A multi-scale life cycle water analysis framework for residential buildings

André Stephan[a,b,1], Robert H. Crawford[b]

[a]Building, Architecture and Town Planning, Université Libre de Bruxelles (ULB), 50 Av.F.-D. Roosevelt, Brussels 1050, Belgium
[b]Faculty of Architecture, Building and Planning, The University of Melbourne, Victoria 3010, Australia

[1]Corresponding Author: André Stephan
Tel: +32 485 443 248
Fax: +32 2 650 27 89

Current address:

Faculty of Architecture, Building and Planning
The University of Melbourne
Victoria 3010,
Australia

Permanent address:

Building, Architecture and Town Planning
Université Libre de Bruxelles (ULB)
50 Av.F.-D. Roosevelt,
Brussels 1050
Belgium
e-mail: andre.stephan@ulb.ac.be

Abstract

Most existing studies related to the environmental performance of buildings focus on energy demand and associated greenhouse gas emissions. They often neglect to consider the range of other resource demands and environmental impacts associate with buildings, including water. Studies assessing water use in buildings typically consider the operational water alone, excluding the embodied water in building materials or the water associated with the mobility of building occupants.

This paper presents a framework which quantifies water requirements at the building scale, i.e. the embodied and operational water of the building as well as its maintenance and refurbishment, and at the city scale, i.e. the embodied water of nearby infrastructures (such as roads, gas distribution and others) and the transport-related indirect water use of building occupants.

Results from a case study house located in Melbourne, Australia, show that each of the embodied, operational and transport requirements are nearly equally important. By integrating these three water requirements, the developed framework provides architects, building designers, planners and

decision makers with a powerful tool to effectively reduce the overall water use and associated environmental impacts of residential buildings.

Keywords: Life cycle water analysis; Residential buildings; Embodied water; Operational water; Transport water; Hybrid analysis

1 Introduction

1.1 On the importance of water

Water is one of our most important resources since it is necessary for all life. Yet, water is becoming scarce in some regions of the world due to urbanisation and reduced access (Bourne and Wouters, 1997). Moreover, an increasing number of regions are expected to be subject to more frequent droughts in the coming decades (IPCC, 2007). This climatic deregulation will increase water stress (Parish et al., 2012). The regions at risk include parts of Africa, eastern Australia, southern Europe and other densely inhabited areas around the world (Dai, 2011). For all these reasons, water is and will increasingly become a critical aspect to consider regarding the environmental sustainability of our societies.

In order to measure water use, accounting tools such as the so-called ‘water footprint’ (Water Footprint Network, 2013) are needed. The water footprint of a product or service represents the total amount of water required to manufacture or provide this product or service, respectively. In the last decade, the water footprints of a wide range of consumer goods and food products have been determined (e.g. a pair of jeans (Chico et al., 2013) or meat products (Gerbens-Leenes et al., 2013)). Yet, the total water use associated with buildings has rarely been assessed.

1.2 Water use and buildings

While a significant body of knowledge exists on how energy is used within buildings, very few studies have considered their water use. Indeed, energy has been the major focus of building environmental improvement efforts for many decades. The implementation of particular regulations for building energy efficiency such as the Energy Performance of Building Directive (EPBD) in Europe (European Parliament and the Council of the European Union, 2002) or the development of facultative certifications such as the Passive House standard (Contributors of passipedia.passiv.de, 2013) are testimony of this. Numerous studies have been performed with the aim of reducing energy use within buildings. More recently life cycle assessment (LCA) and life cycle energy analysis (LCEA) are being used to measure the total environmental and energy use over a building's useful life, respectively. For example, Gustavsson and Joelsson (2010) have quantified the total energy use of different low-energy buildings in Sweden. Also, Blom *et al.* (2011) have investigated the effect of energy use in a Dutch residential building on multiple environmental impact categories such as human toxicity, acidification and others. Despite many quite comprehensive studies, the water used across a buildings life cycle is rarely considered.

However, water is not completely neglected in current studies and practice. For instance, major building environmental assessment tools such the United States Leadership in Energy and Environmental Design (LEED) and the United Kingdom's Building Research Establishment Environmental Assessment Method (BREEAM) include water as one of their environmental parameters. The contribution of water towards the total score for a building's environmental performance is 6% and 9% for LEED and BREEAM, respectively. Yet, these tools provide only a qualitative assessment rather than quantifying total water requirements.

