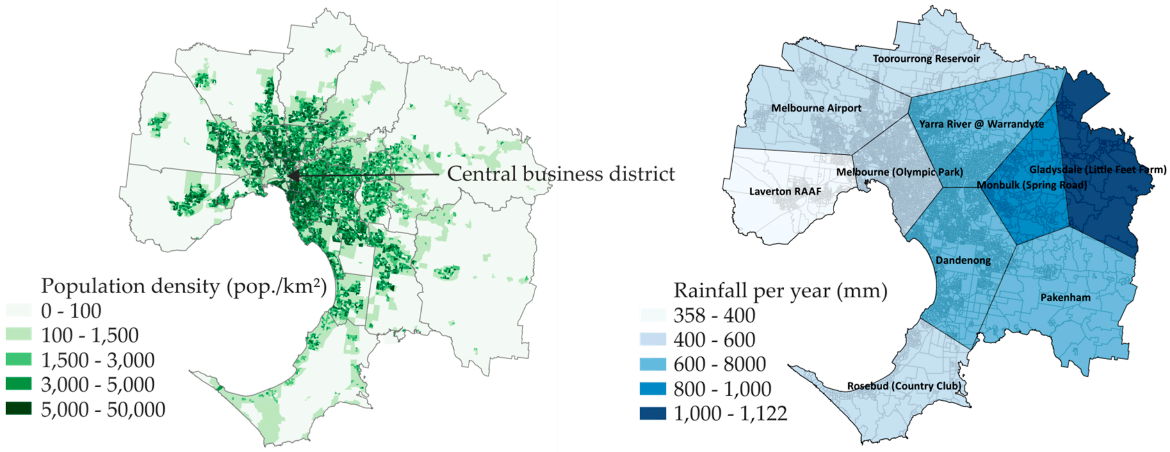

Figure 8. Melbourne: population density (**left**); and rain distribution in mm/year (**right**).

The initial model represents the current situation in Melbourne. Statistics show that currently 28% of the houses in Melbourne use rainwater harvesting, 25% a simple method of greywater utilisation and 13% as integrated greywater system [47]. The purpose and the extent of this reuse could not be identified entirely (e.g., because it is not part of the model like filling pools). Hence, we simulate this base reference scenario without reuse measures. As starting conditions, storages are empty.

3.3. Alternative Scenarios

We use the model to assess measures to reduce the external potable water demand and to support the design of future water policies. We investigate two types of scenarios. The fit-for-purpose policies (FFP-policies) aim at an efficient utilisation of available water recourses. This is realised by adapting water quality requirements for the quality assignment. The other type are the infrastructure related scenarios. These are water saving appliances (WSA) and decentralised storage facilities

(DWS), which influence water demand and water availability, respectively. The FFP-policies and the infrastructure measures influence each other, which is why the infrastructure scenarios are always performed in combination with an FFP-policy. Several scenarios were developed to cover some of the main ideas from current planning and management of alternative water supply and demand reduction strategies and are summarised in Table 4. We discuss the individual details of each scenario in the following sub-section.

Table 4. Overview of the evaluated scenarios and the number of combinations.

Scenario Overview	ID	Number of Scenarios	Scenario Combination
Quality requirements:	FFP-0/FFP-1 to FFP-3	1/3	4
Water infrastructure scenarios:			
water saving appliances	WSA-scenarios		24
decentralised water storages	DWS-scenarios	6	9
		3	37

3.3.1. Water FFP-Policy Scenarios

An essential model input is the definition of the minimum water qualities for the end use applications. We developed four scenarios for the quality assignments, distinguished by the availability of the resources on lot scale (Table 5). They represent an increasing rate of water reuse implementation in ascending order. The assignment combinations do not cover every possible combination, but are a reasonable selection of typical applications for the water qualities. It is important to note that the reuse of water always requires an adequate treatment. In this context, the scenarios can be seen as a progress in decentralised water treatment in the future. The technical process of water treatment is not part of this investigation. Technical specifications and guidelines for water reuse can be found in Australian guidelines for water recycling [32,52].

- FFP-0: Reference scenario without reuse (reference scenario)
- FFP-1: A conservative reuse where rainwater without treatment is used on household level and stormwater for non-private irrigation
- FFP-2: Implementation of light greywater with simple treatment and rainwater treated for indoor use
- FFP-3: Intensive reuse with light greywater and rainwater treated for indoor use and stormwater available on-site

Table 5. Water quality assignment scenarios (in: demand/inflow; out: outflow after usage).

Application	FFP-0 (ref)		FFP-1		FFP-2		FFP-3	
	in	out	in	out	in	out	in	out
Toilet	po	bl	**ra**	bl	**lg**	bl	**st**	bl
Hand basin tap	po	bl	po	bl	po	**lg**	**ra**	**lg**
Kitchen tap	po	bl	po	bl	po	bl	po	bl
Bath	po	bl	po	bl	po	**lg**	**ra**	**lg**
Shower	po	bl	po	bl	**ra**	**lg**	**ra**	**lg**
Washing machine	po	bl	po	bl	**ra**	**lg**	**lg**	**lg**
Dish washer	po	bl	po	bl	po	bl	po	bl
Private irrigation	po	-	**ra**	-	**lg**	-	**st**	-
Public irrigation	po	-	**st**	-	**st**	-	**st**	-
Farm Irrigation	po	-	**st**	-	**st**	-	**st**	-

po: potable; ra: rain; lg: light grey; st: storm; bl: black water.

