ASSESSING WATER FOOTPRINT AND ASSOCIATED WATER SCARCITY INDICATORS: A CASE STUDY OF CONCRETE MANUFACTURE

Amber Garnett (BRANZ, Wellington, NZ)
Ranvir Singh (Massey University, Palmerston North, NZ)
Sarah McLaren (Massey University, Palmerston North, NZ)
David Dowdell (BRANZ, Wellington, NZ)

ABSTRACT

Water scarcity is a growing issue of concern across the globe. In recent times, a complex suite of water footprint impact assessment tools and concepts have supplemented traditional management approaches. A water footprint is a measure of humanity’s appropriation of fresh water in volumes of water consumed and/or polluted. There are several methods proposed in the literature to both quantify water use and assess its environmental impacts at defined spatial scales. In New Zealand, case studies in the water footprinting space are sparse, and are for the majority focused on the agricultural industry.

This research focuses on the building and construction sector in New Zealand, and takes a case study approach. The water footprints of 1 m^3 ready mix concrete manufactured at 27 concrete batching plants throughout New Zealand were calculated and characterised by locally calculated characterisation factors to assess the environmental impact of water use for 1 m^3 ready mix concrete at the catchment scale. The water footprint impact assessment methods of Hoekstra et al. (2011) and Boulay et al. (2016) are presented, calculating the WS_{blue} and *AMD* characterisation factors, respectively.

The average volumetric blue water footprint of the 27 ready mix batching plants was quantified at 0.18 m^3 (180 litres) of water per m^3 of concrete, and ranged from 0.15 (150 litres) to 0.29 m^3 (290 litres) of freshwater per m^3 of concrete. In terms of their environmental impact, the water footprints of the Ashburton and Manawatu catchments post-characterisation, were found to have the greatest impact, based on the methods of Hoekstra et al. (2011) and Boulay et al. (2016), respectively.

The overarching goal of this research was to investigate how adaptable these globally developed methods are at the finer resolution in New Zealand. It is the aim that the findings from this research might aid water demand management strategies of New Zealand businesses. Furthermore, in recognition of the spatial complexity of water use, there is the potential for the development of a rating or marketing tool concerning the comparative water footprints of New Zealand products.

KEYWORDS

Water footprint, water scarcity, lifecycle assessment, impact assessment, concrete

PRESENTER PROFILE

Having gained a BSc at Waikato University, Amber Garnett recently graduated with a Master of Environmental Management from Massey University. A strong research focus to date has been environmental monitoring and resource management; in particular freshwater science.

1 INTRODUCTION

Freshwater has been described as New Zealand's greatest natural asset (Ministry for the Environment [MfE], 2014a), and is regarded as essential to New Zealand's social, cultural and economic wellbeing (MfE, 2007). The availability and demand for freshwater are both spatially and temporally variable across different regions of New Zealand. Thus, the abundance of freshwater in New Zealand can differ drastically depending on topography and regional characteristics. Freshwater availability in New Zealand is, by international standards, abundant due to plentiful rainfall experienced across the country, and comparatively low population density (MfE, 2007). In fact, the total freshwater available per person in New Zealand is reported to be higher than 180 other countries across the world (MfE, 2007). Per capita, freshwater availability in New Zealand is ranked fourth amongst members of the Organisation for Economic Co-operation and Development (OECD) (New Zealand Institute of Economic Research, 2014). However, at the same time, New Zealanders use two to three times more freshwater per person that most other OECD countries (MfE, 2007).

Critically, the distribution and allocation of freshwater (by source) in New Zealand, differs greatly between regions. Figure 1 shows the maximum allocated surface water as a percent of the calculated minimum flow expected during dry periods (MfE, 2010). Eastern regions such as Otago, Canterbury and Marlborough have a larger proportion of catchments at risk from potential allocation pressures during dry periods. These regions tend to have higher freshwater allocations from catchments considered potentially pressured. For example, nearly three-quarters of allocated water in the Otago region is from highly pressured catchments (MfE, 2010). Comparatively, the West Coast and Manawatu-Wanganui regions have less than one percent of catchments considered at risk.

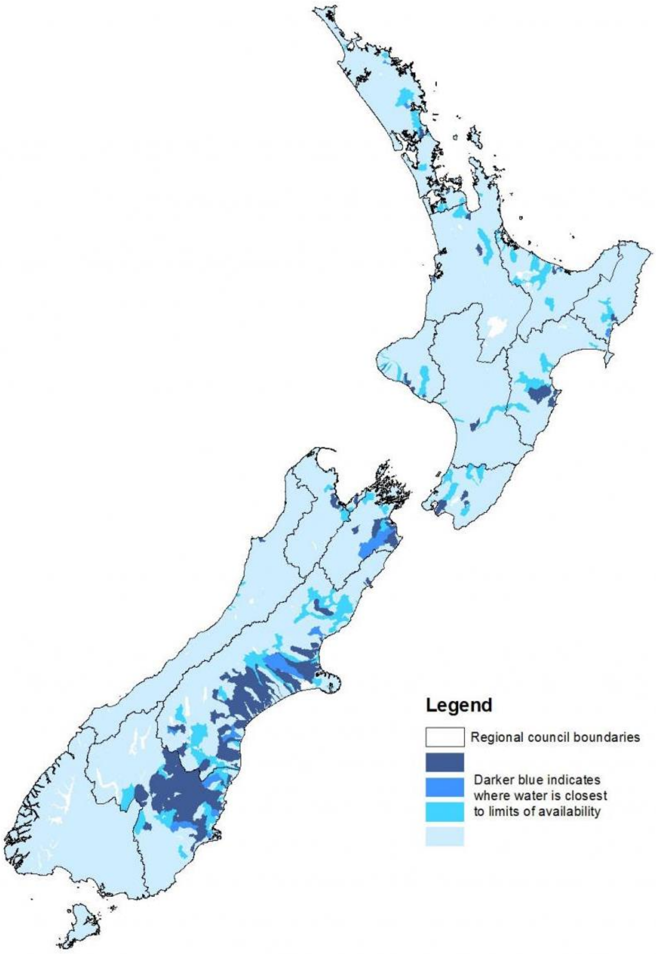

Figure 1 Potential surface water allocation pressures across New Zealand (MfE, 2010)

In recent times, the concern over the country's freshwater resource has begun to grow as some regions reach environmental limits for part, or all of the year. Generally, the demand for freshwater peaks during the summer months (December to February), particularly for agricultural uses (irrigation). However, it is during these months that the availability of freshwater is at its lowest. This has resulted in most regions having at least one river and/or aquifer that is either fully or over allocated, or is likely to be so in the next five years (NZBCSD, 2008).

Freshwater abstractions from regions with a higher proportion of at risk catchments may be considered to have reduced water security, when compared with regions with lower potential pressure, as restrictions are more likely to be imposed to conserve water (Mfe, 2010).

2 THE WATER FOOTPRINT CONCEPT

Given the current global water challenges, traditional approaches to water management are being supplemented with a more complex suite of concepts and tools to assess freshwater use and its associated environmental impact. Included in these recent advances is the concept of water footprint, and related analytical water footprint methods and tools.

