An Approach for Simulation in Support of the Design of Net-Zero Water Buildings (NZWB)



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Current approaches towards making buildings more efficient in terms of water consumption are often qualitative and simply based on the inclusion of certain water-saving and recycling design features, or simple water quantity assessments. This paper presents a conceptual framework of an approach that will allow an objective qualification of whether or not buildings qualify as Net-Zero Water Building (NZWB) on the basis of a detailed water supply and demand balance. It also allows to contribute and move beyond traditional deterministic calculations.

Efforts to manage a sustainable use of resources in the built environment predominantly focus on efficient use of energy and materials. However, sustainable use of water is of increasing interest in the built environment, especially since climate change is leading to longer and more severe droughts. Where initial efforts focused on the application of relatively straightforward design principles such as rainwater collection and the reuse of grey water, more holistic approaches to manage water in and around buildings are now appearing. In parallel to towards the design of a Net-Zero Energy Buildings (NZEB), the concept of a Net-Zero Water Building (NZWB) has emerged.

Water is an increasingly scarce resource, with rainfall reduced by climate change while population growth puts pressure on the demand side. As with energy, buildings are responsible for a significant percentage of national water use; for instance, figures reported for the USA are in the order of 15% [1]. The cost of water and energy is quickly approaching the same order of magnitude as gas and electricity, with annual household bills in the UK reported at around £ 600 for gas, £ 750 for electricity, and £ 400 for water [2]. Current approaches towards making buildings more efficient in terms of water consumption are often qualitative and simply based on the inclusion of certain water-saving and recycling design features, or simple water quantity assessments.

This paper contributes to efforts towards NZWB design, with the ultimate aim to develop buildings that are more resilient towards changes in rainfall patterns due to climate change. It has the following objectives: i) review the state-of-the-art in NZWB, ii) develop and initial simulation-based water performance assessment method that allows to quantify water use and to identify which buildings qualify as NZWB, iii) explore strategies to turn existing as well as newly designed buildings into NZWBs.

Methodology

This paper builds upon a literature review of the state-of-the-art in Net-Zero Water Buildings, which is used to underpin the development of a conceptual framework for the qualification of buildings as NZWB. The framework is demonstrated though application to a simple residential case in Ankara, Turkey.

NZWB: State-of-the-Art

There is a small emergent body of literature on NZWB. In the USA, the ANSI/ASHRAE/USGB/IES Standard 189.1 [3] on the design of high-performance green buildings gives some generic guidance on making buildings water efficient, but does not include the net-zero concept. In the UK, CIBSE Guide G [4] provides details about the design of water supply and plumbing systems, but again does not address net-zero buildings. The US Department of Energy has published a handbook that provides general guidelines for the development of Net-Zero Energy, water and waste buildings. This discusses system boundaries in some detail and provides a general sequence of development stages, but no calculation formulas [5]. A comprehensive academic overview of NZWBs is provided by Joustra and Yeh (2015) [6] [7]. Further publications typically relate to specific aspects of the water balance, such as: rainwater harvesting [8], flow in drainage systems [9] or general water resource management [10]. Another body of work addresses water use at the urban scale, see for instance Rathnayaka et al. (2017) [11]. Empirical studies are also reported, see for instance Costa Proença and Ghisi (2010) [12]. However, most quantification efforts are deterministic, and unsuitable for the propagation of uncertainties in both supply and demand. Joustra and Yeh, 2015 [6] explore the application of the net-zero and net-positive concept to the building water cycle; they claim that each building water cycle is unique and that this limits the development of a generic net-zero water strategy.

Water is used in or near buildings for drinking, hygiene, cooking, cleaning, sanitation, irrigation, safety, recreation and aesthetics, and for various machines and processes [6]. Water use can be studied at different scales: that of individual buildings, clusters or districts, and the regional level [13]. Water use in cities is sometimes named 'water footprint' and is measured in litres used per person (capita) per day; footprints range from as low as 20 ℓ/pd in poor countries to as high as 650 ℓ/pd in the USA [13].