3.3.2. Water Infrastructure Scenarios—Water Saving Appliances

Besides raising awareness on water demand behaviour, water saving appliances are an important tool to reduce residential water demand. We use the Australian/New Zealand standard AS6400:2016 rating system for water efficient products [39] as a reference for the model. The adaption ratios in Table 6, as defined in Section 2.2.1, represents the difference between current average water demand and a 6-star rated efficiency product. They scale the end use demand data during the aggregation process. Each scenario represents a model-wide implementation of one of the water efficient products. Beside potable water reductions, the combinations with the FFP-policies show relations to applied and available water QCs.

Table 6. Water saving appliances (WSA) scenarios.

Appliance	"6-Star" Water Saving Appliances	Adaption Ratio
Toilet (WSA-t)	2.5 L/flush	0.445
Hand basin tap (WSA_ht)	1.1–4.5 (2.8) L/min	0.518
Kitchen tap (WSA-kt)	1.1–4.5 (4.5) L/min	0.328
Bath	-	1.0
Shower (WSA-s)	4.5 L/min	0.614
Washing machine (WSA-wm)	30.3 L/load (6 kg)	0.254
Dish washer (WSA-dw)	8.3 L/event (12 place settings)	0.572

3.3.3. Water Infrastructure Scenarios—Decentralized Water Storage Strategies

The aims of rain- and stormwater harvesting are to capture, treat and store water during times of availability, while reducing runoff peaks in extreme rain events and, to utilize the stored water in times of scarcity. This requires not just short-term storages but seasonal reservoirs. For hygienic reasons, greywater systems have to operate as short-term storages. In both cases, the storage volume is an important parameter. For this scenario, the TIR (technology implementation rate. see Section 2.3) of rain-, storm- and greywater storages is varied (Table 7). The initial dimensions of the storages are based on established systems within the examined region and literature values (see Section 3.2). Design parameters scale the initial dimensions to Block-specific tank sizes. A TIR of 100% means a block wide implementation of the initial tank size, a higher value indicates an increase of the implemented tank size. The chosen TIRs are based on a sensitivity analysis [53] and the scope of literature values. The wide range intends to give an overview of the impacts of chancing tank sizes, local and individual boundary conditions are not considered.

Table 7. Decentralised water storage (DWS) scenarios.

Storage Tank	Design Parameter	TIR
Rainwater (DWS-ra)	Households	28 to 250%
Stormwater (DWS-st)	Block size	0 to 500%
Greywater (DWS-lg)	Residents	0 to 100%

The analysis of spatially resolved storages helps us to better understand the connection between runoff generation, runoff peaks and available free storage volume. It can provide insights for efficient urban drainage management, for example to utilise storages within the city to avoid an overload of the existing drainage system. By systematically increasing the TIR, effects on potable water demand can be examined. Furthermore, the decentralised storage capacity will alter runoff volumes entering the stormwater drainage system, the sewer and the inflow to the WWTP's. The potential load removal for these facilities will be displayed. The scenarios are performed in combination with the FFP-policy Scenarios 1–3.

3.4. Performance Indicators

The model generates a wide range of spatially and temporally distributed results. Evaluations can be done for detailed regions and time frames or for the entire simulation. For a comparison of results on city scale, we defined the following indicators (Table 8).

Table 8. Performance indicators.

Performance Indicator	Description
Demand (td) [%]	Demand for each water quality class in percent compared to the total demand
Runoff volume (rv) [%]	Stormwater/sewage runoff and runoff peaks compared to the initial model
Filling levels (fl) [%]	The filling level compared to the tank volume, available for every storage in the model. This indicator shows the availability of resources all over the investigation area.
Fit-for-purpose factor (ffp-factor) [%]	The ffp-factor symbolises the percentage of a QC's demand, which is not upgraded and met by the intended QC. In the case of potable water, no upgrade is possible, so the ffp-factor is turned to represent the ratio of the used potable water that must be potable by definition. (Not to be confused with the FFP-policies, which are used for scenario identification)
Reuse rate (rr) [%]	This indicator represents the percentage of greywater that is used again (calculated as greywater use/greywater generation)
Storage rate (sr) [%]	The percentage of generated greywater that is stored in the tanks (calculated as stored greywater/greywater generation)

4. Results and Discussion

4.1. Water FFP-Policy Scenarios

The assignment of applications to water qualities play a decisive role in the model setup. The results for potable water show that, even though the demand decreases with an increase in alternative resources, it could be even lower. The demand of the alternative QCs is not met entirely, which can be seen with the help of the ffp-factor in Table 9. This is because rain- and stormwater facilities are not widespread or large enough in the current model setup. The results for greywater (ffp-factor/lg) must be handled with caution. The numbers indicate that storage tank size is sufficient, but without considering that the resource might not be available for everyone in the block. Regarding the runoff (sewer and drainage), the volumes are decreasing significantly for the later scenarios. The peak flows (runoff/hour) are less affected because there is no runoff buffering in case of full storages.

Table 9. Annual results for water demand, sewage and stormwater runoff and the performance indicator "ffp-factor". Reference scenario (FFP-0) is taken as 100%, FFP-1 to FFP-3 quality assignment compared to the FFP-0 (for this simulation the initial model is used).

