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Value of Water

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BLUE WATER FOOTPRINT OF AGRICULTURE, INDUSTRY, HOUSEHOLDS AND WATER MANAGEMENT IN THE NETHERLANDS

AN EXPLORATION OF USING THE NETHERLANDS HYDROLOGICAL INSTRUMENT

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Contents

Summary

The aim of this report is to explore the possibility of quantifying and mapping the blue Water Footprint (WF) in the Netherlands with the National Hydrological Instrument (NHI) and to identify remaining challenges when doing so. The study looked at the blue WF of the three major water-consuming sectors: agriculture, industry and households. In addition, we considered the blue WF of two activities that are very typical to the Dutch water management situation: flushing of watercourses and water level management.

The blue WF refers to consumption of blue water resources (surface and ground water). Water consumption refers to one of the following four cases: (i) water evapotranspiration; (ii) water incorporation into a product; (iii) water not returning to the same catchment area (for example, it is transported to another catchment area or the sea); or (iv) water not returning in the same period (for example, it is withdrawn in a dry period and returned in a wet period). The blue WF in the agricultural sector was assessed for a dry year (climate conditions as in the year 1989, with a probability of occurrence of 1/10 yr^{-1}). Land use and other boundary conditions have been taken as in the year 2010. For industries and households, blue WFs have been estimated for 2010.

We compare the blue WF estimates as derived from NHI outputs with the results from an earlier, global study, which also included the Netherlands. We conclude that the outcomes from the current study are better than the outcomes of the earlier global study for two reasons: (1) NHI has a much higher spatial resolution and (2) NHI uses detailed Dutch databases rather than data from global databases. However, the precise assumptions taken in the quantification of the blue WF appear to be as important for the final outcome as the model and databases used. The estimate of the blue WF of agriculture is very sensitive to the assumptions regarding irrigation water requirements and actual allocation (which in NHI depends on a certain priority scheme regarding water allocations in the case of shortages). The estimate of the blue WF of industries and households is very sensitive to the assumption regarding the consumptive fraction of water withdrawals. In its current form, NHI does not provide a solid basis to derive this consumptive water use fraction.

For the first time in water footprint studies, the blue WF of agriculture related to capillary rise was studied. The study shows that this can be quite relevant in a quantitative sense. It was found that the contribution of capillary rise to the evapotranspiration from crop fields and pastures is much higher than the contribution of irrigation water.

An interesting element in the current study is the discussion on the blue WF of flushing watercourses and water withdrawals for maintaining water levels. A major challenge is to attribute the blue WF of flushing and water level management to final purposes. Theoretically this can be done based on the relative value of the different final purposes of flushing and water level management, but in practice a bottleneck is data availability regarding those relative values. This raises the interesting question how, in periods of drought and severe water competition, water allocation to these activities can be justified. Trade-offs in water allocation will need to be based on the added value of water in its alternative purposes. Regarding flushing, an important question not answered yet is to which extent water abstractions for this goal are to be considered as consumptive water use.

1. Introduction

This report is the result of a study to explore the possibility of quantifying and mapping the blue Water Footprint (WF) in the Netherlands with the help of the National Hydrological Instrument (NHI) and to identify remaining challenges when doing so. The study looked at the blue WF of the three major water-consuming sectors: agriculture, industry and households. In addition, we considered the blue WF of two activities that are very typical to the Dutch water management situation: flushing of watercourses and water level management. Both activities require that water is withdrawn from the main surface water system, thus potentially causing a blue WF.

The WF in governmental policy

The question of how to allocate scarce freshwater resources has become more complex as a result of globalized trade and production. Feed for livestock, for example, can be obtained locally, thus requiring local water resources, but can be imported as well, which will lead to a claim on water resources elsewhere. Because of the existence of trade, there is no direct relation between the demand at a certain location for products that need water in their supply chain and the water demand at that location. Production and consumption are essentially disconnected in space, so that the question of how to efficiently allocate the world's scarce freshwater resources has an international dimension (Hoekstra and Chapagain, 2008). Besides, water allocation is a political issue. Policy makers and strategists in government and industry are increasingly demanding information that reflects this complexity in water allocation. Water Footprint Assessment (WFA), an analytical framework developed over the past ten years, helps to understand how water use relates to production, trade and consumptions patterns. WFA can help to visualize the hidden water use behind consumer products (the water use in the various steps of the supply chain of products), and the other way around, to show how the water use of various activities can be attributed to certain final products or services.

WFA as input for better water management increases in importance. The Spanish government has adopted a regulation that makes WFA mandatory in developing river basin plans in line with the European Water Framework Directive (Official State Gazette, 2008). In Spain, WFA is now used as an analytical framework to make more informed judgment on how to optimize water allocation in relation to social and economic policy goals (Garrido et al., 2010). The extent to which domestic freshwater resources are used to produce export products and the extent to which the country imports water-intensive commodities are treated as important parameters in the discussion about how to allocate scarcely available national water resources. Within the European Union, the WF is viewed with great interest because of the expected increase in droughts, especially in southern Europe, but also because of the fact that Europe has a huge external WF, which partly lies in water-scarce regions where water use is not sustainable. It can be expected that other regions in the world, like China and India, will increasingly externalize their WFs, so that the strong dependence of Europe on water resources elsewhere cannot be sustained (Hoekstra, 2011). This may lead to a partial re-internalization of Europe's external WF and thus an increase in the demand for water within Europe. To date, the Dutch government has not used the WF to support decisions in the field of water management, water allocation, trade and sustainable consumption.

However, this will probably change in the coming years, especially when droughts will occur more often and more intensely, as forecasted in many of the climate change scenarios.

The WF in business water strategy

Consumers and major companies, including for example Unilever, Coca-Cola and Heineken, increasingly pay attention to the sustainability of the WF of their products. A study for Coca-Cola showed that the WF of a bottle of cola produced in the Dutch factory in Dongen is among the lowest in the world, due to the relatively small WF of the Dutch sugar beet used in Dongen (TCCC and TNC, 2010; Coca-Cola Europe, 2011). This may set a benchmark for other countries. Many companies start considering the reduction of the WF of their products as a part of their environmental strategy, just like the reduction of the carbon footprint. Addressing freshwater scarcity and pollution is viewed as part of the corporate social responsibility. In addition, investors consider water risk in the supply-chain of companies as a factor to be taken more serious in investment decisions (Levinson et al., 2008; Barton, 2010). The interest of companies in sustainable water governance has led to a large variety of initiatives in the field of accounting, reporting, awareness raising, certification and labelling. Those developments largely took place without governmental involvement. The French government, however, is planning to introduce a compulsory product labelling scheme that requires for certain products information on the carbon footprint, the water footprint and the impact on biodiversity. According to The Economist (2011), other European countries will be watching the French experiment closely, also because their own exporters may soon have to adhere to the French rules. In the Netherlands, the water footprint has entered the political debate as well. Recently, the Dutch Parliament submitted a resolution that calls on the Government to strive in its economic policy towards Dutch companies to become transparent about their water footprint and reducing it in areas with water scarcity (Dutch Parliament, 2012). Businesses thus put water higher on their strategic agenda for three different but related reasons: from the perspective of taking corporate social responsibility, from the perspective of water risk and accountability towards investors, and from the perspective of possible future governmental regulation in the area of product WFs.

The uptake of the WF by the Dutch public and private sector

The WF is a revolutionary and innovative indicator that generates tremendous interest worldwide, witness the success of the Water Footprint Network launched in 2008 (www.waterfootprint.org). The Water Footprint Network operates internationally but is hosted by the University of Twente in the Netherlands. In the field of water management, the Netherlands is still at the forefront of knowledge development. This leadership, however, has not yet led to an examination of how the WF concept could be used in a beneficial way in Dutch water and environmental policy. Four years ago, in response to an earlier study on the WF of Dutch consumers (Hoekstra and Chapagain, 2007a,b) and as a preparation to the Nature Balance 2008 (PBL, 2008), the Netherlands Environmental Assessment Agency commissioned a study to the University of Twente to study the sustainability of the external WF of the Netherlands (Van Oel et al., 2008, 2009), but no follow-up was given to this initiative, because the sustainability of the WF of Dutch consumers is not yet on the political agenda of the Dutch government and not within the mandate of one if its ministries. Traditionally, responsibilities over water and environmental issues are divided over different departments within government (not only in the Netherlands, in most countries of the world), whereby the concern for sustainability falls under the mandate of the governmental bodies developing and implementing environmental policy and whereby the responsibility for water management resides under the mandate of the governmental bodies developing and implementing water policy. The WF, which connects the two worlds – the world of sustainable production and consumption and the world of water management – does not clearly fall under the mandate of a specific part of government, which hampers the effective uptake of the concept in policy making. In the Netherlands, the responsibilities for water management and the environment have traditionally fallen under two different ministries, and although since 2010 the two policy fields have come together under the Ministry of Infrastructure and the Environment, the two policy fields still fall under strictly separated departments within that one ministry. The question of sustainability lies with the Directorate-General for the Environment and International Affairs (policy development) and the Netherlands Environmental Assessment Agency (analysis and advice). The responsibility for managing Dutch waters lies with the Directorate-General for Spatial Development and Water Affairs (policy development) and the Directorate-General for Public Works and Water Management (implementation). While governmental interest in the WF in the Netherlands has been limited until date, the interest among Dutch companies, consultants and non-governmental organizations is very substantial. In general, the Netherlands has a good representation in the Water Footprint Network, with 24 partners registered in the Netherlands (out of a current total of 183 partners). Other countries relatively well presented in the Water Footprint Network are the US (22 partners), Chile (15), Brazil (12), the UK (11), Switzerland (9), Spain (8), France (8) and Germany (7).

Freshwater scarcity and allocation in the Netherlands

The WF is essentially about freshwater allocation, which is mostly an issue in the case of freshwater scarcity. Water scarcity is not the first problem that comes into one's mind when thinking about water management in the Netherlands, which traditionally has to cope with (the risk of) flooding. There is however, increasing attention to water scarcity in the Netherlands, witness the priorities in the Dutch Delta Programme (Government of the Netherlands, 2012). One of the components of the Delta Programme is the sub-programme Freshwater, which focuses on the question how the Netherlands can provide enough freshwater to the right place at the right time and the right quality in the long term. The demand for freshwater from agriculture, industry and households is expected to increase, while at the same time the supply of fresh water may diminish through climate change (Klijn et al., 2011).

In the vision of the Water Footprint Network, national governments need to move towards an information system with which the WF of different activities can be visualised, spatially explicit and over time. The WFs of the various activities would need to be translated to various ultimate goals for which the WFs are made (e.g. the production of flowers, sugar, potatoes, tomatoes, feed-for-meat, feed-for-dairy, crops-for-biofuels, paper industry, petrochemical industry, etc.). This is especially interesting when it comes to allocation decisions made in times of drought. Every goal for which water is allocated can be associated with certain benefits. When, with the help of the WF concept, the water allocation to certain activities can be attributed to certain final goals or products, it can inform trade-offs in water allocation, as economic and social benefits of water allocation can be visualized.