Findings on the benefits of 'green' water systems vary. Ghimire et al. (2017) [14] have conducted life cycle analysis and report that rainwater harvesting outperforms municipal supply systems; yet Hasik et al. (2017) [15] claim that water-efficient buildings perform better than net-zero water buildings. Yan et al. (2018) [16] conclude that water from a point-of-use treatment system performs worse in terms of Life Cycle Analysis (LCA) than water from a centralized treatment plant. Stephan and Stephan (2017) [17] note that wastewater treatment requires subsidies to be financially competitive.

Rainwater harvesting is one solution to coping with water scarcity. However, rainwater harvesting still faces environmental, political, economic, societal and technical challenges. For instance, Lee et al. (2016) [18] discuss these issues in the context of Malaysia. A study on the wash-off from road surfaces is presented by Andrés-Doménech et al. (2018) [19], with the recommendation to install off-line water retention systems in SUDS in order to improve the quality of discharge water.

Some demographic variables that are known to have an impact on water end use are household size, presence of children, efficiency of appliances, and more in general the dwelling type [11]. Water management in buildings often lacks an integrated approach; while there is attention to use alternative sources such as rainwater or to reuse wastewater there is no systematic approach. Joustra and Yeh (2015) [7] present an Integrated Building Water Management (IBWM) framework that tries to address this issue. For water management, comparison with the water use of peer households may help to incentivize water saving behaviour by occupants [20]. Challenges to the use of rainwater harvesting systems may be economic and legislative. Furthermore, there is a lack of empirical data on system operation, and on the relation between water quality and system maintenance [8].

Looking at water in a different way, cities and the buildings therein also need to consider an increased risk of flooding. In this context, urban flood resilience can be defined as "*the ability of an urban system exposed to a flood hazard to resist, absorb, accommodate, adapt to, transform and recover from the effects of flooding in a* *timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions*" [21].

Water systems

Water sources include potable water, reclaimed water, rainwater, storm water, condensate, greywater and blackwater [6]. The main components of a water distribution system are reservoirs, pipes, pumps, tank and junctions [22]. Rainwater harvesting systems typically consist of collection surfaces, gutters and downpipes, a tank, and a water distribution system; mostly it also includes pumps, debris screens and filters [8]. Water use can be reduced by flow limiters, which may be incorporated in different appliances. Benefits of such reduction are both environmental and financial [23]. Sustainable Urban Drainage System (SUDS) may include water retention ponds which store water and dampen the effect of floods [24]. These ponds harvest water for later use. SUDS reduce the runoff peak flow from rainfall, using a combination of water retention, transport and infiltration mechanisms [25]. Emerging concepts such as smart networks and the Internet of Things (IoT) may also be applied to the water network and help to monitor the network status, manage risk, forecast demand and supply, and handle incidents [26].

Important parameters for the evaluation of a rainwater harvesting system are the catchment area, collection efficiency, and tank volume. Further factors include rainfall and water demand. Evaluation often is measured in terms of Rainwater Use Efficiency (RUE), Water Saving Efficiency (WSE) and Cycle Number (CN). Often it is useful to consider V/A, in other words the ratio of tank volume to catchment area [27]. For rainwater harvesting systems, typically rooftop area is defined by building size, and demand depends on use; a key variable for decision makers is tank size [28]. Water storage in 'green' systems may lead to higher water age in building systems, which in turn may have consequences for water quality and human health [29].

A study into the water savings, water supply reliability and potential cost savings of fitting rainwater collection tanks in the Greater Sydney area is the work by Rahman et al. (2012) [30]. It is noted that the evaluation of economic benefits is strongly dependent on incentives such as rebates offered by the authorities. Costa Proença and Ghisi (2010) [12] have explored the water end-use of offices in Brazil, comparing and contrasting the findings from interviews with building occupants with metered monthly water use data.

Net-Zero Water Buildings (NZWB)

A common definition of net zero water, by Joustra and Yeh (2015) [6] citing US Army, is: "*facilities that maintain the same quantity and quality of natural water resources, such as groundwater and surface water, by decreasing consumption and directing water to the same watershed*" [6]. Net-zero water status may be achieved by using low-flow water fixtures as we all a decentralized (local to the building) water treatment and reuse system [15].