		FFP-0 (Reference)		FFP-1 (%)	FFP-2 (%)	FFP-3 (%)
Demand (td)	po	4.230×10^8 m^3/year *	100%	75.5	55.3	39.2
	ra	-	-	10.6	18.3	18.4
	lg	-	-	-	12.4	16.9
	st	-	-	14.0	14.0	25.4
Sewage (ss)	Volume	3.141×10^8 m^3/year	100%	100.0	83.3	77.2
	Peak	7.416×10^4 m^3/h	100%	100.0	83.8	86.5
Stormwater (ss)	Volume	3.957×10^6 m^3/year	100%	80.5	72.5	60.6
	Peak	9.898×10^5 m^3/h	100%	85.5	84.1	76.8
ffp-factor	po	1.0	100%	89.1	61.8	42.7
	re	-	-	87.0	54.0	53.0
	lg	-	-	-	99.0	99.0
	st	-	-	62.0	62.0	86.0

* Measured demand according to Melbourne Water: 4.26×10^8 m^3 water per year, converted to 297 litres per person and day.

The overall values allow a general statement of the differences between the scenarios. A spatial view of the Blocks gives information in which areas the measures are effective. Figure 9 shows the localised reduction in potable water demand between the scenarios. Whilst FFP-1 has the most effect in rural and green area Blocks, no further change can be observed for FFP-2 and FFP-3 for this type and the reductions focuses on urban Blocks.

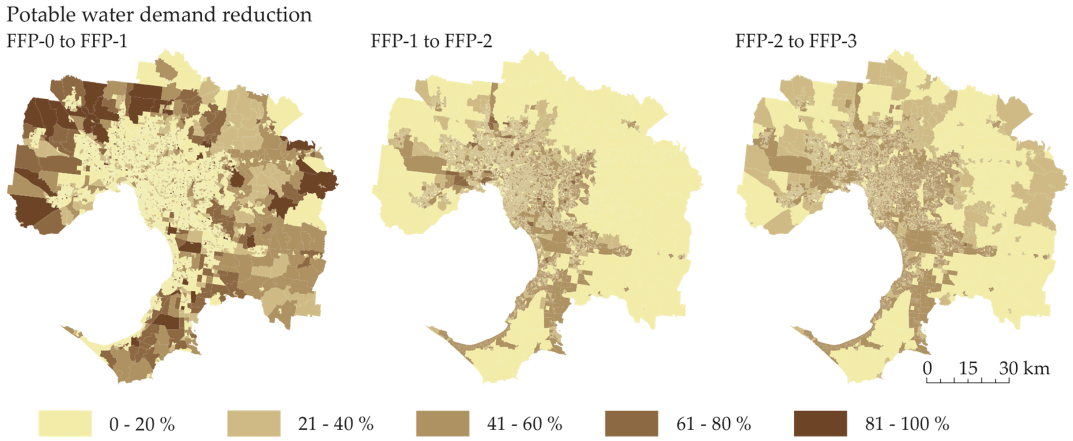

Figure 9. Spatial analysis of the differences in annual potable water demand between FFP-0 to FFP-3.

4.2. *Water Infrastructure Scenarios—Water Saving Appliances (WSA Scenarios)*

The current implementation rate of water saving appliances in the demand data cannot be quantified. However, using the minimum flow rate of water saving appliances, the current data can be customised. For this analysis, each scenario represents a complete adoption for one water saving appliance type (WSA scenarios). The potable water demand of the initial model with FFP-0 and without water saving appliances represents 100% and is the reference for all other WSA scenarios (Figure 10). The scenarios without water saving appliances correspond with Table 9.

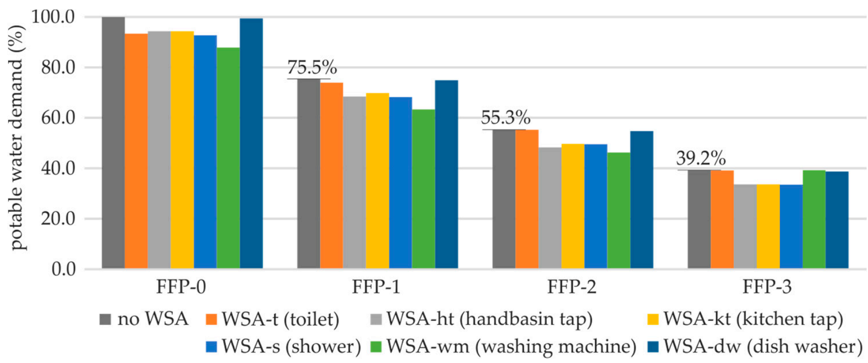

Figure 10. Combination of the water saving appliances scenarios (WSA scenarios) and the FFP-policies. Annual potable water demand compared to the initial model without water saving appliances and with ffp-0 qualities. Each column represents the potable water demand of one WSA/FFP combination.