This report

The current report is commissioned by the Dutch Directorate-General for Public Works and Water Management. It focuses on the WF of activities within the Netherlands. It does not address the external WF of Dutch consumers, i.e. the WF outside the Netherlands for producing products that are imported into and consumed within the Netherlands. The underlying rationale of this study has been to start with a technical focus. To be able to use the WF in an effective way to inform policy (on themes such as food security, energy security, water security, international trade, sustainable consumption, climate change adaptation), it is considered of utmost importance to ensure that there is a good scientific and technical basis that allows quantification and mapping of the WF with trusted tools. That is why linking the WF to the National Hydrological Instrument (NHI) is considered a first relevant step. The study aims to contribute to laying a solid foundation for the WF in Dutch water management by first analysing, without the ambition to immediately make the step towards policy, how the concept can be incorporated into one of the most important analytical instruments that is used by Dutch government in developing policy on freshwater allocation: the National Hydrological Instrument.

The methods used in this study are described in Chapter 2. The results are presented in Chapter 3. A discussion of the results and an identification of the remaining challenges when using NHI for the estimation of the WF of activities in the Netherlands follows in Chapter 4. Final conclusions are formulated in Chapter 5.

2. Methods

2.1 Water Footprint (WF)

Regarding the definitions of terms and water footprint accounting methodology, we use the standard as set out in Hoekstra et al. (2011). The WF is a measure of humans' appropriation of freshwater resources and has three components: blue, green and grey. The blue WF refers to consumption of blue water resources (surface and ground water). 'Water consumption' refers to one of the following four cases: (i) water evapotranspiration; (ii) water incorporation into a product; (iii) water not returning to the same catchment area (for example, it is transported to another catchment area or the sea); or (iv) water not returning in the same period (for example, it is withdrawn in a dry period and returned in a wet period). The first component, evaporation, is generally the most significant one. The blue WF is thus often smaller than the water withdrawal, because generally part of a water withdrawal returns to the ground or surface water. The green WF is the volume of green water (rainwater) consumed, which is particularly relevant in crop production. The grey WF is an indicator of the degree of freshwater pollution and is defined as the volume of freshwater that is required to assimilate the load of pollutants based on existing ambient water quality standards. In this study we only consider the blue WF.

The WF within a nation is defined as the total freshwater volume consumed or polluted within the territory of the nation as a result of activities within the different sectors of the economy. It can be calculated by summing the WFs of all water consuming or polluting processes taking place in the nation. Generally, one can distinguish three main water-using sectors: the agricultural sector, the industrial sector and the domestic water supply sector. In this study for the Netherlands, we have included two other relevant water-using activities: flushing of watercourses and water level management.

WF accounts give spatiotemporally explicit information on how water is appropriated for various human purposes. The WF of a process is expressed as water volume per unit of time. When divided by the quantity of product that results from the process, it can also be expressed as water volume per product unit.

2.2 National Hydrological Instrument (NHI)

The National Hydrological Instrument (NHI) is an integrated groundwater and surface water model covering most of the Netherlands (only Zuid-Limburg and the Wadden islands are not included). The aim of NHI is to support policy and operational studies at the national and regional level (NHI, 2008). NHI is increasingly used to support water management in the Netherlands. NHI has been used for calculations on the desired ground and surface water levels for the water boards and for the assessment of climate change impacts on fresh water availability in the Netherlands within the sub-programme Freshwater of the Delta Programme.

NHI consists of four coupled models: MODFLOW for the saturated zone (groundwater), MetaSWAP for the unsaturated zone, MOZART for regional surface water, and DM for national surface water. The instrument has three spatial levels: plots (250 x 250 m^2), land-surface-water units (LSWs, about 8500) and districts (about 150).

Evapotranspiration and irrigation supply are calculated at plot level, and therefore also the blue WF related to irrigation can be presented at plot level. NHI calculates on a daily basis, but outputs are saved per 10 days. Since we use existing runs (Klijn et al., 2011), we use the NHI output per 10 days. Moreover, availability of surface water is calculated per 10 days within the models MOZART and DM.

2.3 Blue WF based on NHI output

We have chosen to present the blue WF in the agricultural sector in a dry year (climate conditions as in the year 1989, with a probability of occurrence of 1/10 yr^{-1}), in order to provide a good illustration of a blue WF calculation (in an average or wet year, some crops will be hardly irrigated). Land use and other boundary conditions represent the reference year 2010. We estimate the blue WF in agriculture based on ten-day totals on precipitation, irrigation and evapotranspiration as they result from runs with NHI. For the industrial and domestic water supply sectors, blue WFs will refer to the reference year 2010 as in NHI.

The blue WF in the agricultural sector related to irrigation is calculated in three different ways:

A. WF_b(agr,irr) = irrigation × efficiency, whereby efficiency is defined as the fraction of irrigation water supplied to the plot that evaporates or transpires. We have used an efficiency of 100%.
B. WF_b(agr,irr) = irrigation/ (irrigation + precipitation) × evapotranspiration.
C. WF_b(agr,irr) = irrigation/ (irrigation + precipitation + capillary rise) × evapotranspiration.

Methods B and C assume that a fraction of the water lost from the field through evapotranspiration originates from irrigation water. In both cases we have to be careful about the time step applied in the calculation. The methods can better not be applied at the scale of one day, because some days the sum of irrigation and precipitation will be zero, resulting in an error. Besides, evapotranspiration mostly comes from the soil water, which contains water from precipitation and irrigation from the past few days, not just water from one day. Therefore, the equation is applied at the scale of ten days. NHI calculates the evapotranspiration based on a model that includes soil water, replenished by precipitation, irrigation and capillary rise and depleted by evapotranspiration and percolation. When we apply method B, we ignore the contribution of capillary rise to evapotranspiration. In ten-day periods wherein soil water replenishment is zero, the ratio irrigation / (soil water replenishment) is taken from the preceding ten-day period.

All three methods look at the blue WF of agriculture related to the application of irrigation water only. It is noted that the evapotranspiration of soil water that originates from capillary rise can also be considered as a blue WF, a ground-WF. The blue WF related to capillary rise can be calculated as: WF_b(agr,cr) = capillary rise / (irrigation + precipitation + capillary rise) × evapotranspiration. There will thus be a blue WF in crop fields also without irrigation. Then, the total blue WF of agriculture is the sum of two components: WF_b(agr,tot) = WF_b(agr,irr) + WF_b(agr,cr).

The blue WFs of industry and households are determined based on the groundwater and surface water abstractions in NHI for both sectors for the reference year 2010. We assume that:

- For groundwater abstractions: ground-WF = groundwater abstraction, assuming that groundwater withdrawals are deep groundwater withdrawals and that water is not returned to groundwater after use.
- For surface water abstractions for cooling in electricity production: surface-WF = 0 (we assume that 100% returns).
- For surface water abstractions for other industries: surface-WF = 100% of abstractions.
- For surface water abstractions for households: surface-WF = 100% of abstractions.

We note that NHI contains both abstractions for industries and households and disposals from sewage treatment plants, but that the difference between abstractions and disposals cannot be interpreted as blue WF for three reasons: (1) the difference can refer to evaporation but to leakages as well, (2) sewage treatment plants also collect rainwater, (3) not all industries are connected to a sewage treatment plant. It is important to know that the disposals from sewage treatment plants in NHI are based on measurements and are not calculated in the model based on returning fractions of water abstractions.

It has been assumed here that water abstractions for flushing will return, so that the blue WF is zero. Abstractions for water level management will not be returned to the stream from which they were abstracted, at least not in the same part of the year, so they need to be regarded as a blue WF. Water intake into an LSW unit for water level management will be stored in that unit and eventually evaporate or be pumped out in a period of water excess. Water intakes for flushing and water level management per LSW unit are part of the output of NHI and can thus be used as direct input to this study.

3. Results

3.1 Blue WF of agriculture

The blue WF of agriculture related to irrigation WF_b(agr,irr) is 601 Mm^3/yr according to calculation method A, 648 Mm^3/yr according to method B and 634 Mm^3/yr according to method C. The spatial distributions of the blue WFs according to the three methods are shown in Figures 3.1 to 3.3. The calculated blue WFs for methods B and C are larger than for method A, which is unexpected, because method A takes the total supply of irrigation water, which is an upper limit to the blue WF. The advantage of methods B and C is that they try to measure the fraction of actual evapotranspiration that originates from irrigation water, while method A is just based on water withdrawals for irrigation and not linked to evapotranspiration. The disadvantage of methods B and C is that taking a fraction of evapotranspiration based on the relative contribution of irrigation water to soil moisture in a certain period (in our study ten days) can only provide an approximation. It would be better to keep track in NHI, on a daily basis, which fractions of soil moisture in each plot stem from rainwater, irrigation water and capillary rise, respectively. In this way, it would be possible, each day, to know which fraction of the evapotranspiration originates from irrigation water. In the current study, which was based on the current NHI, in which this soil moisture origin tracking is not done, it was impossible to follow this approach. The calculated blue WF for method B is larger than for method C, because the latter includes the possibility that part of the evapotranspiration stems from soil water that was replenished through capillary rise.

Table 3.1 presents the blue WF related to irrigation (method C) per province, as well as the blue WF related to capillary rise and the sum of both. Figure 3.4 visualizes the blue WF related to capillary rise WF_b(agr,cr) on the map and Figure 3.5 shows the total blue WF of agriculture WF_b(agr,tot). It is clear from these figures that WF_b(agr,cr) generally is much larger than WF_b(agr,irr).

Table 3.1. Blue water footprint of agriculture per province related to irrigation WF_b(agr,irr), capillary rise WF_b(agr,cr) and the sum of irrigation and capillary rise (Mm^3/year).

Province	WF_b(agr,irr)*	WF_b(agr,cr)	WF_b(agr,tot)
Groningen	25.9	227.0	252.9
Friesland	65.6	168.9	234.4
Drenthe	22.3	268.1	290.4
Overijssel	74.3	365.3	439.7
Gelderland	19.6	182.9	202.4
Utrecht	74.3	77.1	151.3
Noord-Holland	155.9	378.3	534.2
Zuid-Holland	52.6	252.7	305.3
Zeeland	27.0	310.5	337.5
Noord-Brabant	24.0	115.4	139.4
Limburg	27.3	200.4	227.7
Flevoland	65.4	282.3	347.7
Total	634	2829	3463

* Calculated based on method C.