Other studies focus on particular water-related systems such as rainwater collection tanks (Eroksuz and Rahman, 2010; Santos and Taveira-Pinto, 2013; Villarreal and Dixon, 2005; Ward et al., 2012) or the efficiency of water delivery fixtures and plumbing (Arpke and Hutzler, 2005). Very few studies consider the total water requirements at a whole-building level, including the water embodied in materials and the water used by building occupants.

Crawford and Pullen (2011) have conducted the most comprehensive study to date regarding life cycle water use in a residential building. In their study, they take into account the water demand associated with manufacturing building materials (embodied water), direct water use inside the building (operational water), water use for the transportation of building occupants (transport water) and also water use associated with consumer goods, food, travel and other expenditures. While the scope of their study is not limited to buildings, they show that each of the embodied, operational and transport water requirements is significant.

The significance of the embodied water in building materials is further reinforced by the findings of McCormack *et al.* (2007). In their work, they assess the embodied water of 17 non-residential buildings and find that it represents on average 20.1 kL/m². This equates to the average water use over a four and a half month period for a person living in Melbourne, Australia, based on an average daily water use of 149 L/capita (Melbourne Water, 2012).

As it has been shown that each of the embodied, operational and transport water requirements associated with buildings are significant, it is critical that a single framework that comprehensively assesses all water requirements associated with residential buildings is developed. This should ensure that demand is not shifted between uses and that a net reduction in water use across the useful life of a building can occur. A similar framework, that measures energy use at both the building and city scales has been developed by Stephan *et al.* (2012). This work expands the existing energy to consider the often neglected and arguably more important water demands.

1.3 Aim and scope

The aim of this paper is to describe a framework that quantifies the embodied, operational and transport water demands associated with a residential building over its life cycle. By integrating the three water demands in a single model, the resulting framework can be used to inform decision making regarding the efficient use of water in residential buildings at both the building and city scales.

This paper first presents the developed framework and provides the equations necessary for the quantification of each water demand. The framework is then applied to a case study building in Melbourne, Australia (see Section 3) to demonstrate its application. The case study results and the framework are discussed in Section 4.

2 Quantifying the life cycle water demand of residential buildings

2.1 System boundary

In order to determine the total water demand of a residential building, a life cycle approach is needed and should be applied at the different scales of the built environment. The developed framework includes water requirements for: raw material extraction, material processing, transport and manufacture, construction, operation and maintenance and occupant transport. These life cycle stages are considered for both the building and city scales.

Fig. 1 depicts the system boundary of the developed framework and provides explanations for each scale considered. The end of life stage of the life cycle is not taken into account because of the high uncertainty regarding the fate of the building at the end of its useful life. Indeed, since buildings can have very long useful lives, sometimes exceeding 100 years, the ultimate fate of materials is hard to predict. Yet, while Winistorfer *et al.* (2007) have demonstrated that the energy associated with the end of life stage is negligible, further research is required to estimate the potential water use associated with demolishing a building and recycling or reusing its materials.