The results represent the differences in potable water demand of each scenario compared to the initial model without water saving appliances. The FFP-policies and therefore a general implementation of water reuse strategies remain the main drivers for potable water reduction (up to 60% reduction). An area-wide implementation of all analysed water saving appliances at once can reach a potable water demand reduction of up to 38% (for FFP-0). This factor decreases with an increase in the utilisation of alternative resources, because the reductions contribute to the other water qualities. This effect can be seen in Figure 10 (for example FFP-2/WSA-t or FFP-3/WSA-wm). These appliances contributed to the potable water reduction in FFP-0 but have no influence as soon as they are supplied by another water quality. Figure 11a shows the part of the potable water demand that must remain potable (ffp-factor) according to the definition of the quality assignment (Table 5). The rate decreases with each step of increasing reuse measures. For the FFP-3 policy, this means that 50–60% could be covered by a lower QC than potable water. The rate is constant for the WSA scenarios. Peaks like FFP-2/WSA-wm (reduced demand for wm/QC for wm: ra) occur when less demand has to be upgraded to potable water. The reason for a lower ffp-factor, like for FFP-3/WSA-kt (kitchen tap is one of the two remaining appliances where potable water is mandatory/reduced demand for kt), is the reduced potable water demand while the upgraded proportion stays constant. These results indicate that, even though there is a clear reduction in potable water demand, it could be even higher. The availability of the alternative resources must be improved to achieve this aim. This statement might not be true in every case and we will come back to it in the next section (DWS-scenarios).

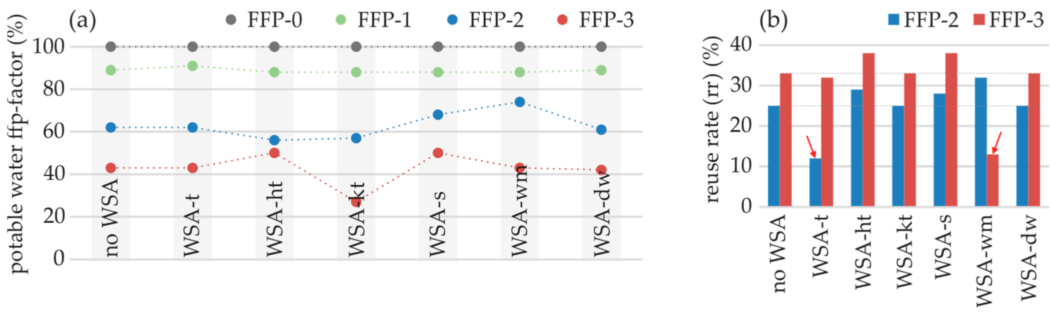

Figure 11. Results from the WSA-scenarios: (**a**) the potable water ffp-factor (part of the demand that must be potable according to the definition); and (**b**) the greywater reuse rate (rr) (%).

The use of different QCs and the reduced water demand from appliances influence each other. In Figure 11b, the effect of water saving appliances and the quality assignment on the greywater reuse rate (rr) is shown. Generally, the higher reuse rate for FFP-3 is caused by the wider range of utilisation of light greywater and stormwater (see also Tables 5 and 9). The outliers (low rr) for toilet (WSA-t/FFP-2) and washing machine (WSA-wm/FFP-3) scenarios result from their direct assignment to greywater and reduced demands from these appliances. Basically, greywater reuse rate is limited with the storage capacity. In our scenarios this is not an issue as the greywater demand can be met (ffp-factor for lg is 99% (Table 9)).

4.3. Water Infrastructure Scenarios—Decentralized Water Storage Strategies (DWS Scenarios)

4.3.1. Rainwater Storages (DWS-ra)

For this analysis, the TIR for rainwater storages is increased starting from the initial model (TIR 28%) to 250% (see scenario description Section 3.3.3). Table 10 shows that a better coverage of the QC rainwater reduces the potable water demand. The results show the demand compared to the initial model. For the prior influence of rainwater harvesting on the initial model see Table 9 (10% to 18% reduction).

Table 10. Annual potable water demand for the rainwater storage scenarios (DWS-ra).

TIR:	28%	50%	75%	100%	150%	200%	250%
(DWS-ra)	(initial model)						
FFP-1	3.192×10^8 m^3	99.2%	99.1%	99.0%	98.9%	98.9%	98.8%
FFP-2	2.339×10^8 m^3	96.3%	94.2%	93.1%	92.1%	91.8%	91.5%
FFP-3	1.659×10^8 m^3	94.9%	91.9%	90.4%	88.7%	87.9%	87.4%

Generally, the impact of further increasing the size of the rainwater tank on potable water demand is comparatively small [49]. Especially for the conservative reuse scenario (FFP-1) and the initial state model, already 87% of the rainwater demand can be met by rainwater (ffp-factor is 87%) (Figure 12a), which prevents any further reductions (Table 10). The ffp-factor for FFP-2 and FFP-3 is much lower and does not increase to the same extent as tank sizes. However, the drainage volume is still significant (Figure 12b) and the filling levels show that the scenario with the largest tanks (250%) also has the highest filling level. This indicates that tank sizes are sufficient for short term storage tasks. As soon as long term storage (seasonal) would be required, tank sizes are considerably too small to bridge the gap between wet periods. This can also be seen in Figure 14d, where the rising level of empty tanks during summer can be observed.

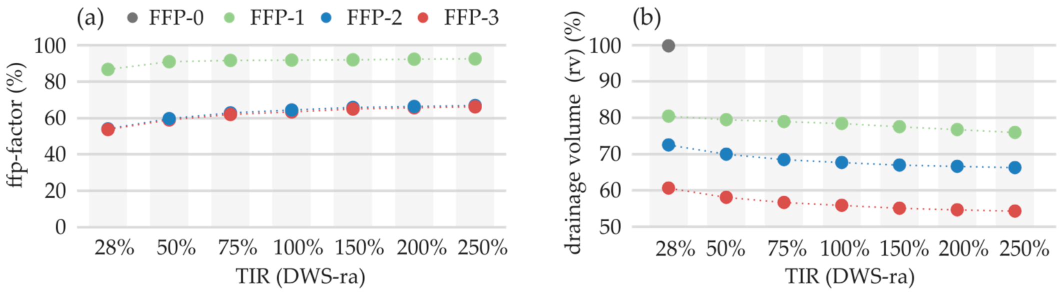

Figure 12. Results from the DWS-ra scenarios (combined with FFP-1 to FFP-3): (**a**) ffp-factor (defined rainwater demand covered by ra); and (**b**) annual drainage volume (rv) (FFP-0 as reference runoff).