2.1 ORIGIN AND CONTEMPORARY DEFINITION

2.1.1 THE VIRTUAL WATER CONCEPT

The water footprint concept has its origins in the 1990s when the term 'virtual water' was coined by Professor John Anthony Allan, after he identified that the consumptive water use of citrus fruit production in water scarce countries of the Middle East, was much greater than the water content of the fruit itself (Allan, 1998). The term virtual water is used in water footprinting to describe water 'embodied' in a product. It refers to the volume of water consumed and/or polluted, as measured throughout the entire production chain of a product (Allan, 1998). The global trade of virtual water embodied in products, such as fruit from the Middle East, can contribute substantially to a countries water footprint, and the concept is important from a water demand management perspective as it can account for a volume of water consumption that is currently unaccounted for in traditional water management approaches.

To demonstrate the concept, a UK study found households used around 150 liters of water per person per day. However, when the virtual water content required to produce food, beverages, clothing and other products consumed by these induvial was included, the water footprint rose to 4,645 liters per person per day (Chapagain & Orr, 2008). It was found that 62 percent of the UK's water footprint is virtual water embedded in agricultural commodities and products imported from other countries; only 38 percent is sourced from domestic water resources (Chapagain & Orr, 2008). The impact of these footprints, however, is not necessarily reflected in the volume of water used. A smaller water footprint can have a more negative impact if the water is sourced from a catchment with a higher water stress. Thus, consideration of the local water scarcity conditions, alongside the volumetric water footprint are crucial to gain a comprehensive understanding of the impact of water use in different locations. As international trade is so important for the global economy, and with increased concern over water security, water footprint assessments can have a role to play in understanding how and where we use water.

2.2 ADAPTATIONS AND THE CURRENT DEFINITION

In 2002, Professor Arjen Hoekstra and colleagues expanded upon the virtual water concept by distinguishing different types of water consumed and/or polluted (Hoekstra, Chapagain, & Mekonnen, 2011). Traditionally, water use assessments have been concerned with defining the amount of surface and groundwater withdrawn and/or directly consumed during a process or in the production of a product (Hoekstra et al., 2011). The water footprint concept is more complex and comprehensive than typical water withdrawal measurements as it quantifies the volume of freshwater used both directly *and* indirectly in the production lifecycle (Figure 2). Water footprint methods are therefore able to account for virtual water flows, in other words, the 'embodied' water being transferred between two geographically delineated areas as a results of product trade (Hoekstra et al., 2011). Furthermore, they allow for differentiation between different 'colours' of water use (based on source and function), and omit the non-consumptive part of water withdrawal (return flow), because it is returned to the environment (Hoekstra et al., 2011).

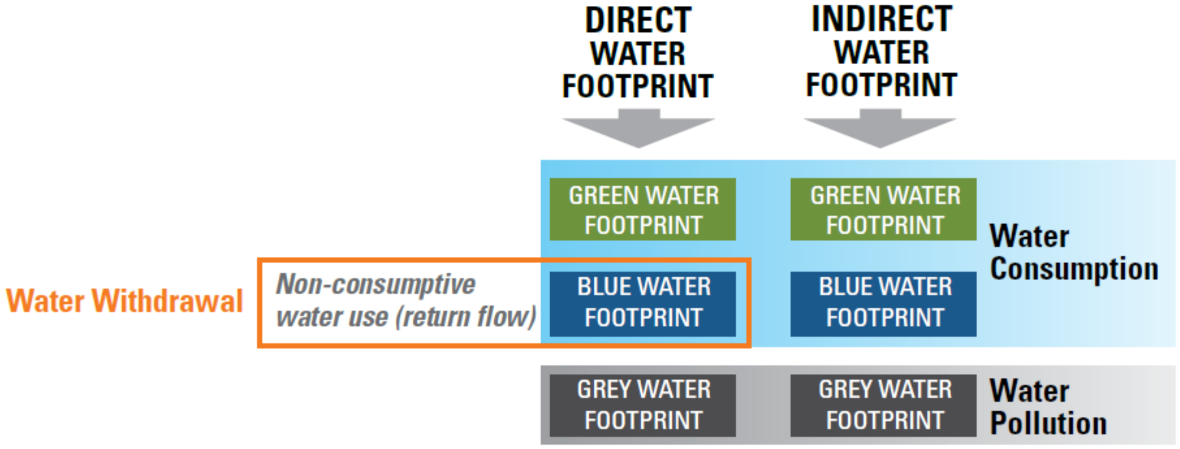

Figure 2 The components of a water footprint assessment, according to Hoekstra et al. (2011)

Three 'colours' of water are commonly differentiated in water footprinting methods, as follows:

Green water footprint - water from precipitation that is stored in the root zone of the soil and evaporated, transpired or incorporated by plants. It is particularly relevant for agricultural, horticultural and forestry products.

Blue water footprint - water that has been sourced from surface or groundwater and is either evaporated, incorporated into a product or taken from one body of water and returned to another, or returned at a different time.

Grey water footprint - the amount of fresh water required to assimilate pollutants to meet specific water quality standards.

2.3 Volumetric vs. Impact Orientated Water Footprints

The methodology for water footprinting is still an emerging subject area and different methods are being proposed, debated, and revised to define and standardise water footprint assessments. There are two main schools of thought with regards to water footprinting methods. The first is concerned with measuring the *volume of water used* (Hoekstra et al., 2011), and the second is concerned with directly assessing the *impacts associated with water use* (Boulay et al., 2016). Those working on impact-orientated assessments take a Life Cycle Assesment (LCA) approach to assess and quantify resource and environmental impacts associated with water use.

2.3.1 VOLUMETRIC WATER FOOTPRINT METHOD

Water footprints based on volumetric calculations determine the appropriation of freshwater for processes, products, and organisations. These methods can be described as taking a "resource efficiency" perspective by focusing on the total quantities of water available, consumed and/or polluted during the production of a product (Berger & Finkbeiner, 2012).

THE WATER FOOTPRINT NETWORK METHOD (HOEKSTRA ET AL. 2011)

The volumetric water footprint method (Hoekstra et al. 2011) produced by the Water Footprint Network (WFN) was the first comprehensive water footprint method to be developed. It is a multidimensional indicator showing volumes of consumed water by source and volumes of polluted water by type, whilst accounting for direct and indirect water use (Hoekstra et al., 2011).

To calculate the water footprint of a product, the water footprints of the predominant processes (defined during a scoping phase) are calculated as follows:

Equation 1

$$WF_{proc} = Water\ Evaporation + Water\ Incorporation + Lost\ Return\ Flow \quad [\text{ volume/time }]$$

The results of each individual process step are aggregated to provide a product's volumetric consumptive water footprint (Hoekstra et al., 2011).

METHOD ADAPTATION (IMPACT ASSESSMENT)

In 2011, the WFN adapted upon their baseline water footprint calculation to include a method for impact assessment. Three water footprint impact indices, one for each colour of water, were developed.