Self-sufficiency of water supply may be available in households of countries with enough rainfall like the Netherlands. Typical measures required include rainwater harvesting, minimization of water demand, cascading, and multisource. However, to achieve self-sufficiency one needs to overcome temporal, spatial and location-bound constraints [31].

Water Use, Flows and Discharge Modelling

The basic water mass balance for buildings or urban areas is presented by Joustra and Yeh (2015) [6] as:

$$\Delta S = I + C + D + P - (W + R + G + ET) \tag{1}$$

where:
ΔS = change is stored water in a system
I = inflow from adjacent systems
C = centralized flows into the system
D = decentralized flows into the system
P = precipitation
W = wastewater discharge
R = stormwater runoff
G = infiltration to groundwater
ET = evapotranspiration

Kenway et al. (2011) [32] show how this balance can also be applied at the city scale. Based on Mun and Han (2012) [27] the water balance for rainwater harvesting systems can be written as:

$$V_{tk} = \sum (Q_{i,t} - Q_{o,t} - Q_{s,t}) \tag{2}$$

where
V_{tk} = tank volume (m^3)
$Q_{i,t}$ = runoff from the roof (m^3/day)
$Q_{o,t}$ = overflow for the tank (m^3/day)
$Q_{s,t}$ = rainwater supply (m^3/day)
t = elapsed time (days)

Water System Efficiency, ET, can be defined as the amount of water conserved in relation to total water demand; in formula $ET = 100 \times (V/D)$ where V is volume of water conserved (m^3) and D is total water demand [33].

The classical method for predicting water use in buildings is based on "Hunter's curve", a method dating back to 1940 which estimates the 99th percentile of water use in public buildings on the basis of the number of fixtures in a building (n), probability that the fixture is busy (p), and the flow rate of a busy fixture (q). A more recent method is the Wistort method from 1994, which proposed a direct analytic method to estimate peak loads. Further work is ongoing to develop a CDF plot that relates peak flow to probability [34].

Moving to modelling and simulation, a model to generate stochastic domestic end-use water demands is SIMDEUM (SIMulation of water Demand; an End-Use Model); this has also been shown to apply to non-domestic cases. SIMDEUM correlates functional rooms, end use, user's frequency of use, pulse intensity, pulse duration, diurnal pattern and time of water use [35]. A simple method to predict water runoff from rainfall is the Soil Conservation Service Curve Number (SCS-CN) curve; this is an empirical relationship that relates rainfall, soil water retention, and rainfall intercepted before runoff [36]. An advanced model for the prediction of urban residential water end-use demands is presented by Rathnayaka et al. (2017) [11]. Their model considers various spatial scales, from household to building development to suburb or district. In terms of temporal scales, they differentiate between hourly, daily, weekly, seasonal and yearly profiles. EPANET is a German commercial tool for the simulation of water distribution systems that computes water flows and hydraulic heads [22] (Hallmann and Suhl, 2016). Detailed modelling of partially filled pipes that contain both fluid flow and gas can be done on the basis of the finite difference method; Campbell (2012) [9] discusses the simulation of such pipes using the AIRNET program. Sahin et al. (2016) [10] note that water systems may be modelled using system dynamics, bayesian networks, coupled component models, agent-based models and knowledge-based models. For an analysis of the impact of water governance decisions they explore system dynamics and agent-based models. Alfredsen and Sæther (2000) [37] present water resource modelling in terms of flood calculations in river systems, which may incorporate reservoirs and water transfer structures. Sulis and Sechi (2013) [38] provide an overview and comparison of regional scale model that can represent a multi-reservoir water use system, discussing AQUATOOL, MODSIM, RIBASIM, WARGI-SIM and WEAP. WEAP21 models' water at the watershed level. UWOT, the Urban Water Optioneering Tool, focuses on the urban environment [7]. Another water management tool is MB or Mike Basin [24]. AQUATOOL is a decision support system that is widely used by river basin authorities. It contains, amongst others, a module to model rainfall runoff in complex river basins and a module to simulate water supply/resources [39].