Another problem is that the resource would be available in the city, but it is not located in the Block where it is needed. Figure 13 shows the spatial allocation of rainwater availability, demand and the spatial disparity for one day in summer. The storages are not filled equally with a concentration in the southeast regions (Figure 13a), whereas the demand is concentrated in the central districts of the city (Figure 13b). In many Blocks, it is necessary to upgrade the ra-demand to potable water, although there would be available resources in the neighbourhood (Figure 13c). This shows that there is potential for an exchange on different levels of the city.

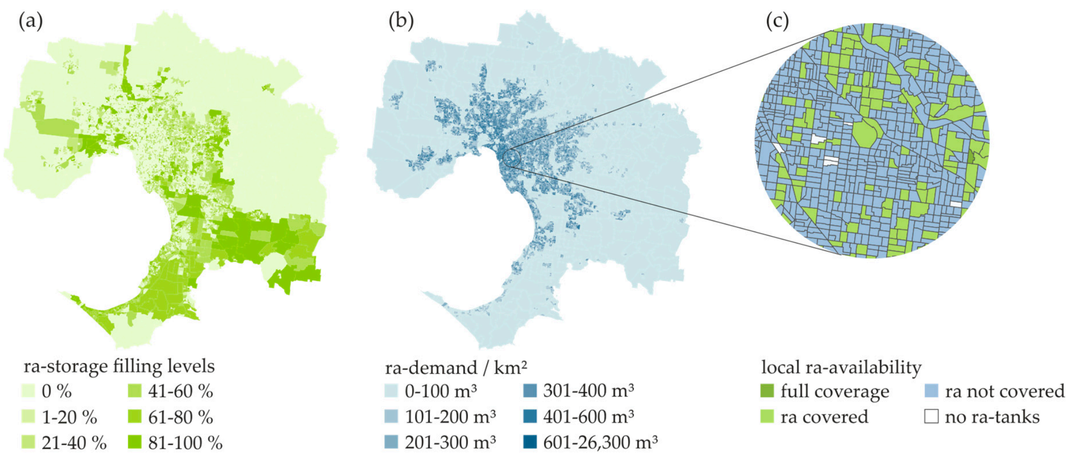

Figure 13. Local difference in rainwater availability. Results from the DWS-ra (TIR 250%, FFP-3) for one summer day (15 December 2015): (**a**) fl for ra-storages (average of the day); (**b**) ra-demand in m^3/km^2 (the highest demand value is caused by very small Block sizes); and (**c**) local disparity between Blocks where ra demand was met and where a QC-upgrade is necessary.

In Figure 12b, the overall stormwater discharge (st and ra tank overflow) is presented. The main runoff reduction can already be achieved with the initial model setup. A higher ratio of reuse

(FFP-policies) increases the runoff reduction for about 20%, whereas a further storage enlargement only contributes up to 5%. Larger storages have more influence on runoff peaks, which can be reduced by up to 25% (250% and FFP-3).

In Figure 14 the rate of full (filling level higher than 95%) and empty (filling level lower than 5%) rainwater storage tanks at each time step is shown. It gives a good picture of the available rainwater in the model and shows the tendencies during the seasons. For the conservative reuse scenario (FFP-1) current average tank size is sufficient. With a higher utilisation rate (FFP-2/FFP-3), the tank sizes are only large enough for winter demand but too small during summer. In Figure 14a,c, the rainwater demand is very well covered, although the larger tanks in Figure 14c show a better performance during dry periods. In Figure 14b, the rainwater tanks are considerably too small. The increase of tank sizes improves the situation during winter month, but still cannot meet the demand during summer. The 250% scenario mitigated but did not solve this problem. The green line stands for the rate of full ra-storages without reuse (FFP-0) and shows the potential of rainwater reuse for potable water reduction as well as for on-site rainwater detention and runoff reduction (Figure 14a,b).

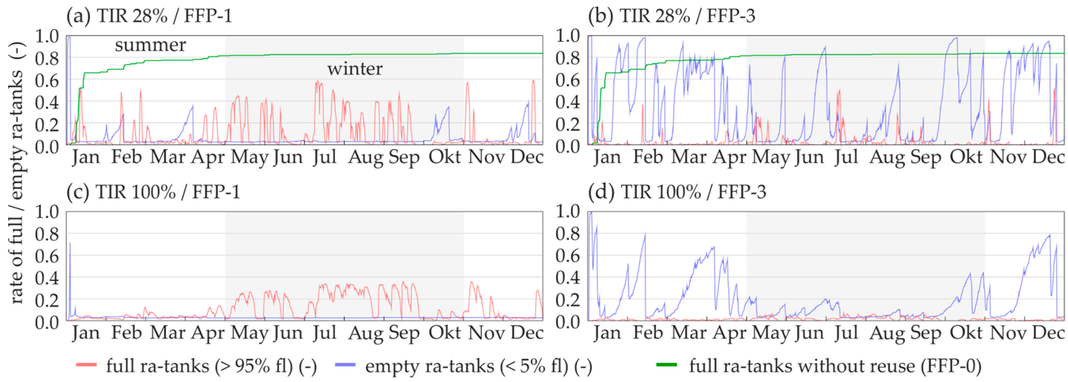

Figure 14. Ratio of full and empty ra-tanks at each time step (DWS-ra): (**a**) TIR 28%, FFP-1; (**b**) TIR 28%, FFP-3; (**c**) TIR 100%, FFP-1; (**d**) TIR 100%, FFP-3; compared to the FFP-0 scenario (green line).