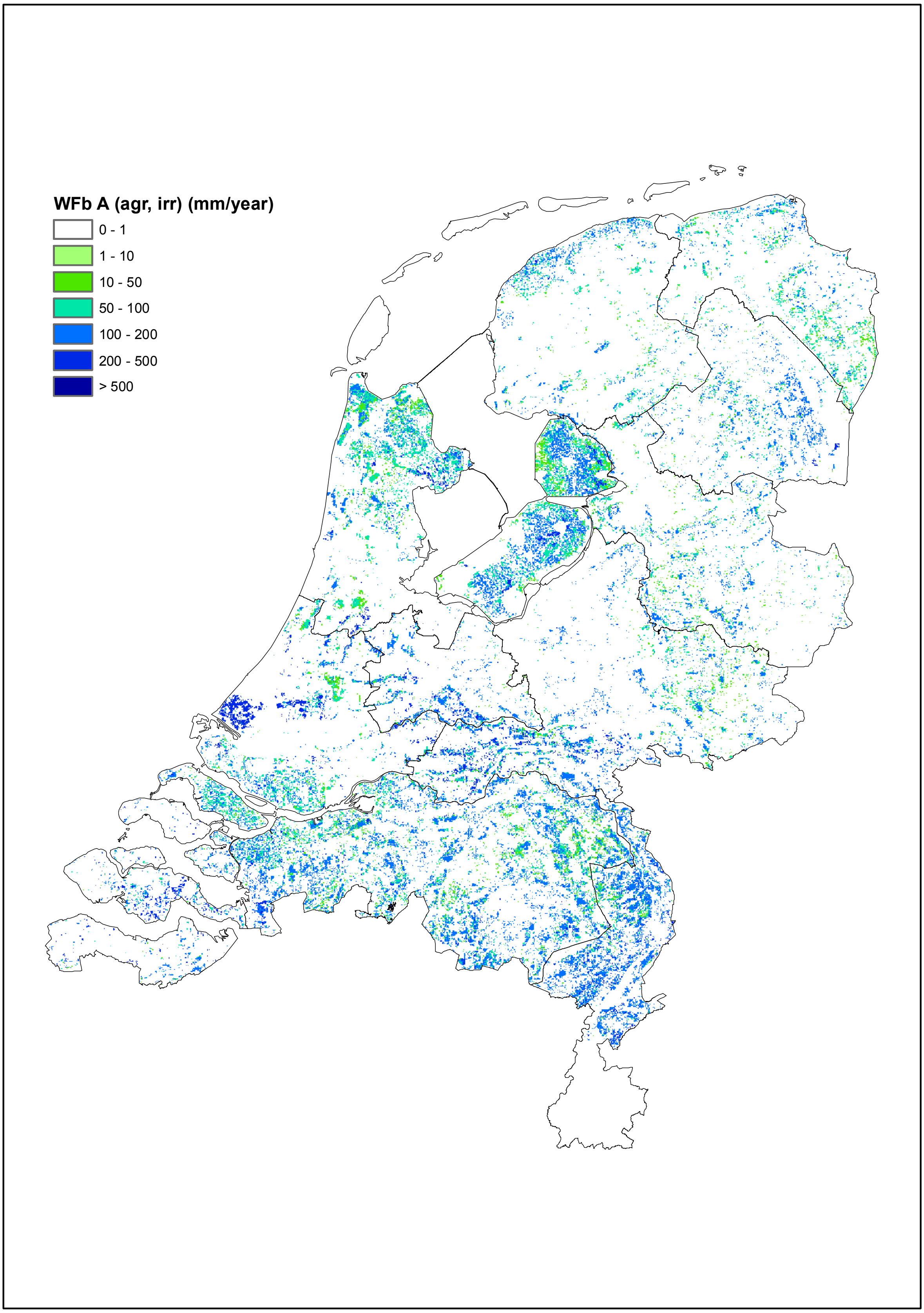

Figure 3.1. Blue WF of agriculture related to irrigation calculated based on method A.

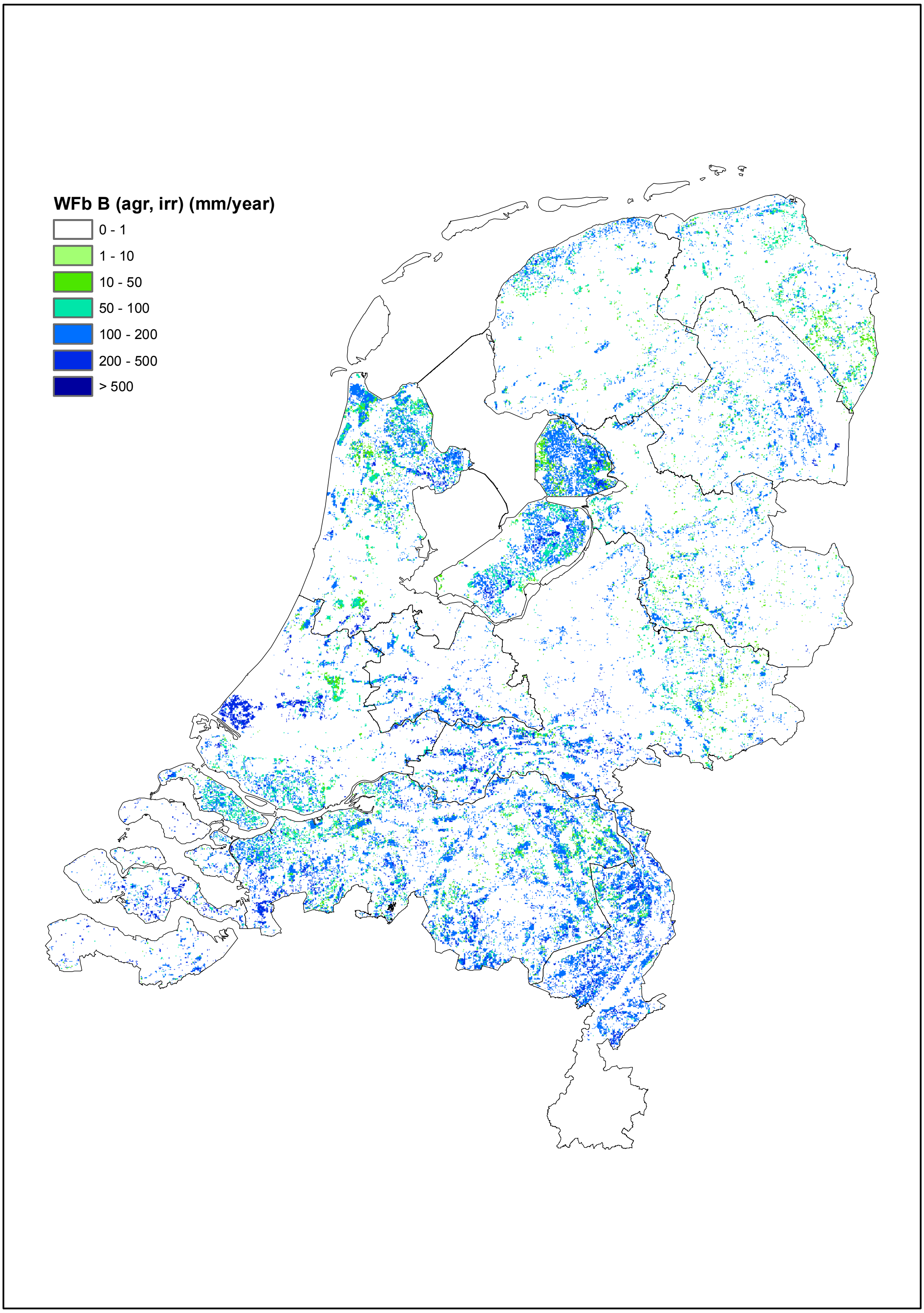

Figure 3.2. Blue WF of agriculture related to irrigation calculated based on method B.

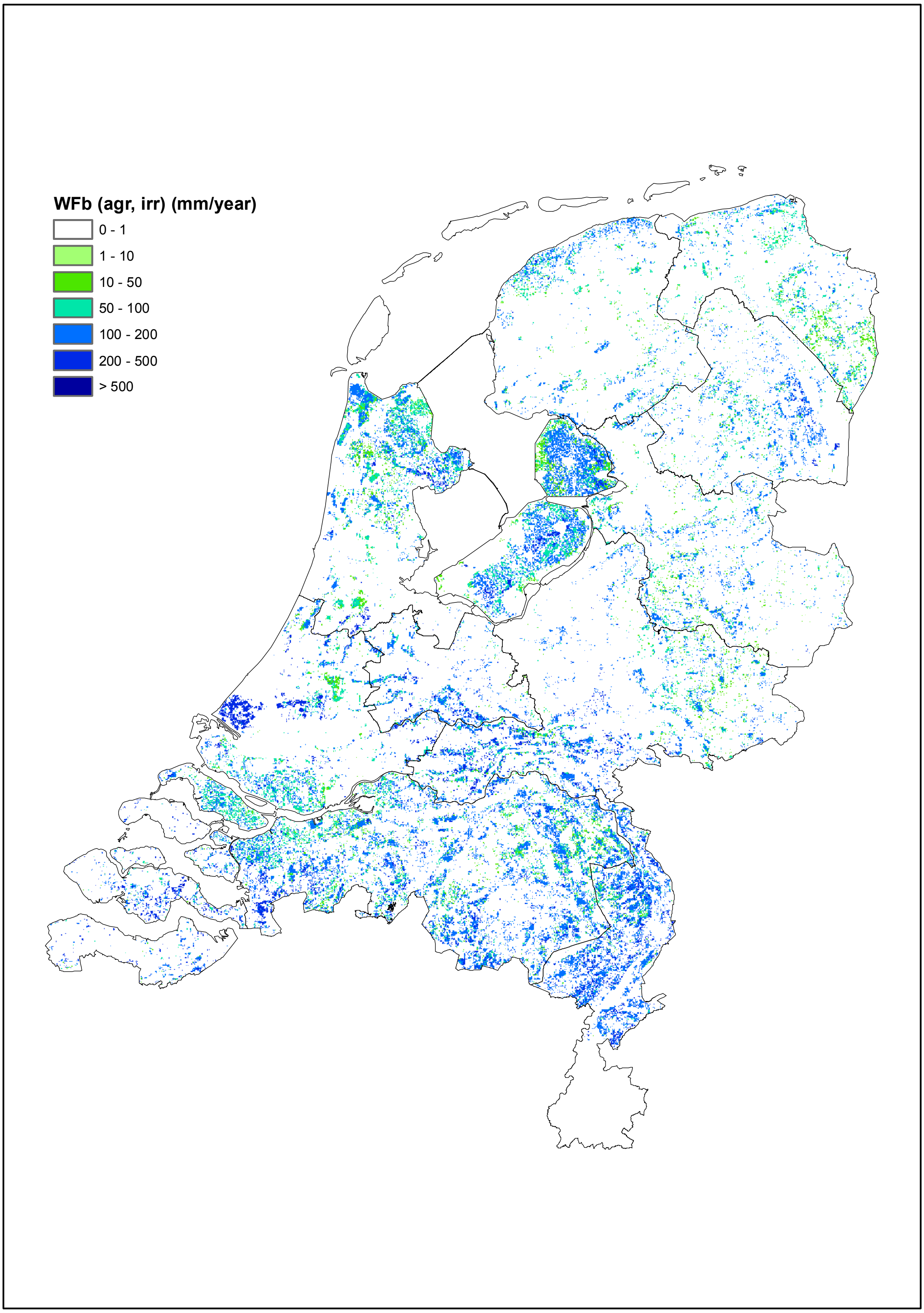

Figure 3.3. Blue WF of agriculture related to irrigation calculated based on method C.