In the case of blue water, the blue water scarcity of a catchment (or specified boundary) is defined as the ratio of the total blue water footprints in the catchment (WF_{blue}) to the blue water availability (WA_{blue}) in that catchment. For the purposes of this research, the calculation for blue water scarcity of a catchment was adapted slightly due to the unavailability of data necessary to calculate the blue water footprint of *all* process in a catchment. The blue water footprint of a catchment was thus calculated based on consented surface and groundwater abstractions for different water user groups (agriculture, industry and ‘other’). The blue water scarcity of a specified boundary was thus calculated, as follows:

Equation 2

$$WS_{blue}[x,t] = \frac{\sum WF_{blue}[x,t]}{WA_{blue}[x,t]} \quad [-]$$

The local water footprint impact indices (*WFIIs*) are obtained by multiplying elements of the two matrices (water footprint and water scarcity). The calculated *WFIIs* can be interpreted as the aggregated and weighted measure of the environmental impacts of the water footprints, in the places and periods in which the various water footprint components occur. The blue water footprint impact index ($WFII_{blue}$), for example, is calculated as follows:

Equation 3

$$WFII_{blue} = \sum x \sum t \, (WF_{blue}[x,t] \times WS_{blue}[x,t]) \; [-]$$

2.3.2 IMPACT ORIENTATED WATER FOOTPRINT METHODS

Water footprint methods that are concerned with the environmental, social and economic impacts associated with water consumption, generally take an LCA approach. They reflect the fact that the environmental impacts of a liter of water used in one region may have very different implications than in another region, depending on local water scarcity levels (Ridoutt, Sanguansri, Nolan, & Marks, 2012). For the purposes of this case study only the environmental impacts are accounted for.

There are a range of different methods in the literature concerned with calculating the impacts of water withdrawals and consumption. This research compared the LCA methods of Pfister et al. (2009), Berger et al. (2014) and Boulay et al. (2016) were compared. It was ultimately determined that the methods of Pfister et al. (2009) and Berger et al. (2014) were unsuitable for adaptation at the finer resolution in New Zealand, so only the results according to Hoekstra et al. (2011) and Boulay et al. (2016) are discussed.

THE AVAILABILITY MINUS DEMAND (BOULAY ET AL. 2016)

The Water Use in Life Cycle Assessment (WULCA) working group developed the Available Water Remaining (AWaRE) method, in accordance with the International Organisation for Standardization 14046 standard (ISO, 2014). The aim of the method was to answer the question "What is the potential to deprive another user (human or ecosystem) when using water in this region?". Boulay et al. (2016) calculate the availability-minus-demand (AMD) per basin (i), where consideration is given to both human water consumption (HWC) and environmental flow requirement (*EFR*) relative to the area (m^3 per m^2 per month), as follow:

Equation 4

$$AMD_i = \frac{Availability - HWC - EFR}{Area} \quad [\mathrm{m}^3/\mathrm{m}^2\ \mathrm{month}^{-1}]$$

In a step similar to the Global Warming Potential (Intergovernmental Panel on Climate Change, 2013), the *AMD* is normalised by a consumption-weighted world average and inverted, representing the value in comparison with the average m^3 consumed worldwide (for demand < availability). In this instance, the global average AMD has been calculated using the WaterGAP global database as 0.0136 m^3 m^{-2} $month^{-1}$ (Boulay et al., 2016). Characterisation factors (CF's) are calculated, as follows:

Equation 5

$$CF = \frac{0.0136}{AMD_i} \quad [-]$$

At present, the development of water footprint methodologies have been focused on the global and national scales. Notably less research has been conducted at the catchment or finer resolution, and there is little in the way of assessing the effects of the different water footprint methods and comparisons between different spatial scales.

2.4 NEW ZEALAND WATER FOOTPRINT ASSESSMENTS

There are few water footprinting studies using New Zealand data. Current literature regarding the water footprint of New Zealand products, processes and organisations is sparse, with some global level studies using data that may be outdated and/or averaged at the national level. Yet Hoekstra and Mekonnen (2012b) stress the importance of scale in water footprinting and make the point that national level data can often have significantly different results than data taken at the catchment level. Thus, the results of water footprinting studies can often yield dramatically different results depending on both the spatial and temporal scale of the assessment.

There have been a handful of water footprint studies conducted in New Zealand. For the most part, these have focused on agricultural products and processes. Examples include kiwi fruit production (Deurer, Green, Clothier, & Mowat, 2011; Landcare Research, 2011), the grey water footprint of potatoes (Herath et al., 2014a, 2014b), and the water footprint of dairy farming in the Canterbury and

Waikato regions (Zonderland-Thomassen & Ledgard, 2012). Furthermore, Herath, Deurer, Horne, Singh, and Clothier (2011b) calculated the blue water footprint of hydroelectricity in New Zealand.

Although the focus of water footprint studies to date in New Zealand has primarily been the agricultural sector (responsible for approximately 70% of global freshwater consumption) (UN Water, 2007), in other parts of the world the consumption of water by industrial sectors has, in recent times, been receiving more attention (Pfister et al., 2011). The building and construction sector is the fifth largest economic sector in New Zealand, with both domestic and export markets (PricewaterhouseCoopers, 2011). To date the volume of virtual water within building products has not been explored in a New Zealand context.

3 METHODS

3.1 CASE STUDY: THE WATER FOOTPRINT OF CONCRETE MAUNFACTURE

Ready mix concrete is a multi-purpose product that is used in infrastructure and building construction applications. This case study assesses water use in 27 concrete batching plants located throughout New Zealand. These plants make pump and standard grade Normal ready mix concrete at eight compressive strengths (15, 20, 25, 30, 35, 40, 45 and 50 MPa). Data were provided by Allied Concrete (Allied Concrete, 2014). In accordance with the method of Hoekstra et al. (2011), the volumetric blue water footprint of concrete production was quantified and normalised, using 1 m^3 of concrete as the functional unit. The green and grey water footprints were omitted from the analysis. Data for the eight compressive strengths were aggregated to calculate the water footprint of 1 m^3 of concrete (for each of the 27 concrete batching plants). The system boundary of this case study is the manufacturing phase of the concrete lifecycle (or a 'gate to gate' approach according to LCA) and can be seen in Figure 3.