Rain run-off simulations may be used on GIS data, describing the terrain, buildings, catchment properties and sewer network. Simulation also requires the definition of a design storm that describes the amount of rain and the rainfall intensity over time. A tool that can capture how Sustainable Urban Drainage Systems (SuDS) deal with rainwater is Storm Water Management Model (SWMM) [25].

SWMM is a tool developed by the US Environmental Protection Agency (EPA). SWMM allows the dynamic simulation of rainfall runoff from surfaces in urban and suburban areas. Palla et al. (2017) [40] present a case study where SWMM is used to analysis system performance of a domestic urban block in Genoa, Italy. Stave (2003) [41] presents the first-principle development of a water conservation management systems dynamics model for Las Vegas, USA. Xi and Poh (2013) [42] use system dynamics to model water management in the city state of Singapore.

Rainfall data may consist of historical observations or could also be synthetic; one way of creating artificial rainfall data is by means of Markov chain models [28]. The adequacy of short-term (1 or 2 years) and long-term (10–30 years) rainfall time series for the assessment of using rainwater to supply potable water in homes is discussed Ghisi et al. (2012) [43]. Various water usage scenarios can be generated using Monte Carlo simulation [28].

One way to express how rainwater harvesting systems are meeting the demand by building occupants is through the Deficit Rate or DR – the amount of water that needs to be bought when the system is unable to provide the water that is needed [28]. Crawford and Pullen (2011) [44] categorize embodied water analysis methods as process analysis, input-output (I-O) analysis, and hybrid analysis. Park et al. (2018) [45] model the rain flow on facades in order to predict the collection of dirt caused by runoff and to assess aesthetic impact using a CFD tool named RealFlow. STUMP, Stormwater Treatment Unit model for MicroPollutants, is a dynamic model that describes the movement of MicroPollutants in both the particulate and dissolved phases [46]. SGMP, Standard Groundwater Model Package, is a tool that allows to analyse the impact of water management measures on groundwater levels using partial-differential equations [47]. Another tool that allows to model groundwater and surface water is HydroGeoSphere [48]. Zeng et al. (2016) [49] demonstrate the modelling of a wetland ecosystem, which predicts system discharge and allows allocation to human activities while considering wetland pollution and ecological effects. The underlying model is based on linear programming. Leenhardt et al. (2012) [50] present case studies that explore how scientist and stakeholders can use water-resource models to make informed water management decisions.

Like all construction objects, sewer and sanitation systems, treatment plants and similar can all be modelled using BIM technology [51]. Calculations of risks in drinking water supply may require advanced approaches such as Dynamic Fault Tree (DTF) analysis combined with Markov chain and Mote Carlo simulations; see for instance Lindhe et al. (2012) [52]. A theoretical discussion of urban wastewater system reliability, risk and resilience is provided by Sweetapple et al. (2018) [53].

Water measurement and monitoring

Monitoring of hot water consumption, measured at a time step of 1 minute for 119 homes in Canada, is reported by George et al. (2015) [54]. De Gois et al. (2015) [55] evaluate the water use of a mall in Brazil, combining both on-site observation and monitoring with calculation of the daily water consumption. Marzouk and Othman (2017) [51] describe a bespoke program in C# which analyses flow meter readings from different sectors in a sewer system. Vezzaro et al. (2015) [46] present water quality analysis conducted across the catchment area of the Albertslund municipality in Denmark, which is fed into a simulation model to study the efficiency of a range of control strategies. Blokker et al. (2011) [35] report on the validation of a water end use prediction model using measurements from an office building, a hotel and a nursing home. Ward et al. (2012) [33] describe the empirical assessment of a university building with a large rainwater harvesting system in the UK; their paper provides an overview of further studies in other countries across the world. An empirical study of sediment retention in SUDS is presented by Allen et al. (2018) [56]. Empirical studies using scale models of urban surfaces combined with artificial rain are reported by Liu et al. (2018) [36]. Water use is sometimes reported as one of the parameters in more wide-ranging monitoring efforts on buildings that report energy use; see for instance Gill et al. (2011) [57] who report on the monitoring of affordable houses in the UK.