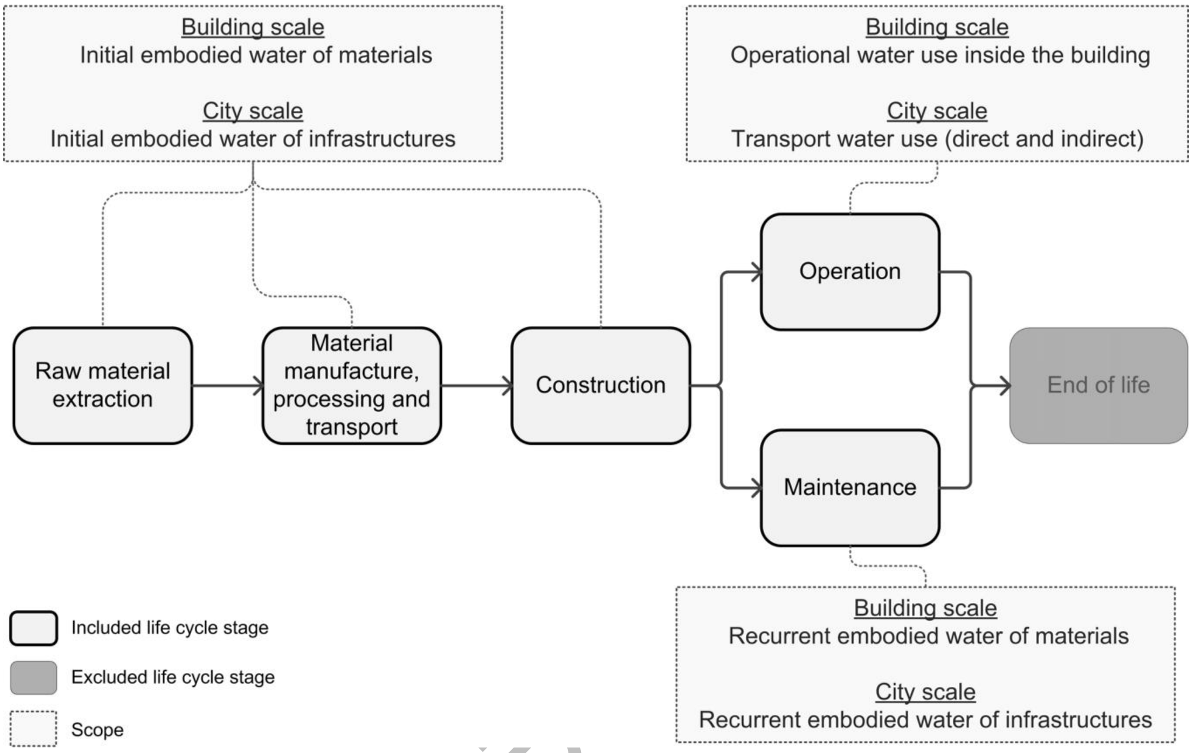

Fig. 1: System boundary of the multi-scale life cycle water analysis framework

2.2 Embodied water demand

Water is required to produce building materials, either directly such as in the aluminium manufacturing process or indirectly such as water used in the administrative buildings managing the production process. The total amount of water required to produce a building material, across its supply chain, is known as embodied water. At a whole building level, embodied water can be divided into two main components: initial embodied water and recurrent embodied water. The initial embodied water represents the sum of the embodied water content of all materials included in the building at its first use. Recurrent embodied water represents the amount of water necessary to produce and replace materials across the useful life of the building. Both initial and recurrent embodied water demands for buildings are significant as shown by Crawford and Pullen (2011).

Three main techniques can be used to quantify embodied water requirements across a supply chain: process analysis, input-output analysis and hybrid analysis. These are the same techniques used to quantify embodied energy or other types of inventories. For this reason, they are referred to as life cycle inventory techniques in LCA terminology (International Standard 14040, 2006). Process analysis is a bottom-up technique that quantifies the inputs and outputs for known processes of the supply chain of a product or service. These can then be studied to determine the environmental impact of each stage of the supply chain. Input-output analysis is a top-down macroeconomic technique that relies on monetary transactions and the associated environmental flows to calculate the total environmental impact of a product or service. However, process and input-output analysis suffer from various flaws. Process analysis tends to truncate the system boundary of a product, leaving out sometimes crucial processes. This can lead to an underestimation of the total environmental impact of a product. Input-output analysis provides only aggregated environmental loadings by economic sector. Therefore it produces an average figure which depends on the level of disaggregation of the input-output matrices representing the economy. This aggregation error which leads to high uncertainty levels can counter-balance the benefit of the very wide system boundaries that input-output analysis provides.

Studies by Suh *et al.* (2004), Crawford (2011), Crawford and Stephan (2013) and Dixit *et al.* (2013) have demonstrated that hybrid analysis produces the most comprehensive and reliable results. By combining process and input-output data it covers the complete system boundary and maximises reliability by using process data where available. Hence, hybrid analysis is considered to be superior to the other two life cycle inventory techniques.

The life cycle water analysis framework relies on the input-output-based hybrid analysis technique developed by Treloar (1997) and adapted to water use (instead of energy). To facilitate the use of this technique, Treloar and Crawford (2010) have compiled a database of hybrid water coefficients for building materials in Australia. This database constitutes the basis of embodied water calculations in this framework.