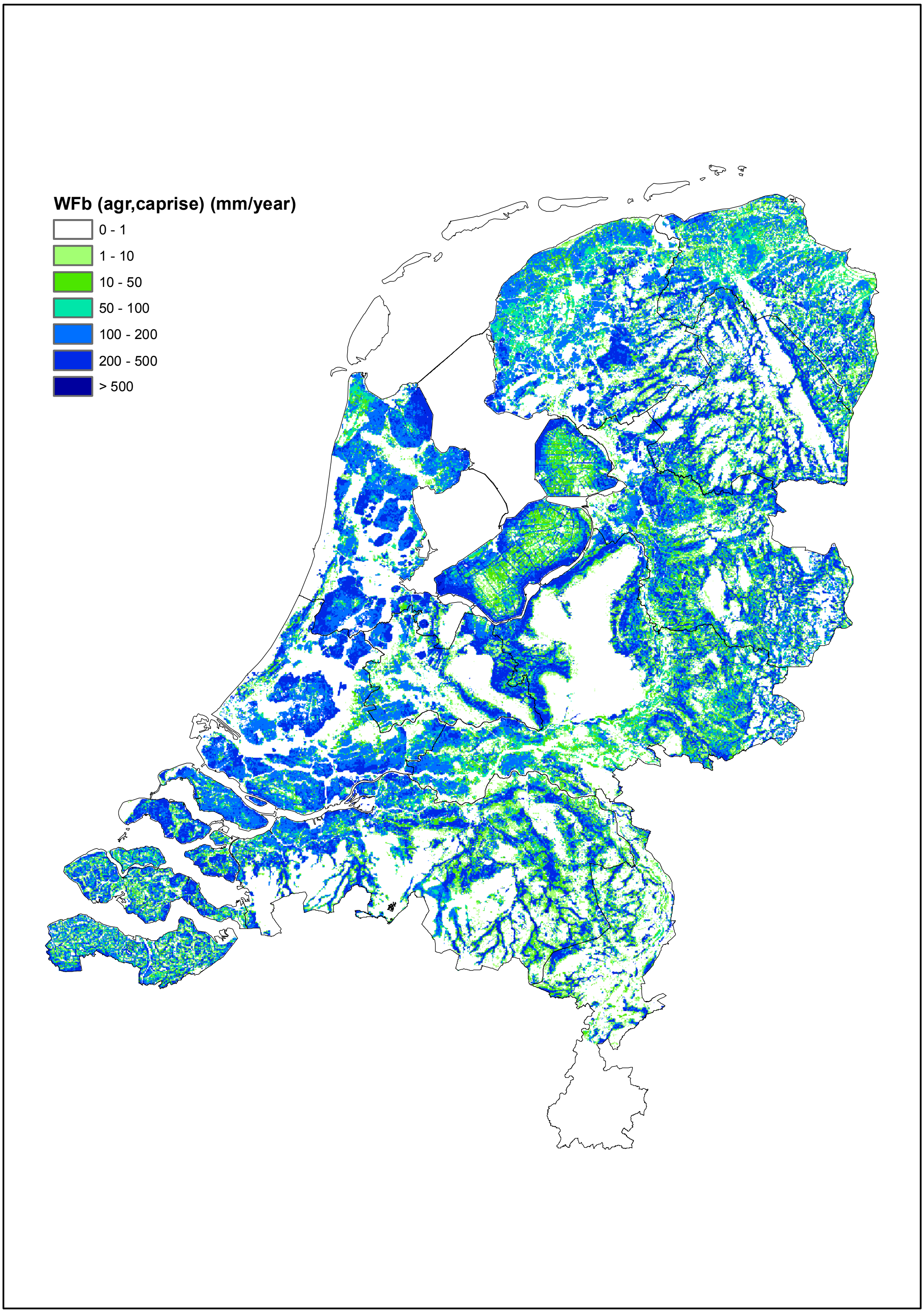

Figure 3.4. Blue WF of agriculture related to capillary rise.

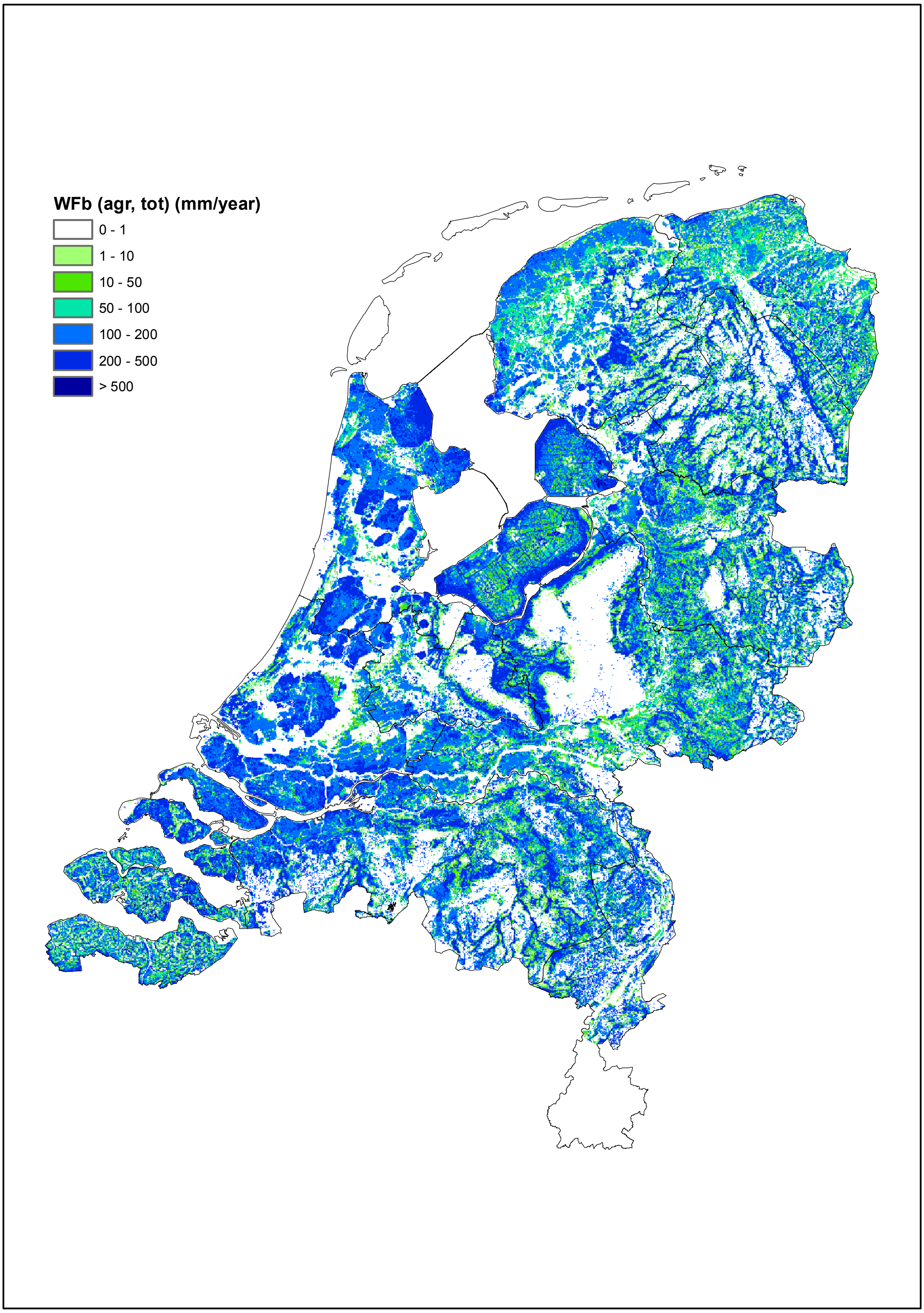

Figure 3.5. Total blue WF of agriculture, related to irrigation and capillary rise.

The blue WF of agriculture per land use type is shown in Table 3.2. The blue WF of agricultural grass, maize, beets and cereals is mainly due to capillary rise, while for potatoes, other crops, tree nurseries, orchards and flower bulbs irrigation and capillary rise contribute more or less equally to the blue WF. For greenhouses, only irrigation contributes.

Table 3.2. Blue water footprint of agriculture per land use type related to irrigation $WF_b(agr,irr)$, capillary rise $WF_b(agr,cr)$ and the sum of irrigation and capillary rise (Mm^3/year).

Land use type	$WF_b(agr,irr)$	$WF_b(agr,cr)$	$WF_b(agr,tot)$
Agricultural grass	209	1652	1861
Maize	22	148	170
Potatoes	103	137	240
Beets	9	95	104
Cereals	0	189	189
Other crops	63	140	203
Tree nurseries (*boomkwekerijen*)	12	12	24
Greenhouses (*glastuinbouw*)	51	0	51
Orchards (*boomgaarden*)	78	33	111
Flower bulbs (*bloembollen*)	15	18	31

Tables 3.3 and 3.4 show the blue WF of agriculture per province and per month related to irrigation and capillary rise, respectively. The seasonal pattern of evapotranspiration is clearly reflected by the seasonal patterns of both sources for the blue WF. The blue WF related to irrigation in the winter half-year is zero for all provinces and has its peak values mostly in June and July. The blue WF related to capillary rise is always above zero for all provinces and has its maximum values in May and June.

Table 3.3. Blue water footprint of agriculture related to irrigation, per province and per month (Mm^3/year).

Province	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Groningen	0.0	0.0	0.0	0.0	6.1	10.5	6.5	2.8	0.1	0.0	0.0	0.0	25.9
Friesland	0.0	0.0	0.0	0.0	1.5	34.1	21.0	9.0	0.1	0.0	0.0	0.0	65.6
Drenthe	0.0	0.0	0.0	0.0	4.2	11.5	5.1	1.4	0.0	0.0	0.0	0.0	22.3
Overijssel	0.0	0.0	0.0	0.0	22.1	21.0	23.2	7.7	0.3	0.0	0.0	0.0	74.3
Gelderland	0.0	0.0	0.0	0.0	3.1	7.9	5.9	2.6	0.0	0.0	0.0	0.0	19.6
Utrecht	0.0	0.0	0.0	0.0	11.4	17.7	27.3	17.2	0.7	0.0	0.0	0.0	74.3
Noord-Holland	0.0	0.0	0.0	0.0	28.5	40.3	59.8	26.5	0.7	0.0	0.0	0.0	155.9
Zuid-Holland	0.0	0.0	0.0	0.0	10.1	27.0	12.0	2.9	0.5	0.1	0.0	0.0	52.6
Zeeland	0.0	0.0	0.0	0.0	9.5	10.2	6.8	0.4	0.0	0.0	0.0	0.0	27.0
Noord-Brabant	0.0	0.0	0.0	0.0	7.9	5.7	7.5	2.6	0.2	0.0	0.0	0.0	24.0
Limburg	0.0	0.0	0.0	0.0	5.4	7.7	10.2	3.7	0.3	0.0	0.0	0.0	27.3
Flevoland	0.0	0.0	0.0	0.0	13.3	18.2	23.4	9.4	1.1	0.0	0.0	0.0	65.4
Total	0.0	0.0	0.0	0.0	123	212	209	86	4	0.1	0.0	0.0	634

Table 3.4. Blue water footprint of agriculture related to capillary rise, per province and per month (Mm^3/year).