4.3.2. Stormwater Storages (DWS-st)

The initial model contains stormwater tanks with a size of 10 L/m^2 (100%) Block area (see scenario description in Section 3.3.3). The variation reaches from 10% for short events to 500% as seasonal detention. Table 11 shows the potable water demand reductions in percent compared to the initial model. The prior influence of stormwater utilisation on the initial state can be seen in Table 9 (14% to 25% reduction).

Table 11. Annual potable water demand for the stormwater storage scenarios (DWS-st).

TIR:	10%	50%	100%	200%	300%	400%	500%
(DWS-st)			(initial model)				
FFP-1	108.2%	103.1%	3.192×10^8 m^3	98.3%	97.6%	96.6%	95.9%
FFP-2	112.0%	104.2%	2.339×10^8 m^3	97.8%	96.6%	95.4%	94.4%
FFP-3	115.8%	106.0%	1.659×10^8 m^3	96.8%	95.1%	93.5%	92.0%

Increasing tank sizes above 200% do not influence the potable water demand in the same extent. Here, the main benefit of the tanks is the reduction of runoff volume (Figure 15a) and peak runoff (33% between two outmost scenarios).

Between FFP-1 and FFP-2 is no difference in stormwater demand, the reduced runoff (Figure 15a) is caused by the higher rainwater utilisation. In these scenarios, stormwater in urban areas is a mostly unused resource whereas there is a need in rural areas with irrigation. With the FFP-3 policy, stormwater is not just used for public irrigation but also for on-site demand. Therefore, filling levels (Figure 16) decline especially in Blocks with an urban characteristic and the stormwater ffp-factor increases (Figure 15b). The ffp-factor also increases with larger tanks, but the process is flattening at an early state (50%). This indicates that small systems can already meet a large part of the demand, but for a significantly increased effect, tank size must be enlarged above average. This is the same effect we saw with the rainwater tanks.

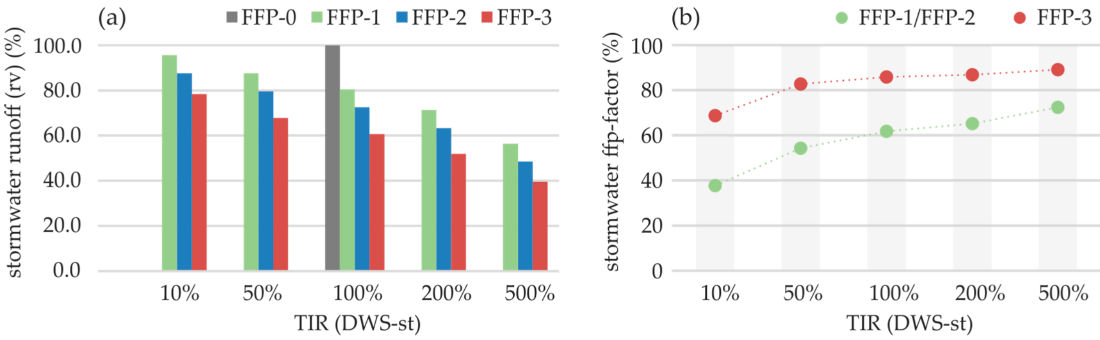

Figure 15. Results for the DWS-st scenarios: (**a**) annual stormwater runoff volume (rv) compared to the FFP-0 without stormwater reuse; and (**b**) stormwater ffp-factor.

Figure 16 gives an overview of the filling levels (fl) of all storages during summer and winter. The seasonal average indicates a declining saturation with increasing tank size with generally higher levels in winter. A closer look at a single time step per season (no rainfall for at least three days before the measurement) shows a more differentiated picture. The larger the storages, the more they are dependent on medium term rainfall and the longer the recovery process takes. The winter-refill process of the two large storage scenarios is in progress, this leads to the effects that these storages have higher filling levels for the summer time steps. The smaller the storages, the stronger they react on the demand and are more dependent on the short-term rainfall. In this context, the FFP-3 scenarios are more striking because the on-site demand influences more Blocks. The highest filling levels in summer are reached with a TIR of 200%. For all scenarios, the filling level declines for a TIR above 200%, which means a capacity above this dimension can serve as safety retention storage for extreme events.