The initial embodied water of the building is determined as per Eq. (1) by multiplying the quantity of materials in the building by their respective hybrid embodied water coefficient. The result represents the water requirements associated with the materials used within a building and is complemented by a so-called ‘input-output remainder’ that covers the non-material water inputs (e.g. water requirements associated with the provision of insurance, advertising and administration).

$$IEW_b = \sum_{m=1}^{M} \left(Q_m \times EW_m \right) + \left(TWR_n - \sum_{m=1}^{M} TWR_m \right) \times P_b \quad (1)$$

Where: IEW_b = Initial embodied water of the building in kL; Q_m = Quantity of material *m* in functional unit (e.g. ton, m³); EW_m = Hybrid embodied water coefficient of material *m* in kL per functional unit; TWR_n = Total water requirement of the building construction-related input-output sector *n,* in kL/currency unit; TWR_m = Total water requirements of the input-output pathways representing the material production processes for which process data is available, in kL/currency unit and P_b = Price of the building in currency units.

Recurrent embodied water (see Eq. (2)) contains an additional factor to account for the number of replacements of each material over the useful life of the building. This number of replacements depends on the useful life of the material and is always an integer in this study (e.g. 4.6→4). The useful life of materials can depend on a range of different technological, construction and social aspects and are often difficult to predict (Conejos and Langston, 2010; Hovde and Moser, 2004; International Standard 15686-1, 2011). Average material service life figures obtained from the literature are used in this framework.

$$REW_b = \sum_{m=1}^{M}\left[\left(\frac{UL_b}{UL_m}-1\right)\times\left[\left(Q_m \times EW_m\right)+\left(TWR_n - TWR_m - TWR_{i\neq m}\right)\times P_m\right]\right] \quad (2)$$

Where REW_b = Recurrent embodied water of the building in kL; UL_b = Useful life of the building in years; UL_m = Useful life of the material *m* in years; $TWR_{i\neq m}$ = Total water requirements of all input-output pathways not associated with the installation or production process of material *m* being replaced, in kL per currency unit and P_m = Price of the material *m* in currency units. All other variables are the same as in Eq (1).

The life cycle embodied water demand ($LCEW_b$) of the building is obtained by simply adding the initial and recurrent embodied water demands as per Eq. (3).

$$LCEW_b = IEW_b + REW_b \quad (3)$$

This quantity represents the total embodied water requirements associated with the building itself but not with the infrastructure systems that are crucial for its functioning. Most residential buildings cannot be operated effectively if critical infrastructure systems are not available. These include but are not limited to: roads, water, gas and electricity distribution systems and sewage. In this framework, the embodied water associated with the construction and maintenance of these five infrastructure systems is taken into account (see Fig. 1, city scale). The calculation of the life cycle embodied water of infrastructure relies on equations similar to Eq. (1), (2) and (3). However, the input-output remainder associated with non-material inputs is not considered in this case since it requires computation beyond the scope of this work. The total life cycle embodied water of these infrastructures ($LCEW_{if}$) is calculated as per Eq. (4) based on the infrastructure density in one square kilometre around the studied building. This figure is then divided equally among all the residents in this same area based on the population density and allocated to the building according the number of occupants, as in Stephan *et al.* (2012).

$$LCEW_{if} = \sum_{i=1}^{I} \left(LCEW_i \times D_i \times \frac{NO}{PD} \right) \tag{4}$$

Where: $LCEW_{if}$ = Life cycle embodied water of infrastructures in kL; $LCEW_i$ = Life cycle embodied water of infrastructure i in kL/m; D_i = Density of infrastructure i in m/km²; NO = Number of occupants in the building and PD = Population density in inhabitants/km².

2.3 Operational water demand

The quantity of water used inside and outside (e.g. watering a garden) the building and throughout its useful life represents the operational water demand. This operational water demand depends on a large number of factors such as the number of occupants in the household, the efficiency of water fixtures and pipes, and other social aspects such as the age of occupants, their cultural background and their income. Water bills should preferably be used if the assessed building already exists. Operational water use can be calculated as per Eq. (5), if the average daily water use by fixture is known. Otherwise, an average aggregated water demand figure can be used to provide an estimation (see Eq. (6)). These average water use figures are often reported by local or regional bodies, e.g. Melbourne Water (2012) in Melbourne, Australia. If a rainwater collection system is installed, the share of operational water supplied by the rainwater tank (rain fraction (*RF)*) is deducted from the total operational water use to deduce the total mains water demand.