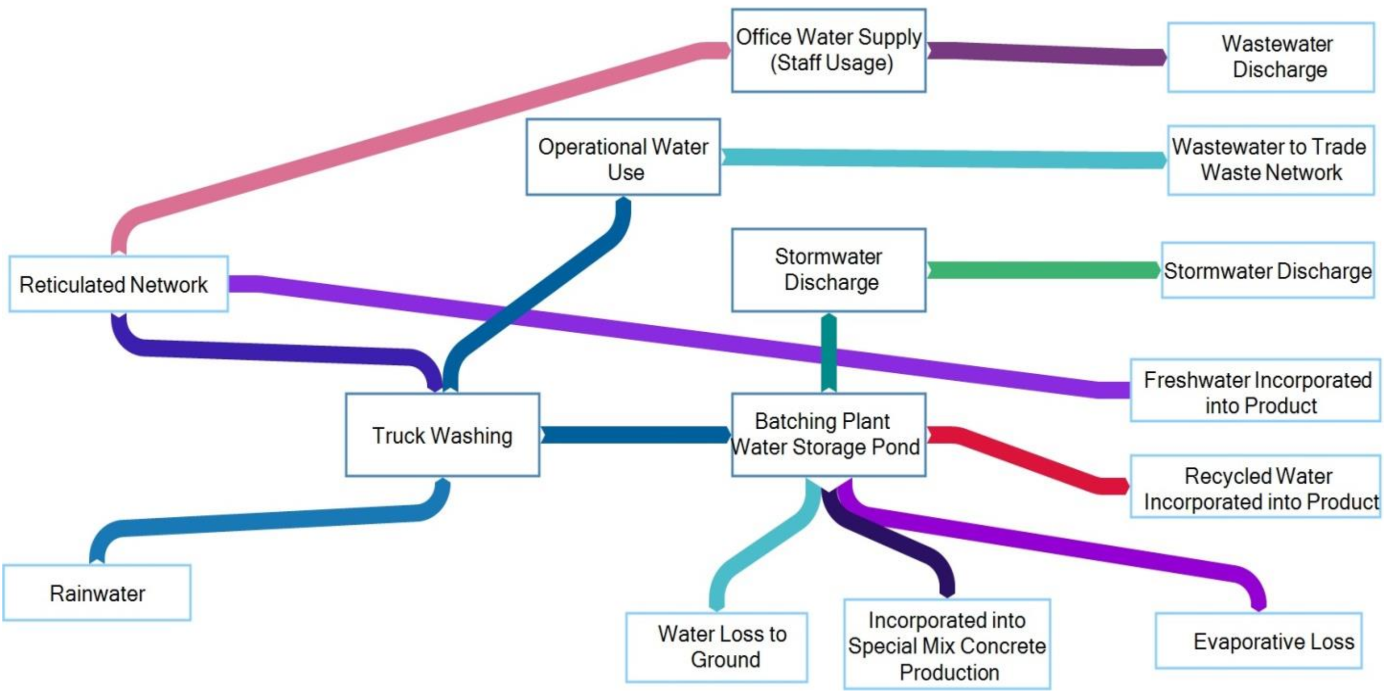

Figure 3 The system boundary of concrete production within selected concrete batching plants

In accordance with Equation 1 the consumptive blue water used by each concrete batching plant was accounted for using data pertaining to the volume of evaporation from storage ponds, the volume of freshwater incorporated into the product itself, and the volume of lost return flow (i.e. volume of 'wastewater' transported to other batching plants). Following the WFN method, each respective plant's process water footprint was then divided by the plant's total concrete production for the year 2013. This enabled the blue water footprint of 1 m^3 of ready mix concrete to be quantified and displayed in 'm^3 water per m^3 concrete'.

Equation 6

$$WF_{blue,concrete} = \frac{WF_{blue}}{Concrete\ Production\ Volume} \quad [\mathrm{m^3 water/m^3 product}]$$

To visualize the flows of the various components of a water footprint calculation, schematic flow diagrams were produced for the 27 concrete batching plants. These flow diagrams represent the system boundary for each individual batching plant (refer to Figure 4). Freshwater withdrawals are either made from the reticulated network and/or from rainwater storage tanks on-site. Freshwater consumption occurs in varying volumes, across the 27 batching plants, as water consumed through the product incorporation, evaporation, loss to ground or disposal of wastewater in a few cases. The Ashburton batching plant can be seen in Figure 5, as an example. The proportion of the total volume of water entering this batching plant that is ultimately exported in the end-product (1 m^3 concrete in this instance) can be seen in red, this is the virtual water content of the concrete.

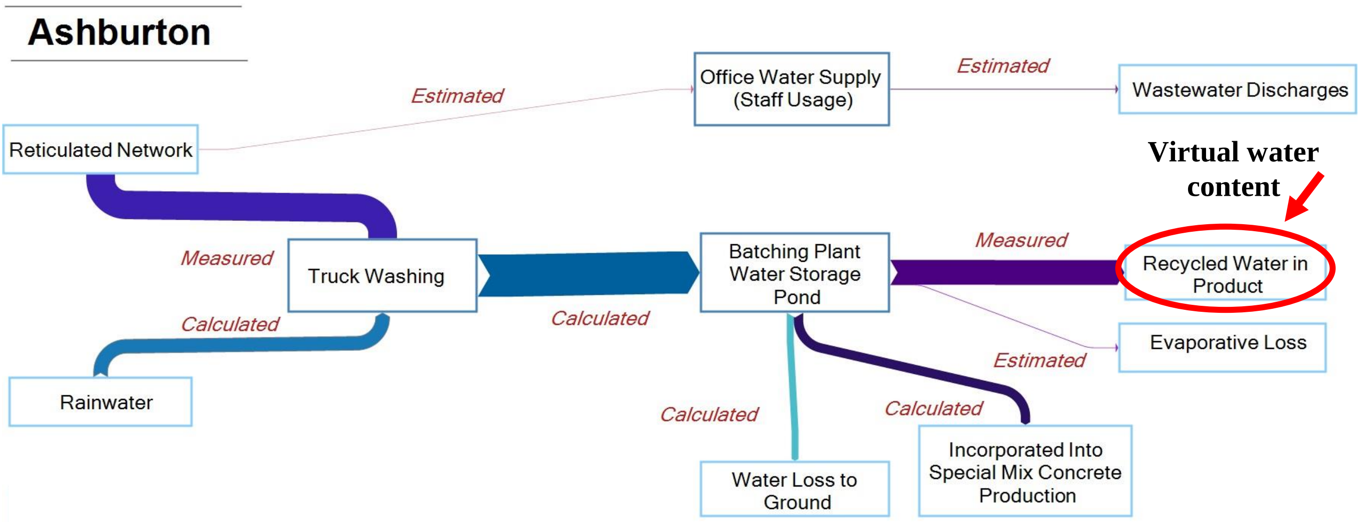

Figure 4 Schematic diagram of water flows in the Ashburton concrete batching plant

3.2 GEOGRAPHIC RESOLUTION

The local environmental impact assessments conducted according to the methods of Hoekstra et al. (2011), Pfister et al. (2009), Berger et al. (2014) and Boulay et al. (2016) were calculated at three distinct scales, i.e. regional, catchment or freshwater management zone. For the purposes of this paper only results presented at the catchment scale are displayed as this scale was ultimately recommended for future water footprint assessments throughout New Zealand. Figure 5 shows the location of the 27 concrete batching plants studied. A water footprint was calculated for all concrete batching plants. A smaller subset of six batching plants was the focus of the impact assessment due to the multitude of methods and spatial scales tested, and due to local data requirements and availability.