Province	Jan	Feb	March	April	May	June	July	Aug	Sep	Oct	Nov	Dec	Total
Groningen	4.6	5.9	7.7	12.4	52.3	54.9	37.2	24.7	15.4	4.9	5.4	1.7	227.0
Friesland	3.7	4.5	5.5	9.4	33.0	33.4	27.9	19.6	16.9	6.0	6.7	2.3	168.9
Drenthe	4.2	4.3	5.2	10.4	87.1	73.8	34.9	20.2	17.1	3.7	5.6	1.6	268.1
Overijssel	7.3	7.0	10.8	17.0	119.9	71.6	58.1	34.9	22.6	6.8	6.6	2.5	365.3
Gelderland	3.5	3.6	3.9	6.6	43.7	59.7	24.8	17.1	10.9	3.0	4.8	1.4	182.9
Utrecht	1.7	1.8	3.1	3.2	18.4	11.8	15.4	11.1	6.0	2.3	1.7	0.6	77.1
Noord-Holland	7.7	7.7	12.8	17.1	91.7	73.2	75.6	43.7	27.5	9.0	8.7	3.4	378.3
Zuid-Holland	4.8	4.7	5.6	9.0	62.2	61.5	47.1	24.0	20.0	5.0	6.2	2.7	252.7
Zeeland	6.1	6.5	9.7	14.3	91.9	69.9	51.7	27.2	17.9	5.8	7.1	2.3	310.5
Noord-Brabant	2.0	2.1	3.0	5.2	34.0	25.5	19.7	10.5	7.8	2.2	2.2	1.0	115.4
Limburg	4.2	3.9	6.4	7.1	35.7	51.1	47.8	19.0	13.9	4.2	5.1	2.1	200.4
Flevoland	5.4	5.0	5.8	9.2	74.8	73.1	55.4	23.6	17.4	4.4	5.1	3.0	282.3
Total	55	57	80	121	745	660	496	276	193	57	65	25	2829

3.2 Blue WF of industry and households

Tables 3.5 presents the blue WF of industrial production and domestic water supply by province. The ground-WF and surface-WF are shown separately. The main contribution for both industrial production and domestic water supply is from groundwater, although in some provinces (i.e. Gelderland, Utrecht, Zuid-Holland and Noord-Brabant) the contribution from surface water is equally important. Figures 3.6 to 3.10 show maps with the ground-WFs and surface-WFs of industries and households in the Netherlands. Regarding the surface-WF of households, we show two maps: surface-WF related to direct surface water abstractions, and surface-WF related to bank infiltration.

Table 3.5. Blue water footprint of industrial production and domestic water supply per province (Mm^3/year).

Province	Industrial production			Domestic water supply		
	Groundwater	Surface water*	Total	Groundwater	Surface water	Total
Groningen	11.2	0	11.2	18.4	6.8	25.2
Friesland	8.5	0	8.5	46.2	0.0	46.2
Drenthe	7.9	0	7.9	58.4	0.0	58.4
Overijssel	3.9	0	3.9	55.8	0.0	55.8
Gelderland	27.8	0	27.8	134.4	77.0	211.4
Utrecht	7.4	0.5	7.9	77.4	126.6	204.0
Noord-Holland	19.3	0.1	19.4	7.2	77.0	84.2
Zuid-Holland	22.8	0.1	22.9	43.9	41.2	85.1
Zeeland	2.5	0	2.5	1.2	0.0	1.2
Noord-Brabant	44.2	0	44.2	205.0	199.0	404.0
Limburg	14.3	0	14.3	69.1	21.5	90.5
Flevoland	3.2	0	3.2	29.9	0.0	29.9
Total	173	0.7	174	747	549	1296

* Based on top 20 users. Excludes surface water use in electricity production.

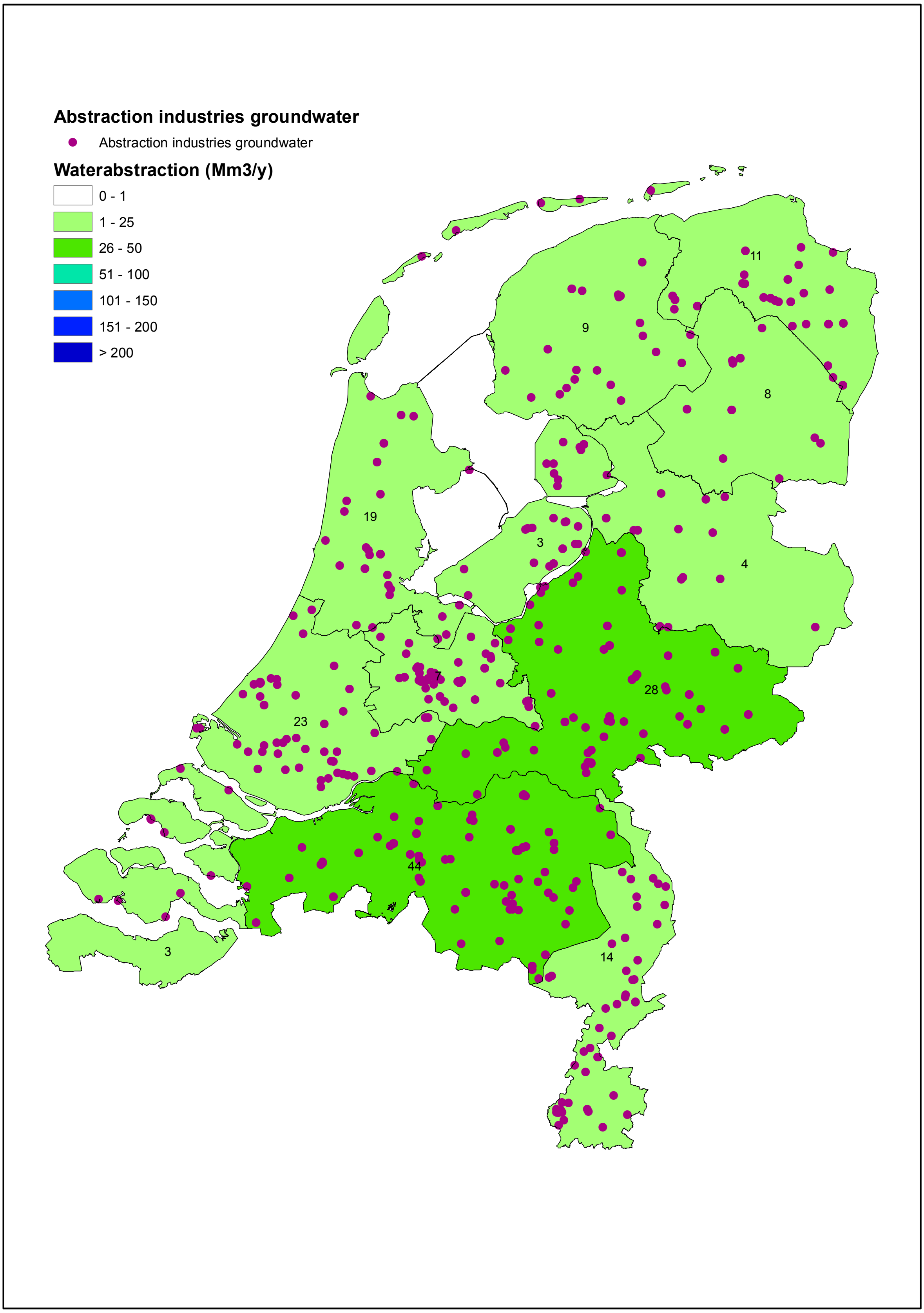

Figure 3.6. Ground-WF of industries per province (Mm^3/yr).

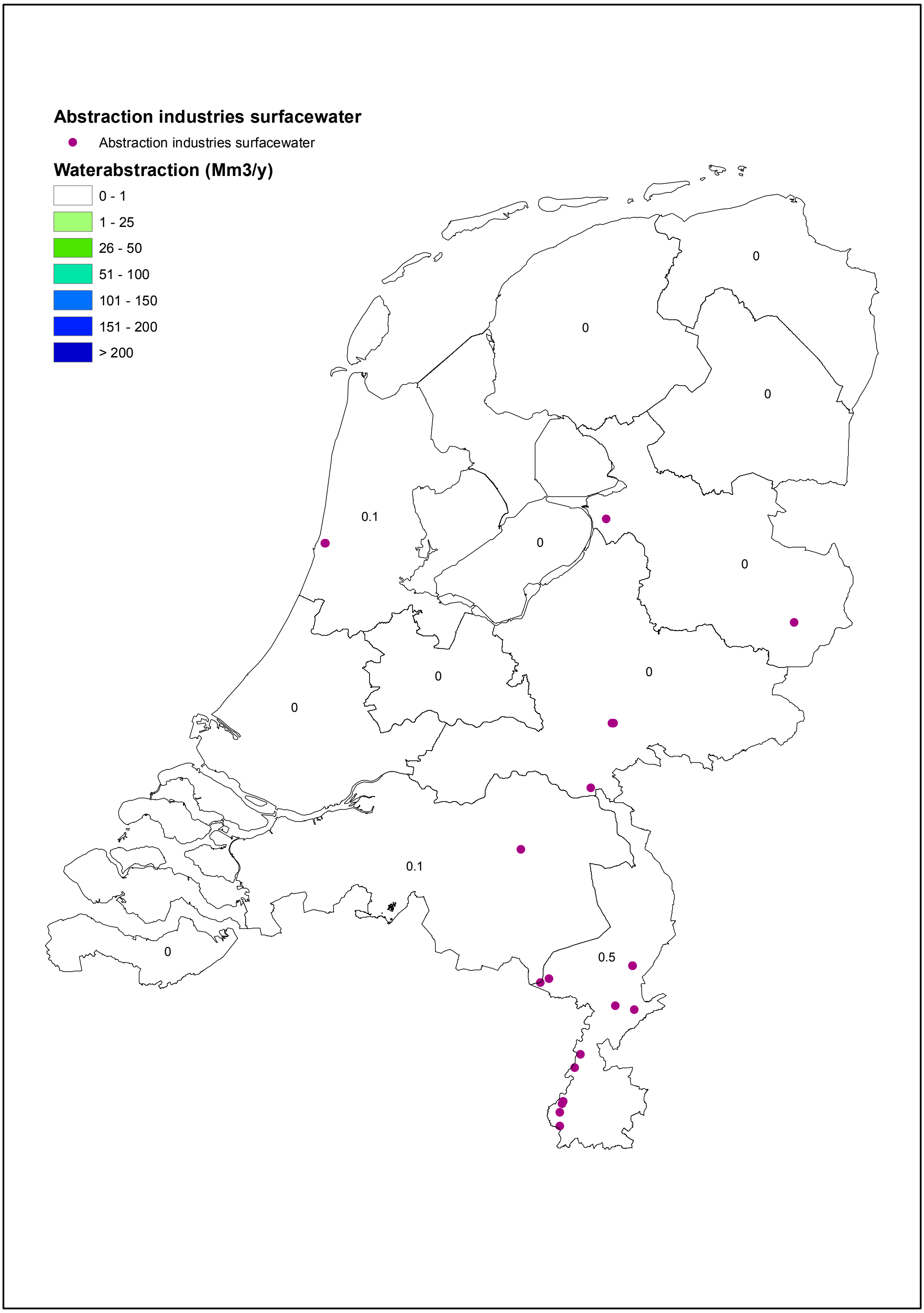

Figure 3.7. Surface-WF of industry per province (Mm^3/y).