$$LCOPW_b = UL_b \times \sum_{f=1}^{F} \left[\left(1 - RF_f\right) \times \frac{WU_f}{1\,000} \times 365 \right] \tag{5}$$

$$LCOPW_b = UL_b \times (1 - RF) \times \frac{WU_O}{1\,000} \times NO \times 365 \tag{6}$$

Where: $LCOPW_b$ = Life cycle operational water demand of the building in kL; UL_b = Useful life of the building in years; RF_f = Rain fraction for fixture *f*; WU_f = Daily water use of fixture *f* in L; *RF* = Rain fraction for total operational water use; WU_O = Daily water use in L/capita and *NO* = Number of occupants in the building.

2.4 Transport water demand

The transport water requirements represent the indirect water demand that is necessary for the mobility of building occupants, throughout the useful life of the building. While energy requirements for transport are both direct and indirect (see Chester and Horvath (2009) and Jonson (2007)), water requirements for transport can be assumed to be solely indirect. Any direct water use in transport, associated with windscreen wipers, the use of water as a coolant and cleaning can be considered to be negligible when compared to indirect requirements. Based on figures from Crawford and Pullen (2011) the indirect water requirements associated with a car can be estimated at 165 kL/annum. Assuming a combined use of 8 L for windscreen wipers and radiator coolant every month and a car wash of 120 L every 2 weeks, the annual direct water demand would be 3.2 kL/annum or less than 2% of the indirect demand.

The indirect water requirements for transport can be calculated using input-output analysis, for each transport mode. The study by Lenzen (1999) demonstrates how to calculate the direct and indirect energy and greenhouse gas emissions intensities of private and public transport modes. Indirect energy requirements for a transport mode are determined by multiplying all associated annual expenditures of a public transport operator or a private household by the energy intensity of the relevant input-output sector. By dividing the resulting total energy demand by the number of vehicle-kilometres or passenger-kilometres, an energy intensity can be obtained (in MJ/vkm or MJ/pkm). The same approach can be used to determine indirect water requirements for each transport mode.

The life cycle transport water demand is calculated as per Eq. (7) by multiplying the annual travel distance for each transport mode by the relevant indirect water intensity (in kL/vkm), throughout the useful life of the building.

$$LCTW_b = UL_b \times \sum_{tm=1}^{TM} \left(TD_{tm} \times \frac{IWI_{tm}}{1\,000} \right) \tag{7}$$

Where: $LCTW_b$ = Life cycle transport water demand of occupants in the building b in kL; UL_b = Useful life of the building b in years; TD_{tm} = Total yearly travel distance of all occupants using the transport mode tm, in km and IWI_{tm} = Indirect water intensity of the travel mode tm in L/km.

All transport water requirements are allocated to residential buildings in this study. Yet, a part of these requirements should be allocated to non-residential buildings which also condition urban patterns and therefore travel distances and the associated transport water. However, the allocation of this transport water demand to other building types is extremely complex since it depends on a wide range of socio-economic and land-use factors such as the employment density, the ratio of residential to commercial and office buildings, the type of industry and the ratio of jobs to population. The determination of allocation factors falls well beyond the scope of this work.

2.5 Life cycle water demand

The life cycle water demand of a building is the sum of its embodied, operational and transport components. It is calculated as per Eq. (8).

$$LCW_b = LCEW_b + LCEW_{if} + LCOPW_b + LCTW_b \quad (8)$$

2.6 Uncertainty, variability and computation aspects

The developed framework relies on a range of databases for the calculation of embodied, operational and transport water demands. As in any quantitative analysis, the uncertainty present in the data and the variability of certain parameters can greatly influence the reliability and relevance of the results.

Uncertainty and variability are taken into account in this framework using interval analysis. Interval analysis is preferred to other techniques (such as Monte Carlo analysis) since it can be applied without detailed knowledge of the specific uncertainties of parameters. Indeed, since the framework relies on a range of different figures, the uncertainty for each parameter is extremely hard to estimate. An uncertainty range is therefore applied to each aggregated quantity in the framework as in Stephan *et al.* (2012). The level of aggregation differs between uses. For instance, uncertainty is calculated at the material level for embodied water while it is computed at the whole building level for operational water. This depends on the availability of uncertainty data for each use.