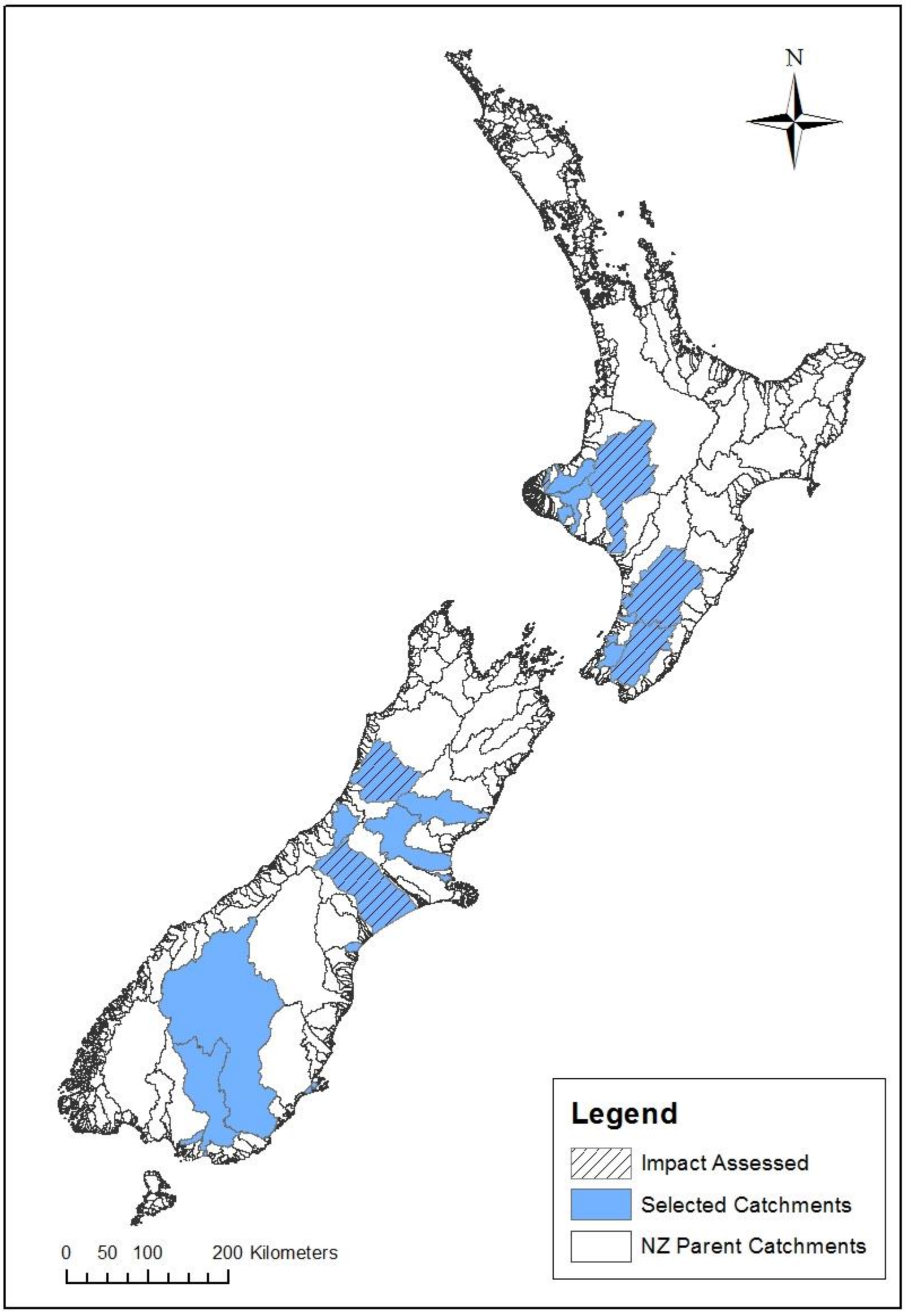

Figure 5 A map of catchments where selected concrete batching plants are located

3.3 TEMPORAL RESOLUTION

The data used to quantify water consumption in each concrete batching plant was provided for the year 2013. All other hydrological data used for the environmental impact assessment of concrete's water consumption is based on the average annual datasets (as opposed to averaged monthly datasets) due to the availability and scale of data collected by the relevant organisations.

4 RESULTS

4.1 THE VOLUMTERIC WATER FOOTPRINT OF CONCRETE MANUFACTURE ACROSS NEW ZEALAND

The volumetric blue water footprints of 1 m^3 concrete were calculated for the 27 concrete batching plants using the method of Hoekstra et al. (2011). In accordance with Equation 6, the volumetric water footprint of each concrete batching plant (m^3 water per m^3 concrete) can be seen in Figure 6. The water footprint of concrete varies between batching plants. Eight batching plants have water footprints greater than the average, of 0.18 m^3 water per m^3 concrete. Three of plants: Mosgiel, Palmerston North and Masterton, can be seen to be greater than all other batching plants at 0.22, 0.24 and 0.29 m^3 water per m^3 concrete, respectively. The lowest volumetric blue water footprint of 0.15 m^3 water per m^3 concrete was calculated at the Ashburton, Levin, Cromwell and Ashby's Ready Mix batching plants.