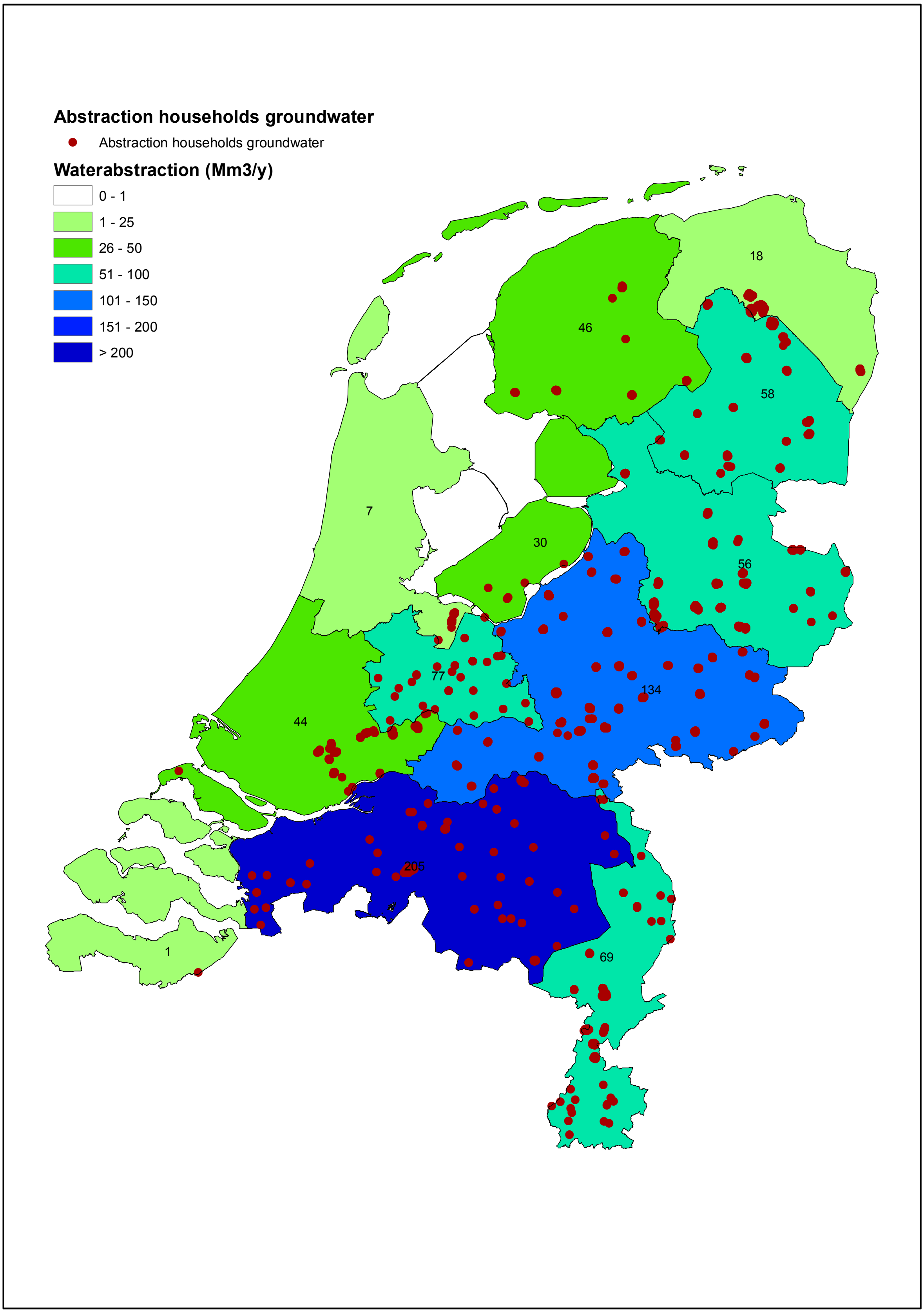

Figure 3.8. Ground-WF of households per province (Mm³/yr).

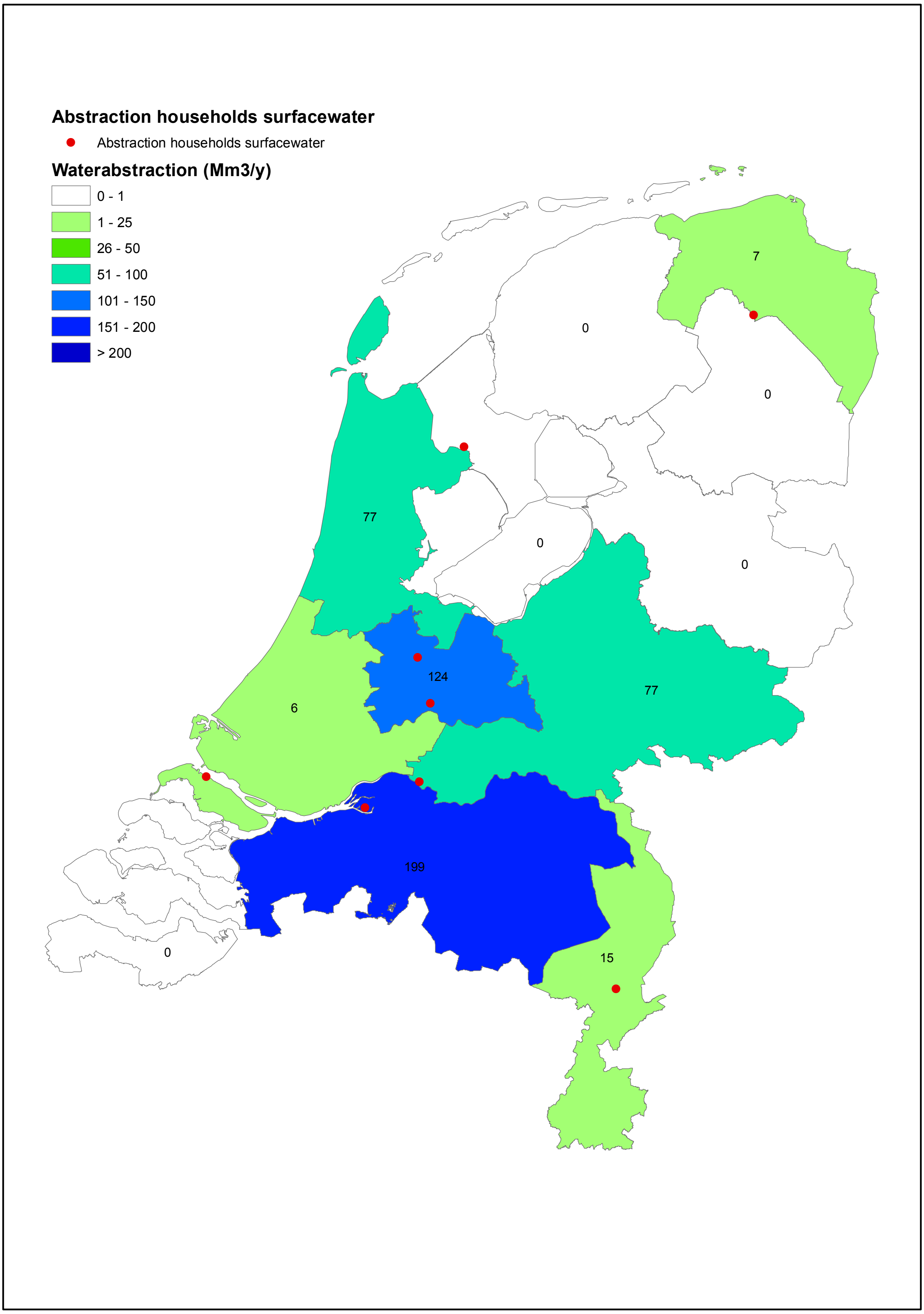

Figure 3.9. Surface-WF of households per province related to direct surface water abstractions (Mm^3/y).

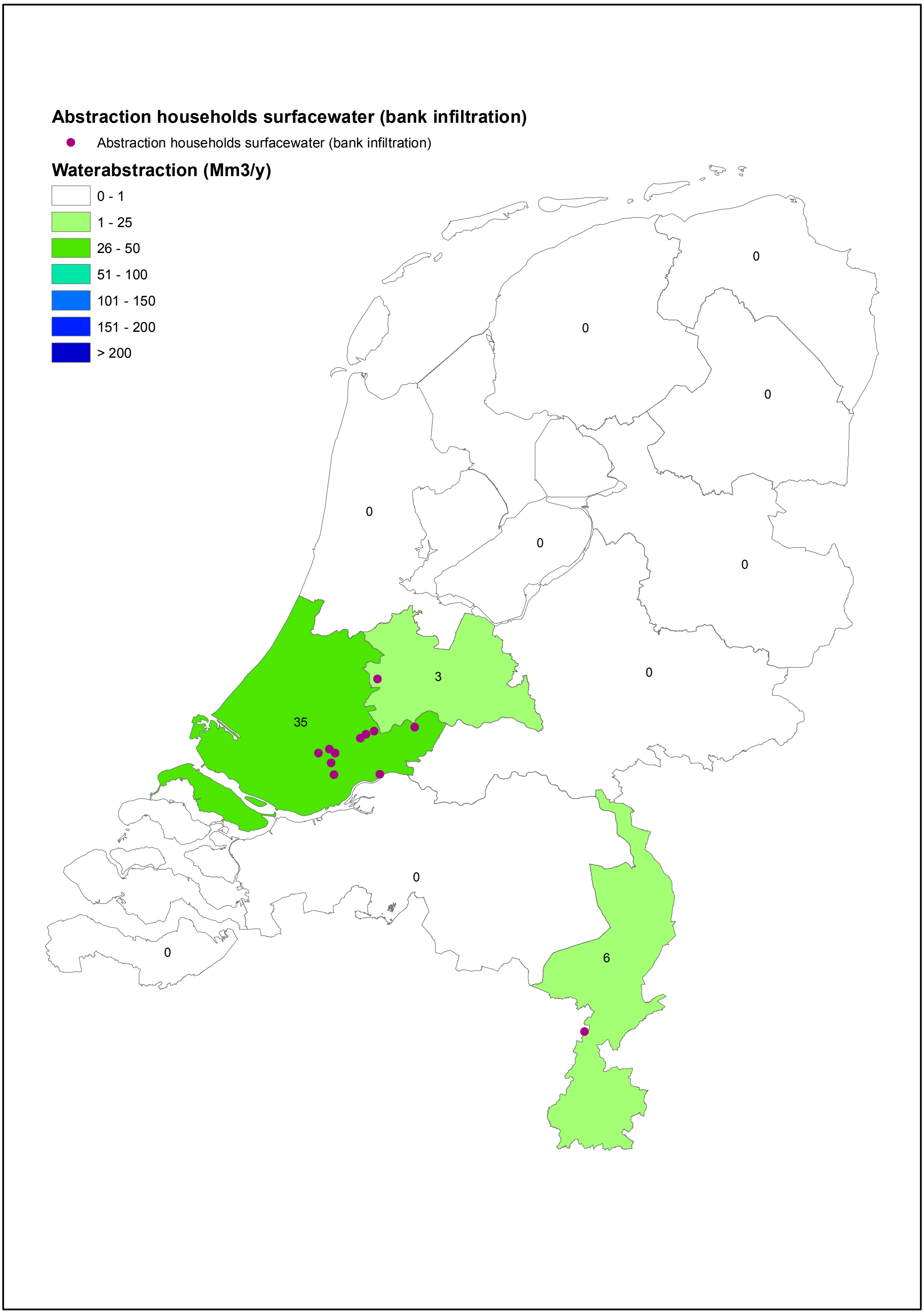

Figure 3.10. Surface-WF of households per province related to bank infiltration (Mm^3/y).

3.3 Blue WF of water management

Water from the main surface water system in the Netherlands is not only used for water supply to agriculture, industries and households, but also for flushing (*doorspoeling*) of smaller water courses to maintain water quality and for water level management (*peilbeheer*) to maintain desired ground and surface water levels in the various parts of the country.