Computing the total life cycle water requirements of a building as defined in this framework is a highly demanding task involving hundreds of calculations. In order to simplify this task the software program previously developed by Stephan (2013) to calculate life cycle energy demand and the associated greenhouse gas emissions of residential buildings (see Stephan *et al.* (2012) and Stephan and Crawford (2013)) was further improved to incorporate water requirements. All details pertaining to the software tool can be found in Stephan (2013). This software tool automates all the calculations necessary to determine the total life cycle water demand of a residential building. The calculation steps include, but are not limited to: the bill of material quantities based on the geometrical input, the embodied water of the building and the related infrastructures based on input-output-hybrid analysis, the operational water demand based on the average water use per fixture per day, the life cycle transport water demand based on travel distances and indirect water intensities by mode and the total life cycle water demand.

3 Application of the framework to a case study house

The developed framework is used to determine the total water requirements of a case study house in Australia, illustrating the potential of the framework. The initial and recurrent embodied water of the house is determined using the database of energy and water coefficients for building materials developed by Treloar and Crawford (2010). The useful life of building materials used is based on NAHB (2007). Both the initial and recurrent embodied water of infrastructures is taken into account since the house is located in a new suburban area. The life cycle operational water demand is calculated as per Eq. (6) as no detailed fixture-level information is available. The transport water demand is calculated based on Crawford and Pullen (2011) and takes into account water requirements associated with car manufacture, maintenance and repair, insurance, registration fuel. The transport water intensity was calculated by multiplying the average household expenditure for each of the mentioned items (e.g. insurance) by the water intensity of the relevant input-output sector.

Two uncertainty ranges are used for embodied water, based on the source of figures in the database: ±20% for process data and ±50% for input-output data (see Crawford (2011)). Variability associated with operational and transport requirements is estimated at ±20%. The use of water bills for existing buildings can greatly reduce the variability associated with operational water.

3.1 Description of the case study

A single family detached house, located in the outer suburbs of Melbourne, Australia is used to test the framework. These low-density suburbs are often characterized by high car usage (BITRE, 2011). The house size is also typically larger than the national average, per capita. The house is well insulated and scores 7 stars (out of 10) under the Australian energy performance of buildings standard (Australian Building Codes Board, 2010). Table 1 summarises the main characteristics of the case study house.

Table 1: Case study characteristics

Characteristics	Australian 7-Star detached house
Period of analysis (years)	50
Building useful life (years)	50
Gross floor area (m²)	240
Number of occupants	4
Structure	Timber-framed
Façade	Brick veneer wall – 100 mm of fibreglass insulation - Double glazed aluminium framed windows
Roof	Concrete tiles – 200 mm of fibreglass insulation
Finishes	Medium finishes standing
Daily operational water use (L/capita)	149[a]
Cars	2 gasoline[b]
Total car travel distance per year (km)	36 000[b]
Total water intensity of cars (L/vkm)	9.14[c]

Note: [a] based on Melbourne Water (2012), [b] based on BITRE (2011), [c] based on results from Crawford and Pullen (2011).

3.2 Case study results

Fig. 2 shows the breakdown of the life cycle water demand of the case study house, by use. While the software tool can generate a much more detailed breakdown, only an aggregated one is provided in this study. The total life cycle water demand associated with the house over 50 years is 34 753 kL (144 kL/m²) or 8 688 kL/capita. This amount of water is enough to fill the volume of the house 48 times over and represents the drinking water of nearly 400 persons over 80 years (considering that an average person drinks 3 L of water per day). The total life cycle water requirements are divided into embodied (39.1%), operational (31.3%) and transport (29.6%) requirements. This breakdown shows that each of the uses considered represents a significant share of the total and none of them should be excluded.