Yet detailed measurement of water end-use is not always feasible; main water meters do not differentiate between specific fixtures and allowing water meters at a higher resolution level might impair use of the water system [12]. Vieira et al. (2018) [20] discuss a case study that comprised 43 households, where 100 participants kept water diaries and household water consumption was metered on a weekly basis. The paper by Rathnayaka et al. (2017) [11] provides an overview of some water measurement data available from different surveys done by third parties.

Energy consumption of rainwater harvesting systems is reviewed by Vieira et al. (2014) [58]; they report that theoretical studies typically report around 0.20 kWh/m^3 whereas empirical data, which also captures pump start-up energy and stand-by modes, is in the order of 140 kWh/m^3.

Assessment framework for the qualification of buildings as NZWB

Theoretically, qualification of a building as net Zero Water Building can be determined by simple water mass balance equations. However, in practice it is necessary to understand the impact of the relation between water storage and usage by analysing the water balance over time, and under uncertainties. The assessment framework thus requires three elements: i) Urban scale balance: the basic water mass balance for urban areas. This comes from the equation of Joustra and Yeh (2015a) [6] in which the possible water storage can be presented, ii) Building scale balance: within the urban context, a similar water mass balance is used for individual buildings. Building scale parameters vary depending on the design, function and occupant schedule of the building, iii) Monte Carlo Simulation: The data for the site (building scale) is processed in Monte Carlo Simulation to analyse the effect of rainfall variation on the water mass balance.

Achieving the status of net Zero Water Building introduces a specific criterion which needs to be considered during design: averaged out over a year, the water entering the building system boundary from other sources than the utility supply needs to equal the use. The resulting framework is depicted in **Figure 1**. Implementation of the water mass balance is in a spreadsheet application that enables easy MC simulation efforts.

Application to a case study building

In order to develop these ideas, the framework is applied to a residential case study building. This building is an existing house located in an arid climate, Ankara, Turkey. It was constructed late 1990's. The house is a typical single-family house of 250 m² with 4 floors including basement and attic. There are 4 occupants (2 adults and 2 children). The annual measured water consumption of the house is ≈156 m³. The water usage breakdown of the house based on occupants' notifica-

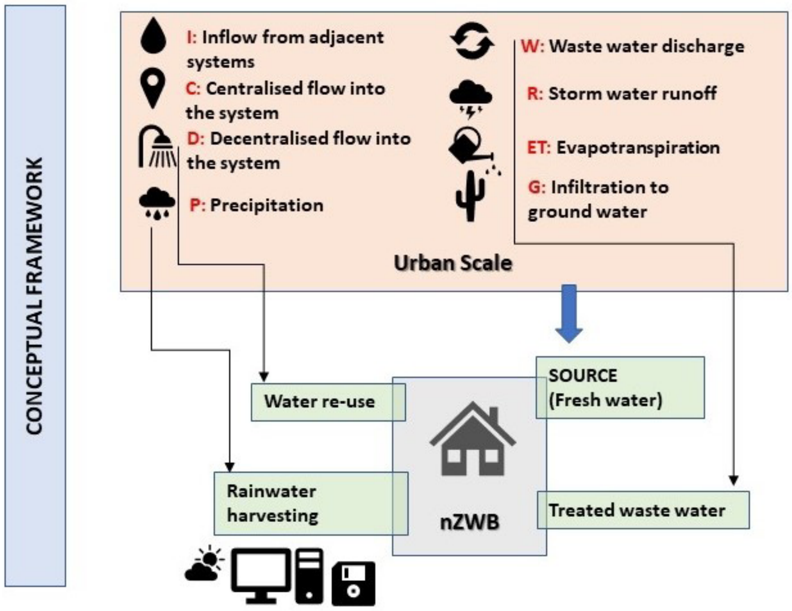

Figure 1. Conceptual nZWB analysis framework.