It can be argued that flushing requires water but has no blue WF, because the water abstracted for flushing is not to be consumed and will be returned to the main surface water system from which it has been withdrawn. At the scale of the country as a whole, this is certainly true: water for flushing does not get lost. On the other hand, one can argue that – at least in the complex system of watercourses in the Netherlands – much of the water abstracted for flushing will not go back to the same main stream as from which it was withdrawn. In those cases, the abstracted water should be considered a blue WF in the watercourse from which the water is abstracted, since it is to be considered consumptive use. Whether water abstracted for flushing is consumptive water use thus depends on the spatial level of analysis. We do not show results here for the blue WF of flushing, because it is difficult on the basis of NHI outputs to determine which fractions of the water abstracted for flushing in the different parts of the country will return to the watercourse from which the water was abstracted. Besides, when adding water abstractions for flushing in different parts of the country there is the risk of double counting. If water is used to flush one area and then another area, it should not be counted twice. Due to the complex nature of the Dutch water system, where watercourses form a network rather then a simple scheme of confluences and where the water in many watercourses can flow both directions, it requires very careful analysis to determine when certain abstractions for flushing need to be considered as consumptive water use.

Abstractions for water level management will not be returned to the stream from which they were abstracted, at least not in the same part of the year. Therefore, they need to be regarded as a blue WF. Figure 3.11 presents the blue WF related to water level management per land-surface-water (LSW) unit. The spatial variability is high, with peak values of more than 500 mm per summer half-year in Central Holland and Southern Friesland / North-western Overijssel.

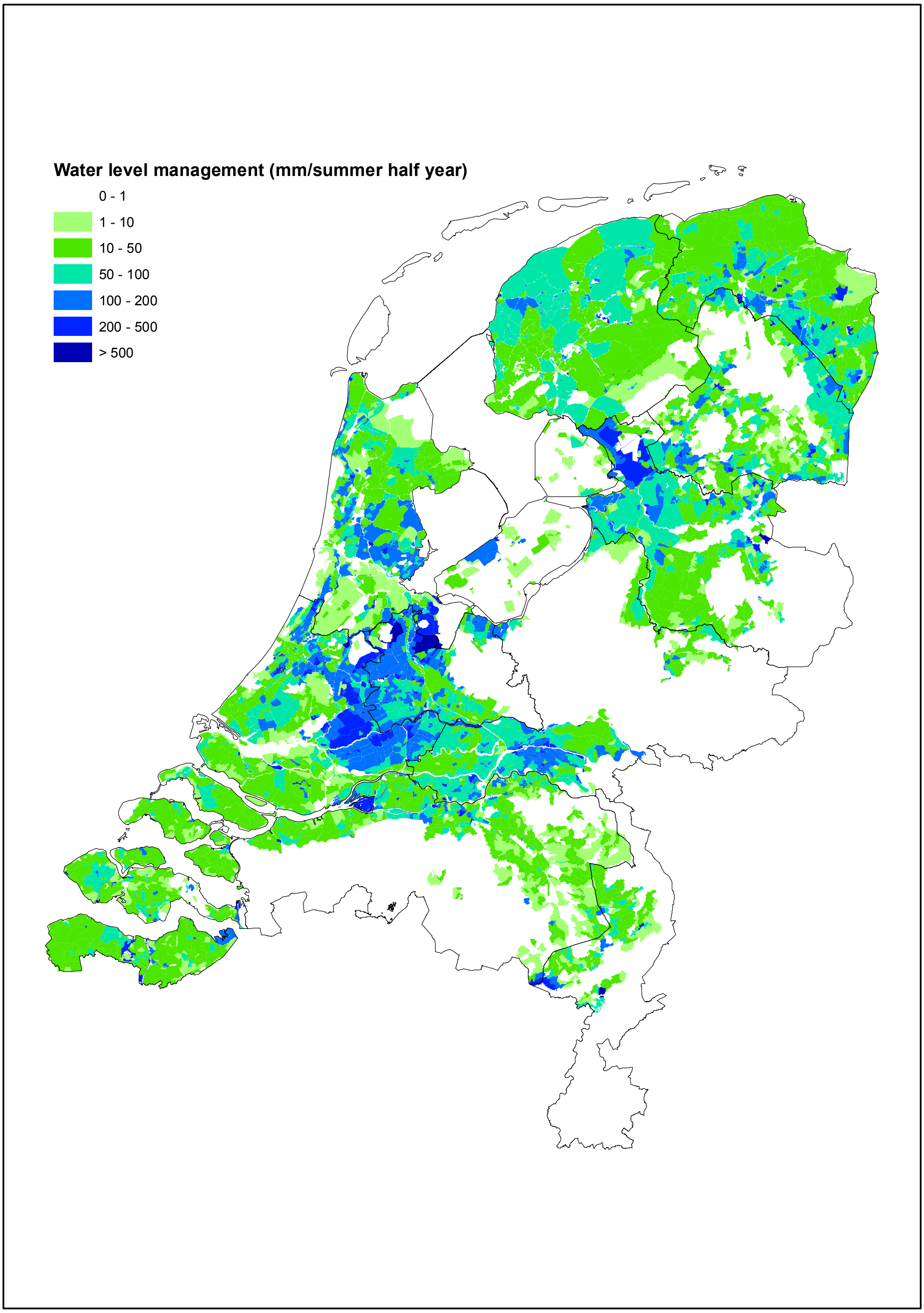

Figure 3.11. Blue WF of water level management per LSW (mm per summer half year).

3.4 Comparison with Mekonnen & Hoekstra (2011a,b)

There has been one earlier spatially explicit study on the total blue WF within the Netherlands (Mekonnen and Hoekstra, 2011a,b; Hoekstra and Mekonnen, 2012). This was a global study, estimating the WF across the globe at a 5 × 5 arc minute resolution level (which comes to grid cells of 9.3 km North-South × 5.8 km West-East in the Netherlands), based on global databases regarding land use, climate, etc. Appendix 1 presents the total blue WF within the Netherlands as was calculated in this global study. There are very substantial differences between the values found in the current study and the global study. The current study gives a total blue WF of agriculture in the Netherlands of 3463 Mm^3/yr (for a dry year). If we look only at the irrigation-related blue WF, we find a value of 634 Mm^3/yr. Mekonnen and Hoekstra (2011a,b) give a much lower value of 116 Mm^3/yr (for an average year, period 1996-2005). The Netherlands Statistics Office estimates the water withdrawal in the agricultural sector in the Netherlands at 71 Mm^3/yr (CBS, 2011), of which 34% would originate from surface water and 66% from groundwater. FAO's AquaStat database provides the same value of 71 Mm^3/yr for the water withdrawal in the agricultural sector in the Netherlands at (FAO, 2012). This value is the upper limit for the blue WF (since not all withdrawals may be consumptive use). The major reason for the relatively large estimate in the current study must be the fact that this estimate is for a dry year. In the current study, about one third of the irrigation-related WF of Dutch agriculture relates to grassland. In Mekonnen and Hoekstra (2011a,b), this is even two thirds. In both cases, this component is the single largest component. Also in both the current and the global study, potatoes come out as the sector with the second largest contribution to the blue WF in agriculture.

The difference between the current and the global study in the estimated WF of industrial production can be understood as follows. The global study considered the sum of water use in manufacturing and electricity production and applied a consumptive water use fraction of 5% to the whole. The estimate is based on a total industrial water withdrawal of 4760 Mm^3/yr, as previously reported by FAO's AquaStat database (after a recent update, AquaStat reports an industrial water withdrawal of 9283 Mm^3/yr). The current study considers the water use in manufacturing (food processing, paper industry, chemical industry, refineries, metal industry and 'other industry'), but excludes the use of surface water in electricity production. Furthermore, for the water withdrawals in the manufacturing industry a consumptive water use fraction of 100% is applied, which is certainly reasonable for the groundwater withdrawals, which are not returned to the groundwater system. The ground-WF of manufacturing found in the current study (173 Mm^3/yr) is a bit higher than the value provided by CBS (2011), which is 155 Mm^3/yr. A final note should be made on the estimated surface-WF of the manufacturing industry in the current study (0.7 Mm^3/yr), which is much lower than indicated by some other sources. According to CBS (2011) and CBS et al. (2011), the aggregated surface water withdrawal in the manufacturing industry is about 3000 Mm^3/yr. It remains unclear where the difference comes from.

The estimates for the WF of domestic water supply appear to differ for two reasons. First, the global study used data from FAO's AquaStat database on domestic water withdrawals as reported before a recent update of the database. Formerly, AquaStat reported a domestic water withdrawal in the Netherlands of 490 Mm^3/yr, while now it reports 1252 Mm^3/yr, in line with CBS (2011). VEWIN, the Association of Dutch Water Companies, reports 1217 Mm^3/yr for drinking water abstractions in the year 2010 (VEWIN, 2012), which is close to the current AquaStat figure. NHI gives a domestic water withdrawal of 1296 Mm^3/yr, which is a bit higher than VEWIN's value. Another reason why the estimates for the WF of domestic water supply in the current study and the global study differ is that the global study assumed a consumptive use fraction of 10%, while in the current study it is assumed that none of the water used in households will return to the water system from which it was withdrawn (and thus a consumptive water use fraction of 100%), which is certainly true for the groundwater withdrawals. If two corrections would be applied to the estimate in the global study (use of the new AquaStat figure and application of a consumptive water use fraction of 100% instead of 10%), then the global water study would give a WF of domestic water supply of 1252 Mm^3/yr, which shows that the difference between the two studies can simply be attributed to these two points of difference between the two studies.

Regarding the WF of animal water supply, the global study gives a rather high estimate (386 Mm^3/yr) compared to the Dutch Statistical Office (CBS, 2011) (75 to 150 Mm^3/yr). The current study does not include the WF of the livestock sector, because this sector is not included in NHI. However, the total water use in the livestock sector in the Netherlands partly consists of tap water (about 35 Mm^3/yr according to CBS, 2011). This part of the WF of the livestock sector is included in this study, as part of the figures presented as 'WF of domestic water supply'.

4. Discussion

In this first exploration of how NHI can be used for assessing the blue WF in the Netherlands we came to an interesting finding regarding the role of capillary rise in the evapotranspiration of crops and we came across a number of challenges with respect to the use of NHI. Below we will discuss the issue of capillary rise in water footprint accounting and the challenges regarding NHI point by point.

Capillary rise. The study raised a new topic for discussion in the field of WF accounting by showing that capillary rise can substantially contribute to the evapotranspiration of crops. Since this capillary rise originates from the groundwater, this evapotranspiration should be considered as a blue WF of agriculture. It is yet to be seen to which extent this finding is typical to lowland conditions as in the Netherlands, whereby high groundwater levels contribute to the water supply to crops. The situation in the Netherlands is even more typical in that groundwater levels are artificially managed, whereby surface water is used in dry periods to maintain certain groundwater levels. Therefore, the question becomes relevant what is the source of the groundwater that evaporates after capillary rise: is it infiltrated rainwater, infiltrated irrigation water or horizontal replenishment from nearby surface water bodies? There may be an overlap between the blue WF in agriculture due to capillary rise and the blue WF of water level management, because capillary rise and thus crops may benefit from groundwater when water is taken into the area in order to maintain a certain groundwater level. However, capillary rise and thus crops benefiting from groundwater may also occur in periods in which no water is taken into the area for water level management. In this case, the origin of the groundwater must be local infiltration of rain or irrigation water.