Embodied water represents the highest contribution towards the total water requirements associated with the house. The initial embodied water (including infrastructure requirements) represents 8 751 kL (64.4%) while recurrent embodied water represents 4 842 kL (35.6%). The specific initial embodied water figure for the house (excluding infrastructure requirements) is 31.5 kL/m² of gross floor area. These results are similar to the figures obtained by Crawford and Pullen (Crawford and Pullen, 2011): 31.3 kL/m² for the initial embodied water and contributions of 65.2% and 34.8% for the initial and recurrent embodied water, respectively. The five materials contributing most to the total embodied water demand are concrete (1 330 kL), plasterboard (1 130 kL), glass (1 075 kL), paint (1 010 kL) and steel (930 kL). While paint has a low embodied water content, its frequent replacement over 50 years leads to a high life cycle embodied water (higher than steel). This shows the importance of the durability of materials in terms of water use but also reveals the sensitivity of the calculations to the average service life of the material. Since this service life can vary significantly depending on various factors, the associated recurrent embodied water figures may also fluctuate across a wide range. Also, the embodied water associated with infrastructures represents 1 472 kL or 10.8% of the total embodied water. This demonstrates the need to take the nearby infrastructures into account when assessing the environmental impact of a building, especially if these infrastructures are recently built.

Operational water represents 10 877 kL (2 719 kL/capita, 45.32 kL/m², 31.3%) over 50 years. Operational water demand can be reduced by using water efficient fixtures such as dual flush toilets, water efficient taps and recovering and reusing the so-called 'grey water' for flushing or gardening. Water efficient fixtures should promoted in order to encourage their use in buildings. Policies such as the "water efficiency labelling and standards (WELS)" in Australia, enforce the labelling of all water fixtures (Department of the Environment, 2013). While schemes such as WELS do not consider embodied water requirements, they can still contribute to reducing operational water use by promoting water efficient fixtures. Also, the installation of a rainwater collection system can reduce the total mains operational water demand. One of the advantages of the developed framework is that the embodied water associated with a rainwater collection system and all water fixtures is taken into account, revealing the net amount of water saved across the life cycle of the building with the use of such systems.

Transport water represents 10 282 kL (2 571 kL/capita, 29.6%) over 50 years. This significant contribution is due to the long distances travelled by the occupants of the house since the highest contribution to transport water is the production of fuel (47%) (Crawford and Pullen, 2011). The use of public transport systems might result in a lower indirect water demand. Further research is needed in this area as indirect water intensities for public transport modes are unknown.