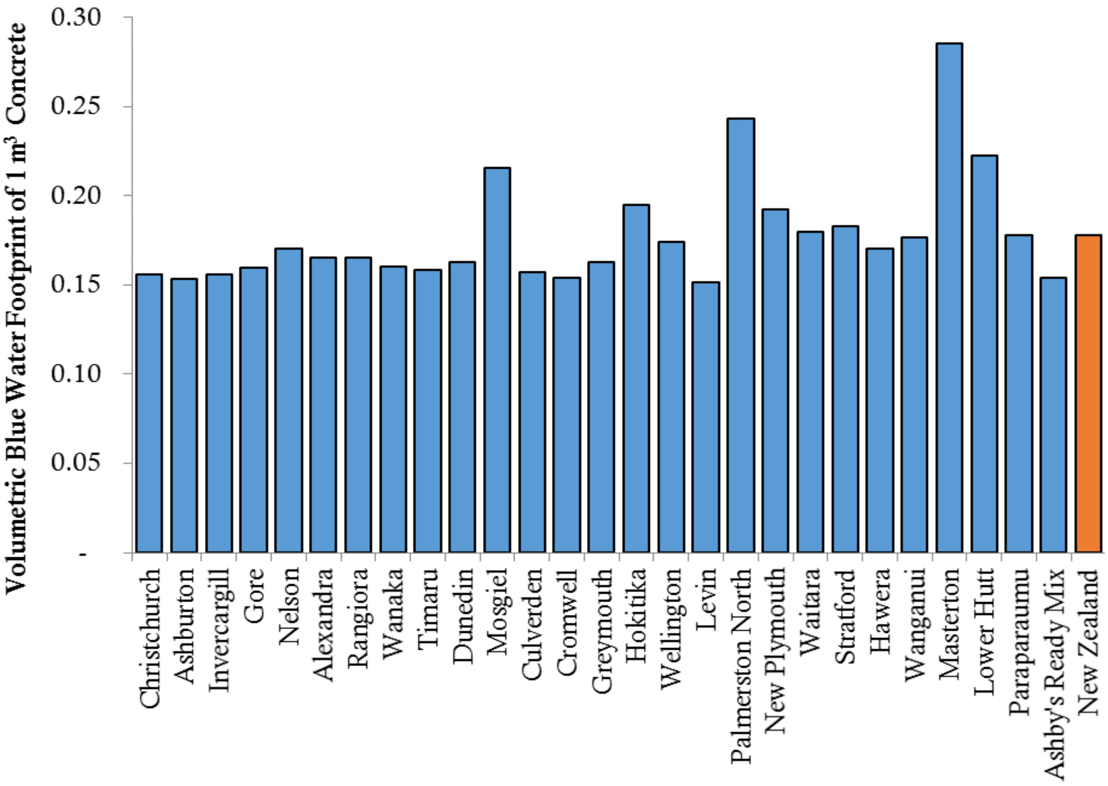

Figure 6 The volumetric blue water footprint of 1 m^3 of concrete throughout 27 New Zealand batching plants (2013 period), according to the WFN method (Hoekstra et al. 2011)

For comparative purposes, the volumetric water footprints shown in Figure 6 have been normalised with the average. Figure 7 shows the normalised water footprints for each of the 27 concrete batching plants throughout New Zealand alongside the volume of concrete production and freshwater consumption (shown as a % of the total across the 27 batching plants). Where the volume of concrete produced exceeds the volume of freshwater consumed, the water footprint of 1 m^3 concrete across the 27 concrete batching plants can be seen to be below the average of one. Where freshwater consumed exceeds the volume of concrete produced the water footprint can be seen to be closer (or above) the average, compared to plants of a similar size with regards to concrete production and freshwater consumption volumes.

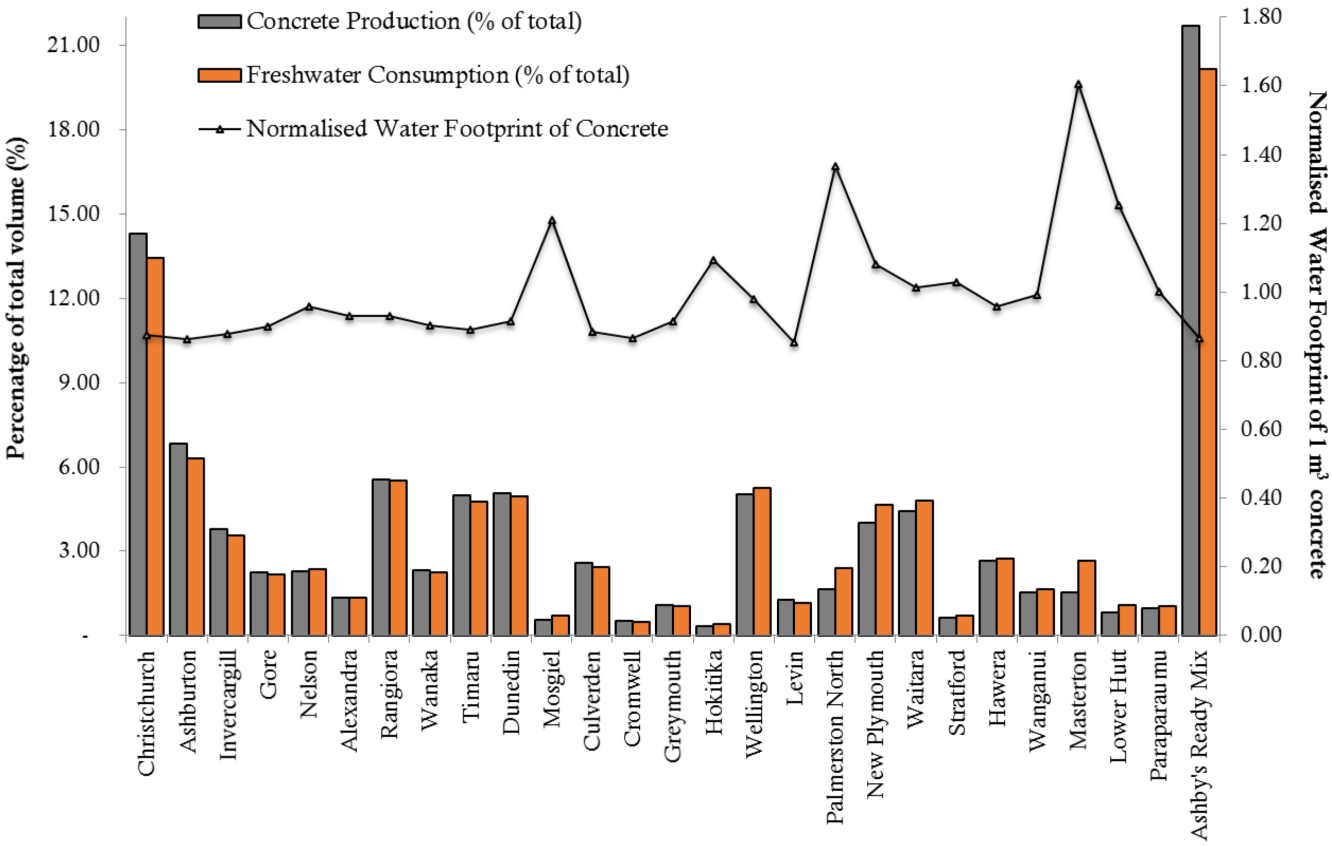

Figure 7 A comparison of concrete production and freshwater consumption volumes (as a % of the total) with the normalised water footprint of 1 m^3 concrete, for the 2013 period.

4.2 ENVIRONMENTAL IMPACT ASSESSMENT OF THE CONCRETE WATER FOOTPRINT

For the purposes of the environmental impact assessment, a sub-set of six concrete batching plants located throughout New Zealand were selected (refer to Figure 5). To characterise the volumetric water footprints of the concrete plants by the local water scarcity, the characterisation factors specific to each method were first calculated. These can be seen in Figures 8 and 9, at the catchment scale.