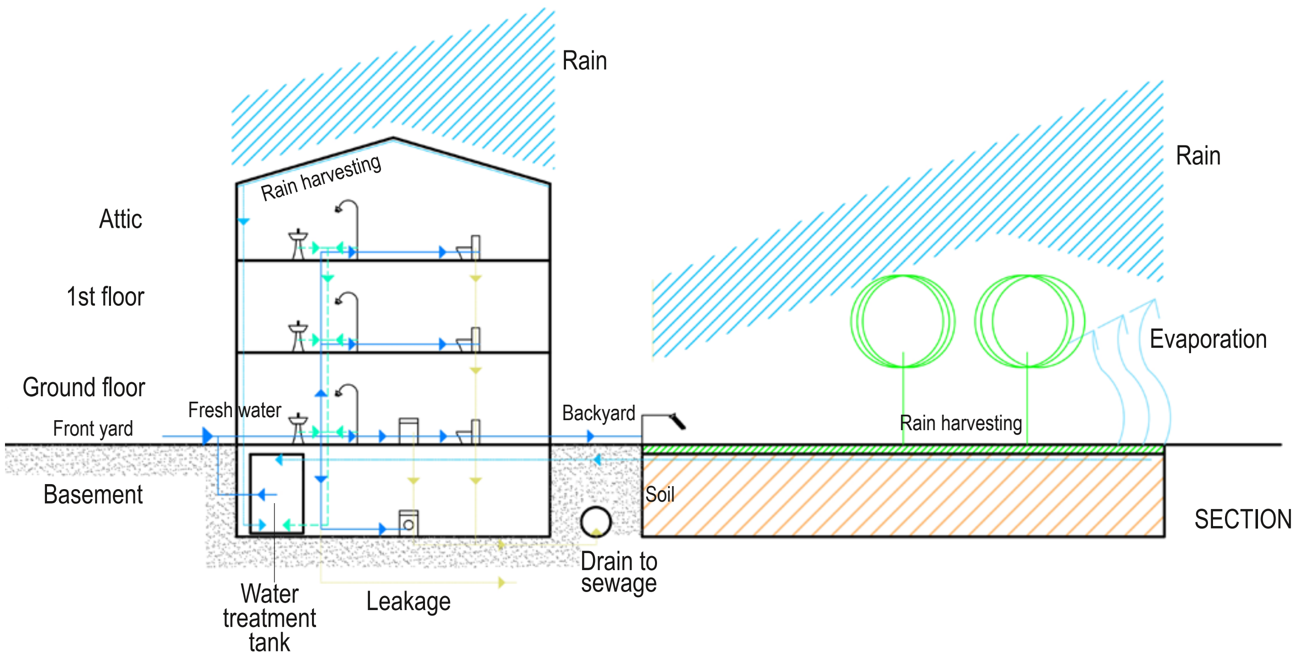

Figure 2. Typical domestic house.

tions is presented in **Figure 3**. Regarding the expression of the home-owners, shower, faucet and toilet usages are the highest percentages relatively.

In terms of rainwater availability, Ankara's annual precipitation value is 387 mm/year. The roof area of the house is 65 m². The slope of the roof has an impact on how much water is collected in the downpipes; for this case, an approximate loss of 25% has been assumed. The total amount of possible rain water harvesting from the roof is therefore: 65 × 387 × 0.75 = 18 866.25 litre /year. The garden area is 100 m². 50% of rainwater leaks into the soil. The rest can be harvested. The total amount of possible rain water harvesting from garden is: 100 × 387 × 0.5 = 19 350 litre/year.

Analysis of treated grey-water and rainwater harvesting is more complex. The treated greywater can only be captured for recycling from the faucet and shower. The treated amount of greywater will be 75% of the total. In other words, 75% of total 26% shower water use + 22% faucet water use can be listed as the treated water recycle. Thus (26 + 22) × 0.75 = 36% greywater recycled.