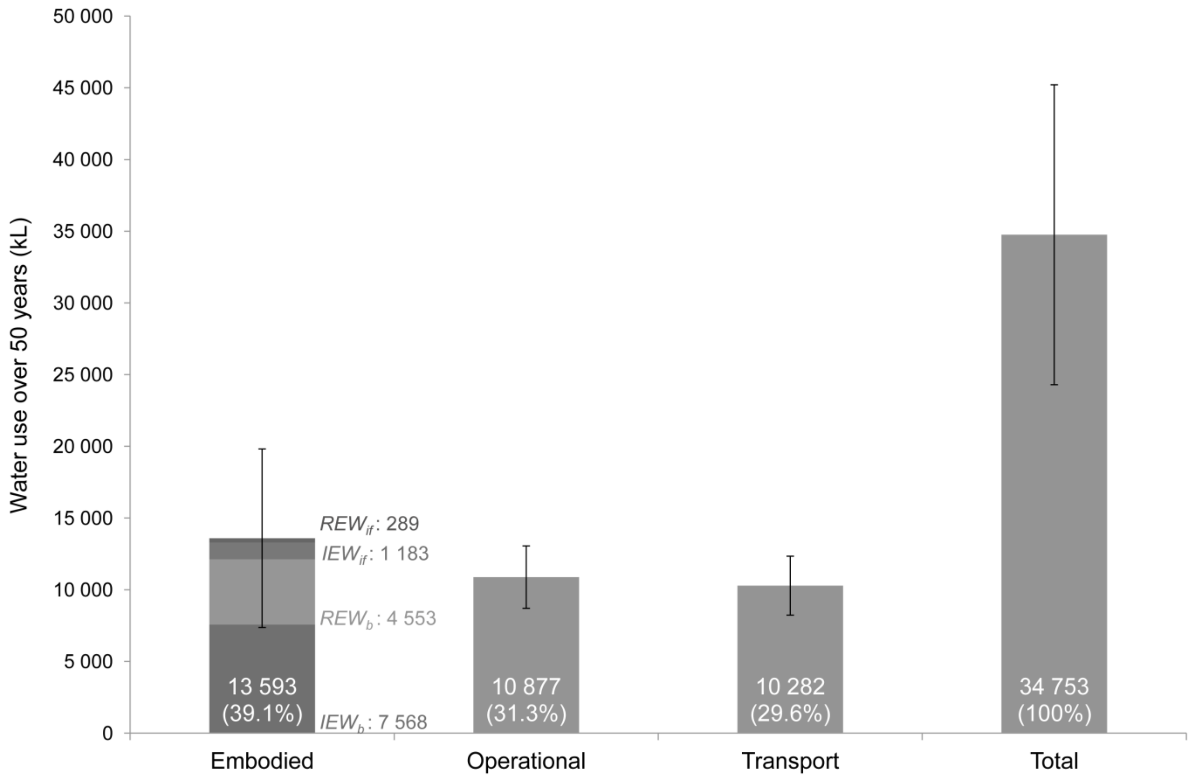

Fig. 2: Life cycle water demand of the case study house over 50 years, by use. Note: IEW_b = Initial embodied water of the house; REW_b = Recurrent embodied water of the house, IEW_{if} and REW_{if} represent the same quantities for infrastructures, respectively. Figures might not sum due to rounding.

When considering the uncertainty and variability present in the data, the contribution of embodied, operational and transport requirements fluctuate between 22.5%-53.9%, 21.3%-45.6% and 18.2%-43.4%, respectively. This shows that more robust databases are needed to minimise uncertainty as it can hinder the identification of the most water-intensive life cycle stage or use.

However, regardless of the uncertainty in the data, indirect requirements, namely embodied and transport water, always represent more than 50% of the total water demand (minimum 54.4%; maximum 78.7%). This shows that the majority of studies focusing on operational water use in buildings alone might fail to identify the most effective solutions for improving the water efficiency of the built environment.

4 Discussion

This paper presents a framework for a comprehensive life cycle water analysis of residential buildings, through their life cycle and across different scales of the built environment. Results from a case study house in Australia show that each of the embodied, operational and transport water requirements over 50 years are significant. This indicates that all three components should be considered in any efforts to improve the environmental profile of buildings. Regardless of the uncertainty in the data, indirect requirements (embodied and transport) represent more than 50% of the total water demand. This demonstrates that the current focus on operational water savings only considers a fraction of the total water demand associated with residential buildings. This finding is similar to the conclusion regarding the life cycle energy demand of residential buildings demonstrated by Stephan *et al.* (2012).

The developed framework will inform architects, building designers and town planners on their decisions regarding water efficiency in residential buildings. By integrating the different life cycle stages of the building at both the building and city scales, a more comprehensive assessment is possible. The coupling of embodied water in rainwater collection systems and water efficient fixtures with knowledge of their water-saving potential will provide a clearer indication of the net benefit of their installation. The framework can also be used at the neighbourhood level in order to test the water efficiency of different housing forms or retrofitting scenarios.

Certain limitations can undermine the performance of the developed framework. The use of an aggregated average figure for operational water can reduce the potential for improvements as hot spots cannot be identified in detail. Also, the large uncertainty present in the embodied water coefficients do not always allow a clear comparison between different scenarios. More robust databases, notably in terms of process data are needed. Moreover, the very notion of indirect water requirements does not distinguish between the quality of the water or its geographical availability. In the approach used, all water has equal value. This is not necessarily true in reality and more detailed databases of indirect water requirements are needed. The example of the distinction between renewable and non-renewable energy in embodied energy databases can serve as an example for future embodied water databases. Finally, the results presented in this study are relevant to the assessed case study house only. More buildings in different countries and contexts should be assessed to develop a deeper understanding of the life cycle water use of residential buildings.

5 Conclusion

As the world's population continues to grow there is an increasing need for new housing or for the retrofitting of the existing building stock. The framework proposed in this paper provides a useful guide to be used in the design of this housing to ensure that the water efficiency of these developments is maximised. This will ultimately lead to a reduction in the water-related environmental impact of buildings and help preserve the world's valuable water resources for future generations.

Acknowledgments

This research is funded by the Belgian National Fund for Scientific Research (F.R.S.-FNRS) and has been conducted during the *Visiting Scholar* stay of André Stephan at the Faculty of Architecture, Building and Planning of the University of Melbourne.

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