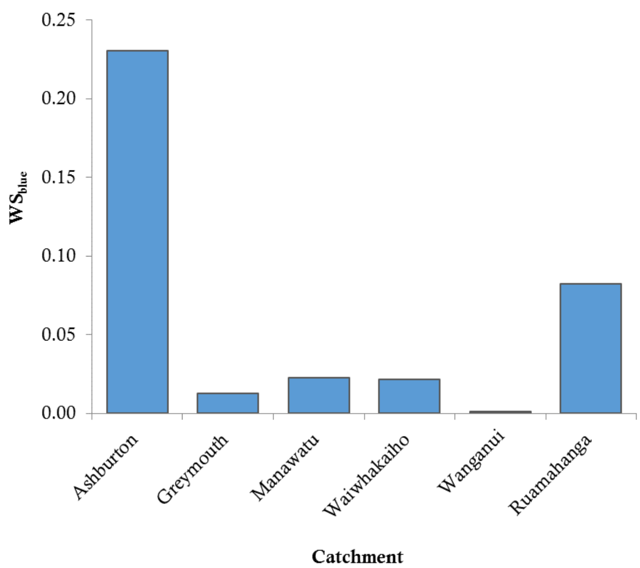

Figure 8 WS_{blue} characterisation factor

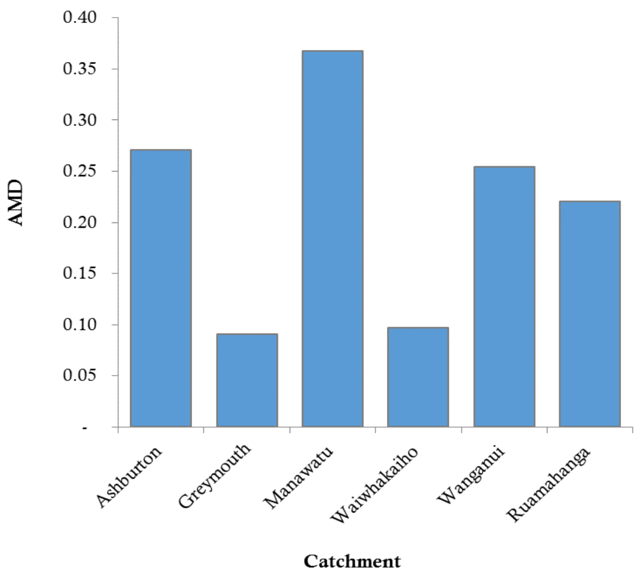

Figure 9 AMD characterisation factor

Referring to *Figure 8*, the WS_{blue} characterisation factors calculated according to Hoekstra et al. (2011) show the Ashburton catchment to have the greatest water scarcity, at almost three times greater than the second highest catchment, Ruamahanga. In contrast, the *AMD* characterisation factor calculated by Boulay et al. (2016) calculates the Manawatu catchment to have the greatest *AMD* (Figure 9). In terms of the lowest characterisation factors calculated, the Greymouth and Wanganui catchments have the lowest water scarcity according to Figure 8. Whereas, the Greymouth and Waiwhakaiho catchments can be seen to have the lowest *AMD* according to Figure 9.

To calculate the final characterised water footprints, the volumetric water footprints (Figure 6) are multiplied by the individual characterisation factors (Figures 8 and 9). The results for both the WFN method (WS_{blue}) and the Boulay et al. (2011) method (*AMD*), are shown below. In accordance with Figure 10, when the volumetric water footprint is characterised by the local water scarcity at the catchment scale, that the Ashburton batching plant has the highest water footprint at 0.035. The batching plant with the lowest characterised water footprint is the Wanganui batching plant at 0.001. In contrast, the *AMD* can be seen to be the greatest for the Palmerston North and Masterton batching plants (at 0.009 and 0.006, respectively). The lowest recorded water footprint was calculated for the Greymouth batching plant (at 0.01), followed closely by the New Plymouth plant (at 0.02) (Figure 11).

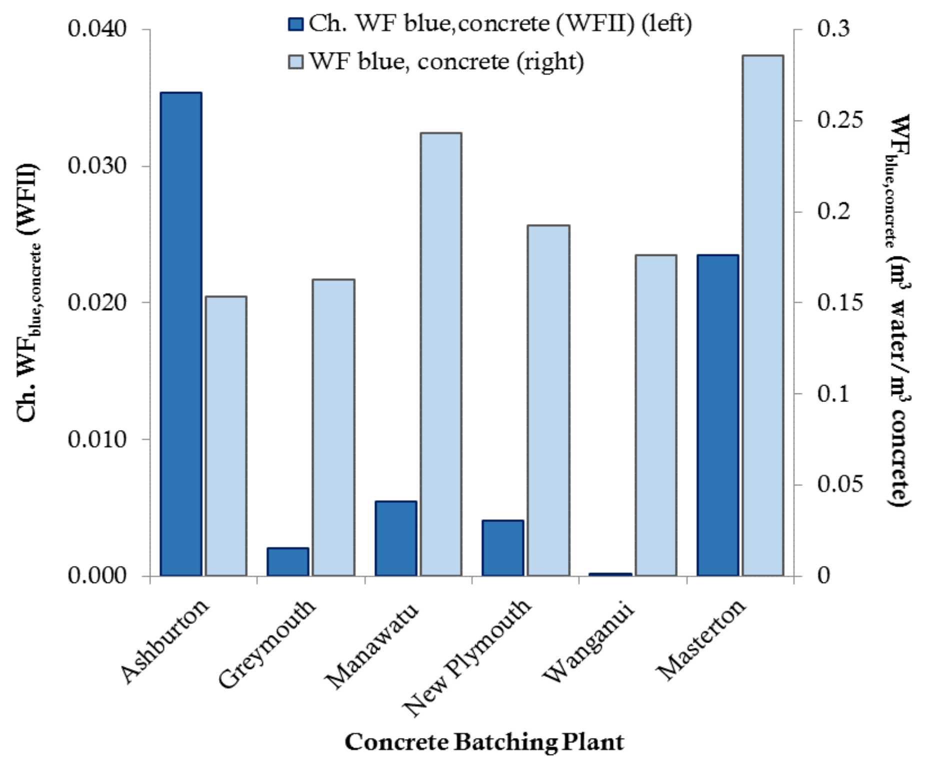

Figure 10 The volumetric water footprint of selected concrete batching plants ($WF_{blue,concrete}$) alongside the characterised water footprints (Ch.$WF_{blue,concrete}$ (WFII)) at the catchment scale.