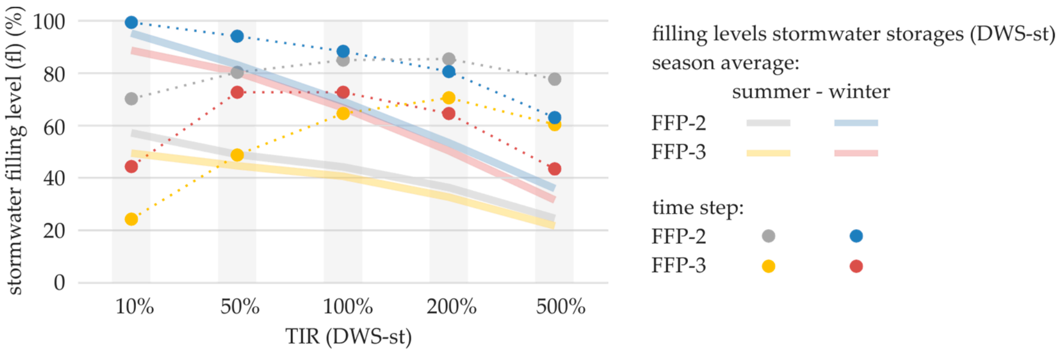

Figure 16. Results for the DWS-st scenarios: filling levels (fl) of all storages for seasonal average and one time step (summer, 15 December 2015; winter, 1 July 2015; no rainfall for at least three days before measurement).

In Figure 17, the annual course of full (filling level higher than 95%) and empty (filling level lower than 5%) stormwater storages is shown. The recovery period during winter is clearly visible as well as the on-site demand with FFP-3. The green line (Figure 17c,d) symbolises full storages without stomwater reuse and shows the potential of reuse as contribution to stormwater runoff reduction.

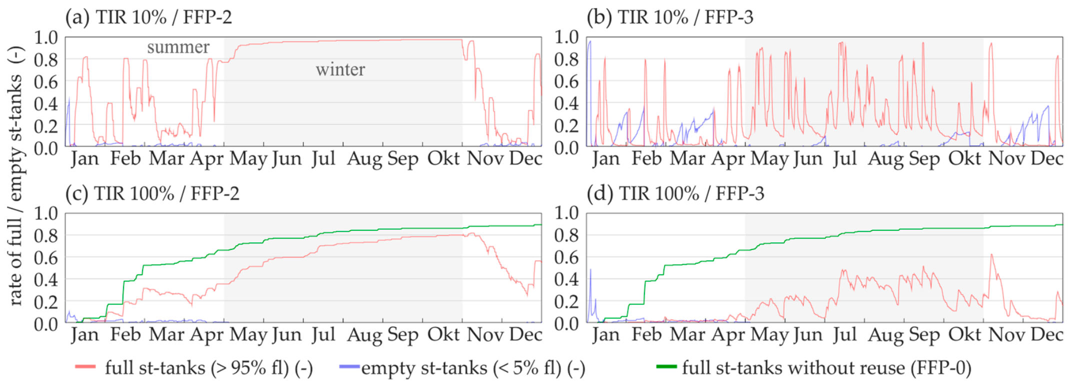

Figure 17. Ratio of full and empty st-tanks at each time step (DWS-st): (**a**) TIR 10%, FFP-2; (**b**) TIR 10%, FFP-3; (**c**) TIR 100%, FFP-2; (**d**) TIR 100%, FFP-3.

4.3.3. Greywater Storages (DWS-lg)

The FFP-polices in Section 4.1 showed that greywater reuse could replace 12.4% (FFP-2) to 16.9% (FFP-3) of the potable water demand. The TIR was varied (see Section 3.3.3) to see the influence of the storage tank size (Table 12). The results show that the greywater generation exceeds the demand and that the storage tanks are full during the whole simulation in nearly all scenarios. For the scenario with the biggest tanks (TIR = 100%) and the most extensive reuse (FFP-3), 97.5% of the tanks have a filling rate higher than 95%. Only the scenarios with the smallest tanks (this corresponds to 0.5 L/person) could not meet the greywater demand entirely (Figure 18a) and result in a higher potable water demand. These results benefit from the fact that all the generated greywater in a block is collected in one virtual storage tank. If every household is using its own greywater system, the efficiency will be significantly lower.

Table 12. Annual potable water demand for greywater storage scenarios (DWS-lg), greywater is only used for FFP-2 and FFP-3.

TIR	1%	5%	13%	25%	100%
(DWS-lg)			initial model		
FFP-2	110.70	100.10	2.339×108 m^3	99.97	99.88
FFP-3	125.09	102.18	1.659×108 m^3	99.93	99.75

Even though the storage rate of greywater is increasing with a higher tank size (Figure 18b), the sewer volume benefits are only very small (Figure 18c). However, compared to the scenario without greywater reuse, a sewage volume reduction of more than 20% is achievable. This shows that even small reuse systems can have a recognisable effect on the runoff. The retention also helps in reducing runoff peaks (up to 20% smaller peaks with the biggest tanks and extensive reuse (FFP-3)). With a controlled greywater system, coupled with the needs of the wastewater treatment plants, the utilisation capacity of the sewer as well as the treatment plant could be optimised.

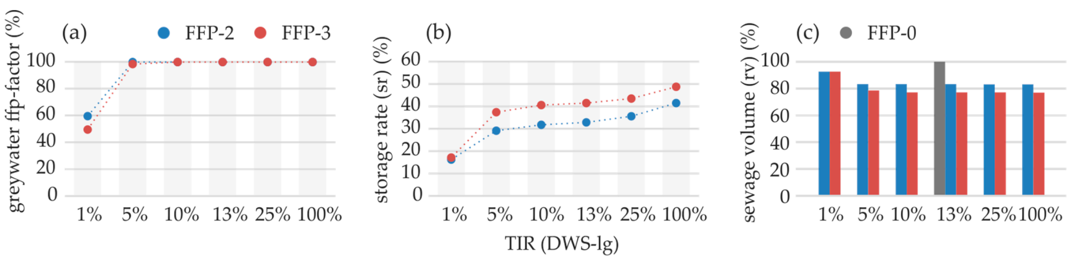

Figure 18. Results for the DWS-lg scenarios: (**a**) ffp-factor for greywater; (**b**) greywater storage rate (sr); and (**c**) sewage volume (rv) compared to FFP-0 (without greywater reuse).