Tracking soil moisture origin. The estimation of the blue WF of agriculture with NHI can be improved by keeping track in the model what fractions of the soil moisture in each plot stem from rainwater, irrigation water and capillary rise, respectively. This can be done on a daily basis, the time step in the model. In this way, it will be possible, each day, to know which fraction of the evapotranspiration from soil moisture originates from each of these three sources.

Distinction between ground- and surface-WF. Distinguishing between a ground-WF and a surface-WF as done in the current study for the industrial and domestic water supply sectors has a great value and diverges from most of the earlier WF studies that did not distinguish between the two sorts of blue WF. The reason that previous studies did not make the distinction has been the lack of data regarding the source of water used in the different sectors. The current study could make the distinction because NHI explicitly includes the source for all water withdrawals. Regarding the source of water supplies to industries and households, NHI uses empirical data. In the case of agriculture, NHI determines for each plot whether the water for irrigation will come from surface or groundwater. We have presented the totals only. It would be valuable to validate the outcomes of NHI regarding the distinction it makes between surface and groundwater withdrawals for irrigation.

Consumptive water use fractions. The study shows the vulnerability of blue WF estimates to the assumptions regarding the percentage of ‘consumption’ versus ‘return flow’. The differences in the WF estimates for the industrial and domestic water supply sectors between the current study and the global study by Mekonnen and Hoekstra (2011b) could be largely explained by the differences in underlying assumptions on the consumptive water use fractions. A relevant issue appears to be the issue of scale. At the scale of the country as a whole and when considering the ground and surface water bodies as one total (the approach in the global study), the return flow from industries and households is much bigger then when the question of return flow is evaluated at the level of smaller land units and separately for ground and surface water (the approach in the current study). NHI would greatly improve if it would include a water balance of industries and households. In NHI there is no modelling of the fate of water supplied to industries and households, so that there is no proper basis to estimate the blue WF. In the current study we have simply shown the total water abstractions as the blue WF, but this assumes that there are no return flows.

<u>Calibration and validation</u>. The blue WF of agriculture is essentially a model-based estimate. The current study, based on NHI, does not differ in this sense from the global study by Mekonnen and Hoekstra (2011a) and other WF studies like for instance Fader et al. (2011). Model estimations are based on a certain simulated 'water demand' (depending on crops grown, soil and climate) and a subsequently simulated 'water supply' (depending on assumptions regarding actual allocation). It is notably difficult to calibrate and validate such models based on empirical data. As a result, the uncertainty in the estimated blue WF in agriculture is probably very large, but how large is unknown. A model like NHI can be substantially improved if more attention is paid to the calibration of the various model parameters and validation of results based on empirical data. From a WF perspective, it would be most valuable to concentrate on the validation of the results regarding the actual irrigation of crop fields and the evapotranspiration over the year from those fields.

<u>Attributing the blue WF of agriculture and industry to final purposes</u>. To take full benefit from the WF concept, it would be useful to extend the scope of this study, by going beyond the question of what are the WFs of the various activities. The outcomes of this study become more interesting when addressing also the question what the benefit is of the various water footprints. It would be interesting to answer questions like: Which fraction of the water footprint in the Netherlands is related to the production of feed for producing livestock for meat? Which fraction of the water footprint is related to producing bio-energy crops? Which fraction of water is used for producing export products? What is the added economic or social value of each component in the WF in the various parts of the country? Only with such additional information, the WF concept can come to its full potential use in policy making.

<u>Attributing the blue WF of flushing and water level management to final purposes</u>. Flushing and water level management are not goals by themselves; these activities serve other final purposes. The blue WFs of flushing and water level management are in fact blue WFs of those final purposes. Flushing is done to maintain a good water quality, which in turn serves the various functions that benefit from the better water quality. Water levels in the Netherlands are managed for nature, agriculture, recreation, prevention of land subsidence and preserving wooden foundations. Each of these purposes has a value. Following the allocation method set out in the Water Footprint Assessment Manual (Hoekstra et al., 2011), the blue WF of water level management per LSW unit needs to be allocated (distributed) over the different purposes of water level management based on the relative

value of each purpose. Establishing the added value of maintaining a certain water level for nature, agriculture, recreation, and prevention of land subsidence in a certain LSW area will not be an easy task, so that probably rough estimates will need to be made. The advantage is that for the allocation of the WF to different purposes, one does not need to know the added values for the different purposes in absolute sense, but only relative to one another.

Green and grey WF. The current study has focused on the use of NHI to estimate the blue WF of various activities. The tool can probably be used without much effort for the assessment of the green WF in agriculture as well. The green WF is equal to the total WF minus the blue WF, whereby the former is equal to field evapotranspiration and the latter can be estimated as shown in the current study. Assessing the grey WF with NHI would require a major extension of the instrument: a module would need to be added that describes the application of fertilizers and pesticides in agriculture and the leaching and runoff to ground and surface water bodies. The scope of NHI is to describe water flows, not water quality, so this extension is not realistic until a major decision would be taken to integrate NHI and existing Dutch water quality models.

WF per unit of production. We have shown that it is possible to use the NHI to estimate the blue WF per activity in a spatial explicit way in terms of m^3 per month. We have not shown the WF per unit of product (per kilogram or per euro). As an example, we calculated the WF of maize in m^3 per month, but did not divide the total WF over the growing period by the total maize production in kilogram or euro per year. NHI does not include a crop growth module to simulate yield as a function of rain, irrigation and other relevant parameters, so that this step would only be possible if such crop growth module would be linked to NHI. There has been experience with this in the past: the agricultural model AGRICOM can be run based on NHI outputs to model crop damage and the reduced yield and production value (Van Bakel et al., 2009; Veldhuizen et al., 2010). Knowing the WF of the various products produced in the Netherlands per unit of product is of interest from an international competition perspective. Furthermore, it can be relevant in the context of water allocation within the country under conditions of shortage. The WF per kilogram of maize can be much larger in one part of the country compared to another part, which means that allocating water to the former rather than the latter area will be much more productive. A considerable difference in WF per kilogram can occur, for example, when in one area just some irrigation water is required, while in another area also substantial water volumes are required for maintaining a certain water level for agriculture or for flushing water courses to keep them fresh.

5. Conclusion

We assume that the blue WF estimates from NHI are better than the outcomes of the earlier global study for two reasons: (1) NHI has a much higher spatial resolution and (2) NHI uses detailed Dutch databases rather than data from global databases. However, the precise assumptions taken in the quantification of the blue WF appear to be as important for the final outcome as the model and databases used. The estimate of the blue WF of agriculture is very sensitive to the assumptions regarding irrigation water requirements and actual allocation (which in NHI depends on a certain priority scheme regarding water allocations in the case of shortages, the so-called *verdringingsreeks*). The estimate of the blue WF of industries and households is very sensitive to the assumption regarding the consumptive fraction of water withdrawals. In its current form, NHI does not provide a solid basis to derive this consumptive water use fraction.

The study shows the relevance of water-balance thinking, as opposed to water-level thinking. Dutch water management has traditionally been driven by the wish to maintain certain water levels to best serve agriculture and nature and prevent land subsidence and degradation of wooden foundations of old buildings. Thinking in terms of water balances and allocation of water volumes over different areas in the country and to different purposes has never been the primary focus. In the case of water scarcity and necessary trade-offs in water allocation, water-balance thinking becomes crucial. Until recently, most water boards were unable to draw a water balance for their area. With NHI, a good step has been made in the direction of making proper water balances at different spatial scales and at a fine temporal resolution. As discussed in the previous section, a major challenge is still the closing of the balance of water withdrawn by industries and households. A challenge for the current Dutch water management practice is to translate what a certain water-level policy means in terms of allocating water volumes. During periods of drought, the water management question centres on allocating water volumes and making trade-offs therein.

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Appendix I. Blue water footprint within the Netherlands as calculated by Mekonnen and Hoekstra (2011a,b) for an average year (1996-2005).

Province	Monthly blue water footprint related to crop production (Mm^3)													Blue water footprint of industrial production* (Mm^3/yr)	Blue water footprint of domestic water supply** (Mm^3/yr)	Blue water footprint of animal water*** supply (Mm^3/yr)	Total blue water footprint (Mm^3/yr)
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total				
Groningen	0,00	0,00	0,00	0,01	1,66	1,60	1,35	1,32	0,45	0,00	0,00	0,00	6,39	8,07	1,68		16,14
Friesland	0,00	0,00	0,00	0,01	0,80	0,84	0,67	0,46	0,12	0,00	0,00	0,00	2,90	10,29	2,11		15,29
Drenthe	0,00	0,00	0,00	0,01	1,69	1,79	1,96	1,63	0,61	0,01	0,00	0,00	7,70	5,58	1,15		14,43
Overijssel	0,00	0,00	0,00	0,02	2,27	2,03	1,77	1,24	0,56	0,00	0,00	0,00	7,90	13,20	2,71		23,82
Gelderland	0,00	0,00	0,00	0,12	4,00	3,41	3,08	2,78	0,67	0,01	0,00	0,00	14,07	30,13	6,28		50,49
Utrecht	0,00	0,00	0,00	0,01	0,38	0,35	0,41	0,28	0,01	0,00	0,00	0,00	1,45	18,10	3,71		23,26
Noord-Holland	0,00	0,00	0,00	0,04	2,36	2,70	3,31	2,07	0,13	0,00	0,00	0,00	10,62	26,34	5,40		42,36
Zuid-Holland	0,00	0,00	0,00	0,12	1,50	1,63	2,03	1,45	0,15	0,00	0,00	0,00	6,88	47,06	9,65		63,59
Zeeland	0,00	0,00	0,00	0,04	0,77	0,80	1,33	0,92	0,15	0,00	0,00	0,00	4,01	9,42	1,93		15,37
Noord-Brabant	0,00	0,00	0,00	0,25	6,88	7,87	7,81	7,53	1,76	0,01	0,00	0,00	32,11	40,47	8,30		80,88
Limburg	0,00	0,00	0,00	0,05	2,45	3,45	2,49	3,47	0,81	0,05	0,00	0,00	12,77	16,94	3,54		33,24
Flevoland	0,00	0,00	0,00	0,09	2,15	1,63	2,43	1,82	0,61	0,00	0,00	0,00	8,73	12,39	2,54		23,67
	0,00	0,00	0,00	0,09	2,15	1,63	2,43	1,82	0,61	0,00	0,00	0,00	115,54	238,00	49,00	386	788,43

* Based on industrial water withdrawal in NL of 4760 Mm^3/yr (as was provided by FAO's Aquastat in the past) and a **consumptive use fraction of 5%**. Distributed over provinces based on population density. Note that currently Aquastat gives a number of 9283 Mm^3/yr

** Based on domestic water withdrawal in NL of 490 Mm^3/yr (as was provided by FAO's Aquastat in the past) and a **consumptive use fraction of 10%**. Distributed over provinces based on population density. Note that currently Aquastat gives a number of 1252 Mm^3/yr. Further note that according to VEWIN, drinking water abstraction in NL is 1217 Mm^3/yr and water use by households is 120 litre/day/cap, which is, with a population of 16.6 million, equal to 730 Mm^3/yr. The difference between 1217 and 730 Mm^3/yr refers to other domestic water users (service sector, industries taking from public water supply and municipalities).

*** Probably an overestimate, because a consumptive water use fraction of 100% was assumed.

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