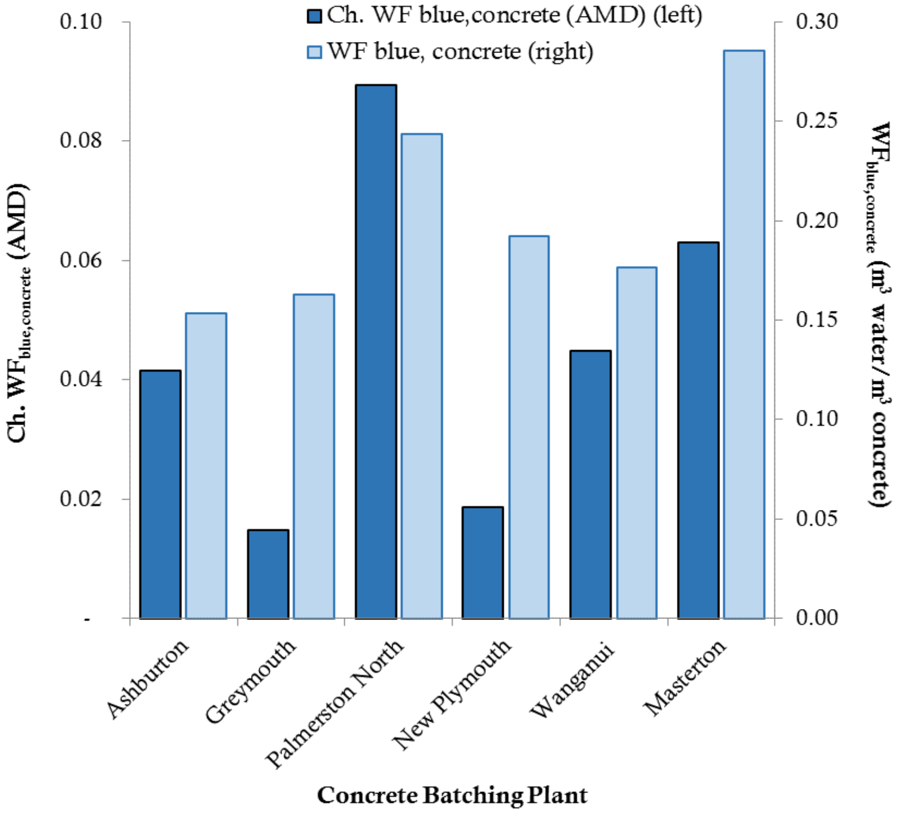

Figure 11 The volumetric water footprint of selected concrete batching plants ($WF_{blue,concrete}$) alongside the characterised water footprints ($Ch.WF_{blue,concrete}$ (AMD)) at the catchment scale.

5 DISCUSSION

5.1 VARIATION IN THE VOLUMETRIC WATER FOOTPRINT OF 1 M^3 CONCRETE

When the volume of freshwater consumed by each concrete batching plant is divided by the concrete production volume in that period (in accordance with Equation 6) variability in the volumetric water footprint between plants is apparent. For example, according to Figure 6, the volumetric blue water footprint of 1 m^3 of ready mix concrete at the Ashby's Ready Mix and Christchurch batching plants are relatively low (at 0.15 and 0.16 m^3 water/ m^3 concrete, respectively). In contrast, the Masterton plant has the highest volumetric blue water footprint at 0.29 m^3 water/ m^3 concrete. This variation in the water footprints amongst concrete plants is interesting because, in theory, the volume of water required to produce 1 m^3 of concrete should be similar (if not identical) for each concrete plant since the manufacturing procedure is the same throughout the 27 concrete batching plants studied, and there is no notable difference in water consumption between compressive strength.

The efficiency of batching plant processes is a potential source of variation in the water footprints amongst concrete batching plants that needs to be considered. As can be seen in Figure 7 the Masterton plant has much higher freshwater consumption that that of the Ashby's Ready Mix plant (2.7% to 20.2% of the total, respectively). However, the Masterton batching plant is amongst the smallest of Allied Concretes national plants, compared with Ashby's Ready Mix, which is the largest Allied plant in the country. To this end, incentives to improve the freshwater efficiency are targeted at larger plants such as Ashby's. Compounding this, the Ashby's Ready Mix plant is in an area with strict wastewater discharge controls, hence the focus on recycling and re-using freshwater.

An analysis between the relative percentages of concrete production and freshwater consumption in relation to the volumetric water footprint, across all 27 concrete batching plants, can be seen in Figure 7. The variation in the volumetric water footprints between batching plants is almost solely explained by the variation in the volume of concrete produced or freshwater consumed (as x is a function of y). For batching plants where the total volume of concrete production exceeds the volume of freshwater consumption, that the normalised water footprint of 1 m^3 is below the average (of one). This is demonstrated clearly for the Christchurch and Ashby's Ready Mix plants, where the relative percentages of concrete production and freshwater consumption are the highest of all 27 concrete batching plants studied. In contrast, they have amongst the lowest normalised blue water footprints at 0.88 and 0.87 m^3 concrete per m^3 freshwater, respectively (Figure 7). In both instances, the volume of concrete produced exceeded the volume of freshwater consumed (by 1.55% at Ashby's ready mix plant and 0.88% at the Christchurch batching plant).

Contrastingly, the Masterton, Palmerston North and Mosgiel batching plants have the highest normalised blue water footprints at 1.60, 1.37 and 1.21 m^3 concrete per m^3 freshwater, respectively. As can be seen in Figure 7, these plants have comparatively lower concrete production and freshwater consumption volumes. However, for each of these plants, the volume of freshwater consumed is greater than the volume of concrete produced. For the Masterton, Palmerston North and Mosgiel plants freshwater consumption is 1.2%, 0.8% and 1.3% greater than the concrete production volume for the 2013 period.

5.2 THE ENVIRONMENTAL IMPACT OF CONCRETE MANUFACTURE

The chosen water footprint characterisation factors; WS_{blue} (Hoekstra et al., 2011) and AMD (Boulay et al., 2016) were chosen as they provide different approaches, using varying hydrological considerations, to characterise volumetric water footprints at the finer resolution. A possible source of the apparent variation between the calculated CFs are the background methods and modelling choices employed.

A variance based sensitivity analysis was conducted, and from the results it was clear that for some methods there is a dominant parameter driving the variation in the overall water footprint. When discussing the WS_{blue} (Figure 10) it is the volume of freshwater consumed (which accounts for almost all variations throughout the spatial scales). When discussing the *AMD*, there appears to be no dominant driver of variation, but a range of contributing variables. It is possible that the interactions between these variables explain more variation than if the variables are considered alone. A limitation of the regression analysis is that the variables are not truly independent, as one hydrological process will affect the next.

5.3 IMPLICATIONS FOR THE CONCRETE INDUSTRY

The volumetric water footprint of 1 m^3 concrete presented in Figure 6 can be interpreted as one component used to measure freshwater efficiency amongst concrete batching plants. When displayed alongside the volume of concrete produced and the volume of freshwater consumed, it can be seen clearly in Figure 7 that plants which have a higher freshwater consumption to concrete production ratio, have the greatest volumetric water footprints. Therefore, if the goal of the assessment is to target batching plants in which efficiency practices could be employed, then Figure 6 is sufficient.

However, if the goal of the assessment is to understand which batching plants are consuming the largest volume of freshwater, then the volumetric water footprint results should be used alongside the consumption and production statistics. For example, by simply looking at the results in Figure 6, the Masterton batching plant appears to have the highest water footprint. When assessed alongside the production statistics, whilst Masterton requires more freshwater to produce 1 m^3 concrete, overall the plant produces a mere 2% of total concrete. An environmental impact assessment can assist in putting the volumetric water footprints in the context of the local hydrological conditions, which can be beneficial in selecting batching plants that could benefit from freshwater management initiatives.

Furthermore, the collection of data required to calculate a water footprint can indicate where in the process chain efficiency opportunities would be the most beneficial. Furthermore, as demonstrated in Figure 4, the volume of virtual water that is being exported in New Zealand products and processes can be disaggregated. Referring to the Ashburton batching plant in Figure 4, it can be seen that a large proportion of the total water consumed is incorporated in the final product. If this concrete were to be exported to a different region in New Zealand, this would represent a loss of water in the Ashburton catchment and a potential gain elsewhere. For internationally imported and/or exported products this could prove a beneficial assessment, particularly if an environmental labelling scheme concerning consumptive water use were to be introduced internationally.

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