For this example, possible potential of water recycle rates of each item are shown in the Sankey diagram in **Figure 4**. Inputs and outputs for the Sankey diagram is derived from actual water meter readings of the residence plus data gathered of the occupants depending on their daily life usage patterns plus estimated calculations of rain harvesting potentials stated earlier in the paper. Actual water meter readings back to a full year and is broke down related to occupant usage patterns. Annual water usage of 156 m³ as taken fresh water from the grid and remarked in the diagram as water (100%).

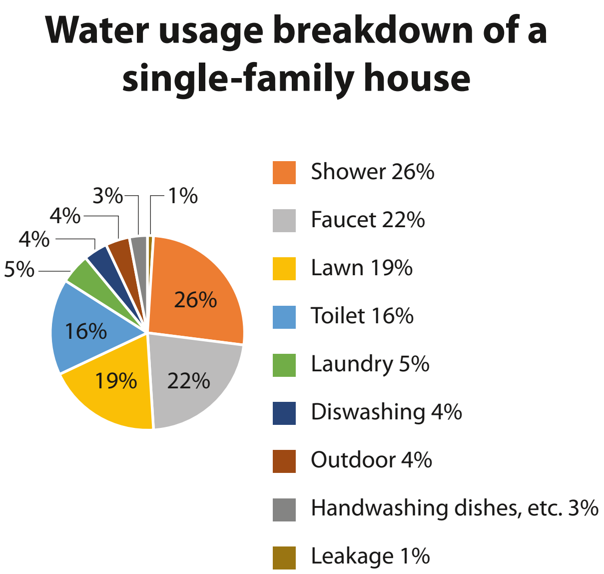

Figure 3. Typical water uses in a single-family home.