4.4. Further Discussion

The scenarios show that the main task should be the achievement of an area wide implementation of alternative resources. Already small investments can have a large impact on the potable water demand. The presented model can help to identify areas with a high potential for alternative water resources, but does not replace the necessity of local water balance models. Local optimisations must be performed by more detailed models, as a distribution within one Block cannot be simulated by the WBM. This is important especially for systems, which are usually installed in each house separately. This leads to the conclusion that greywater or rainwater systems should be designed for larger clusters to achieve a higher efficiency. However, the problems of safety, maintenance and social concerns in this context must be considered.

A benefit of the model is the Block structure based on political borders because administrative information (technical, social) is managed within the same structure. The right placement of decentralised measures does not only depend on the conditions examined in this work. Besides additional technical data (e.g., age of existing infrastructure, regional development plans), more information on the people living in Blocks (e.g., age of the population, income and level of education) is important to predict investment capacity or possible acceptance for new technologies. Mapping model results to this information can give significant insights during the planning process for future water management measures.

There are numerous limitations of our approach, which we should highlight. Despite simplifications, data requirements are still high. The availability, accuracy and spatial detail are key for a good model setup. For example, the seasonal variation of the water demand was limited to summer and winter demand measurements. Our model also currently does not deal with exceptional pollutants and decentralised treatment of the QCs. Furthermore, predicting the demand of an entire city will be fraught with large uncertainty. As such, it is not possible to consider every demand with adequate accuracy, but rather that the proportions between the demand types are consistent. The size of the case study was not easy to handle, and the uncertainties caused by data collection from different sources and scales are high. Absolute numbers in this model dimension must be interpreted with caution. At a finer scale, individual storage tank size distributions were not tested and the case study was performed without exchanges of alternative water supply between the Blocks. This can be done in a next step. Desalinated water and recycled water from large wastewater treatment plants was not considered in the model but is used in Melbourne in the meantime. Finally, evapotranspiration, which can impact the stormwater model, was not considered in the model.

Future studies will consider climate change scenarios and the implementation of low impact development to better understand and represent stormwater management tasks. There is also potential in investigating spatial interrelationships between Blocks and identifying neighbourhoods where the supply and demand of alternative water resources effectively coincide.

5. Conclusions

This paper introduced a new city scale water balance model. The aim was to develop a model to evaluate strategies for decentralised water harvesting, storage and reuse measures and their impact on the city's water balance. Subsequently, external potable water demand should be reduced to relieve reservoirs especially during dry periods. Large investigation areas and the often-difficult situation of data availability requires several simplifications of local scale and distributed information to achieve a conceptual and unit-based model. The consideration of water quality classes and spatial dissociation from local processes are the backbone of the model. The benefits include easier and structured data handling as well as lower computational costs, both of which are appealing to desktop computers.

The simplified overview of the water balance enables users to evaluate location- and time-dependent water resource availability under different water demand conditions. In combination with additional technical and social information, water management tasks like the implementation of water saving measures or the placement of water storages and can be derived from the results. The aim of these measures is to reduce external potable water demand. The decentralised character requires an evaluation on city scale to identify opportunities and problems. It enables the user to see how water efficient products influence the water demand, when it is positive to use alternative water resources and the storage behaviour over the year. It is not possible to display any process that is below the level of simplification. Within a Block (our spatial units are based on the demographic delineation for the national census) areal information is not spatial explicit, water demand is aggregated and water resources are available for all residents.

The model was applied to Greater Metropolitan Melbourne. The developed scenarios examined the implementation of different water resources, an increasing intensity of reuse and the use of water saving appliances and decentralised water storage strategies. The utilisation of alternative water resources could be identified as having the most significant effect on the potable water demand. As an integrated system with water saving measures, potable water demand can be reduced significantly (up to 60%). The filing levels of the storages showed the seasonal variations and the spatially unbalanced occurrence of alternative water resources. Our findings also showed that even small reuse systems can have a large impact on the overall potable water demand. As such, large-scale adoption and local exchange clusters for privately installed systems are important. The potable water demand reductions were significant and alternative resources increased the resilience of the water supply system. However, a complete substitution of potable water mains through alternative resources is not regarded and truly realistic for an established city due to safety reasons.

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Abbreviations

The following is a list of abbreviations used throughout the text and should serve as a global reference.

General

WBM	water balance model
QC	water quality classes
DC	demand curve
D	demand
V	volume
TIR	technology implementation rate
NDVI	normalised difference vegetation index
ffp	fit-for-purpose

Used as abbreviation for scenarios identification

FFP-policies	fit-for-purpose policies
WSA	water saving appliances
DWS	decentralised water storages

Water quality classes (QC)

po	potable water
rr	rainwater
lg	light greywater
st	stormwater
bl	black water
Household appliances	
t	toilet
s	shower
b	bath
ht	handbasind tap
kt	kitchen tap
dw	dish washer
wm	washing machine
Performance indicators (Table 8)	
td	total demand
rv	runoff volume
fl	filling levels
ffp-factor	fit-for-purpose factor
rr	reuse rate
sr	storage rate

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