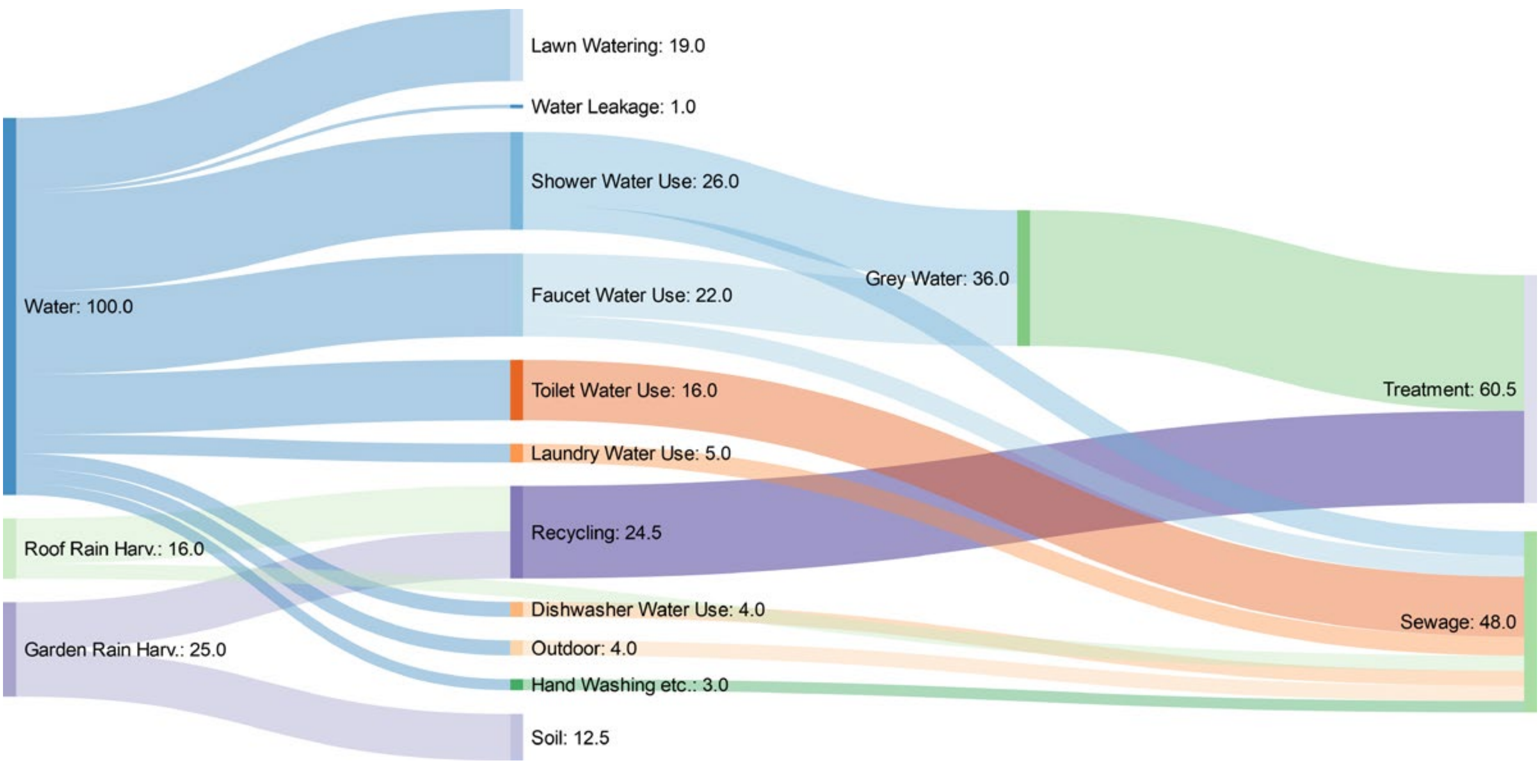

Figure 4. Sankey diagram of domestic water flows.

Roof and garden rain harvesting values (16% and 25% respectively proportional to fresh water) are based on estimated calculations. The diagram also figures out possible grey water usage potentials with other recycling options with their possible percentages.

Attempts by the authors to expand this deterministic quantification to full Monte Carlo simulation are ongoing. However, there are various challenges. An initial and unexpected one is that many of the building simulation weather files provided by sources such as the Energy-Plus weather data for Ankara seem to have missing or erroneous rainfall data. However, even without actual Monte Carlo simulations the simple example already shows that in order to design for NZWB:

- Water storage is crucial:
  Simple annual numbers do not cover the detailed matching of supply and demand. Dynamic, hourly analysis is required to analyse whether a building is actually nZWB throughout the year. This requires a new type of building water simulation not presently available.

- Work on the harvesting side:
  To create NZWB there is a need to design new and better roofs to collect water, and to find innovative ways of collecting rainfall that would not hit the roof but is near enough, collecting water from facades, outbuildings, pavements are the key concepts of harvesting.

- Redesign internal water flows:
  Further work needs to review and redirect internal water flows, taking into account the degradation from drinking water to grey water to black water.

- Water cleaning possibilities:
  Local building-integrated water micro cleaning plants are needed to restore water to a higher quality.

- Water use reduction:
  Efforts are also needed to find further ways to reduce water use, by using efficient appliances, timing, occupant training, right-sizing tanks and reservoirs, reducing pipe length.

Discussion and conclusion

This paper reports on efforts towards NZWB design and its quantification, with the intention to develop buildings that are more resilient towards changes in rainfall patterns due to climate change. It reviews the state-of-the-art in NZWB, noting that most definitions of the concept are aspirational rather than based on well-defined engineering calculation. The paper then develops a conceptual framework that allows to quantify water use and to identify which buildings qualify as NZWB. The proposed assessment framework includes not only urban scale but also building scale approach to water use balance and possible evaluation strategies depending on Monte Carlo analysis. Future work will include an initial simulation-based water performance assessment method and a monitoring campaign that can be used to validate quantification efforts.

The most critical discussion on the subject is the limitations imposed by weather conditions and roof size. NZWB may not be feasible everywhere and the benchmarks of feasibility should be determined by quantitative methods. There are also specific problems as the lack of an option to put water back into the grid, as one can do with energy. The relation between urban scale and building scale water balance is critical at that point. Future work needs to consider these circumstances while performing measurement and monitoring campaign. ■

References are included in the web version of this article rehva.eu/rehva-journal