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Selection of spatial scale for assessing impacts of groundwater-based water supply on freshwater resources

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Abstract

Indicators of the impact on freshwater resources are becoming increasingly important in the evaluation of urban water systems. To reveal the importance of spatial resolution, we investigated how the choice of catchment scale influenced the freshwater impact assessment. Two different indicators were used in this study: the Withdrawal-To-Availability ratio (*WTA*) and the Water Stress Index (*WSI*). Results were calculated for three groundwater based Danish urban water supplies (Esbjerg, Aarhus, and Copenhagen). The assessment was carried out at three spatial levels: (1) the groundwater body level, (2) the river basin level, and (3) the regional level. The assessments showed that Copenhagen's water supply had the highest impact on the freshwater resource per cubic meter of water abstracted, with a *WSI* of 1.75 at Level 1. The *WSI* values were 1.64 for Aarhus's and 0.81 for Esbjerg's water supply. Spatial resolution was identified as a major factor determining the outcome of the impact assessment. For the three case studies, *WTA* and *WSI* were 27% to 583% higher at Level 1 than impacts calculated for the regional scale. The results highlight that freshwater impact assessments based on regional data, rather than sub-river basin data, may dramatically underestimate the actual impact on the water resource. Furthermore, this study discusses the strengths and shortcomings of the applied indicator approaches. A sensitivity analysis demonstrates that although *WSI* has the highest environmental relevance, it also has the highest uncertainty, as it requires estimations of non-measurable environmental water requirements. Hence, the development of a methodology to obtain more site-specific and relevant estimations of environmental water requirements should be prioritized. Finally, the demarcation of the groundwater resource in aquifers remains a challenge for establishing a consistent method for benchmarking freshwater impacts caused by groundwater abstraction.

Highlights:

- The freshwater withdrawal impact on a sub-river basin scale is assessed.
- Spatial resolution is increased from regional to groundwater body scale.
- Increased spatial resolution markedly changes the quantified freshwater impact.
- Regional scale impact assessment does not reveal local water stress.
- Uncertain environmental water requirements influence results.

Keywords: Groundwater abstraction, water supply, water withdrawal impacts, water stress, water footprint

Abbreviations: EU-WFD, European Union Water Framework Directive; *EW*R, environmental water requirements; LCA, lifecycle assessment; RBMP River Basin Management Plan; *WR*, annually available water resource; *WS*: Water supply; *WSI*, Water Stress Index; *WTA*, Withdrawal-To-Availability ratio; *WU*, annual freshwater withdrawal.

Important terms: *Groundwater body*, a distinct volume of groundwater within an aquifer or aquifers; *river basin*, the land area that is drained by a river and its tributaries; *regional scale*, all groundwater bodies in the entire region (in this case Sjælland and Jylland, respectively).

1. Introduction

Many places around the world are experiencing increasing freshwater stress and frequent droughts that are intensified severely by industrial, household, or agricultural water use (Wada et al., 2013). It has been estimated that 20% of the World's major aquifers are being mined at an unsustainable rate (Gleeson et al., 2012) and with major aquifers depleting by up to 40 mm/yr, there are calls for increased appreciation of groundwater's special role in the provision of water for human and environmental needs (Famiglietti, 2014). Environmental consequences of groundwater abstraction are already receiving growing attention, particularly in Europe as a result of the European Union's Water Framework Directive (EU-WFD) (European Union, 2000), which sets the environmental objectives for Europe's water bodies, including both ground- and surface water. As a result of the EU-WFD and requirements for benchmarking (EBC, 2015; Vilanova et al., 2015), there is a growing relevance for water suppliers to use "water footprinting" or freshwater impact assessment as a basis for developing sustainable water strategies. This creates a pressing need for the development of a standard procedure for quantifying freshwater impacts associated with groundwater abstraction in water supplies.

Over the past few years, a wide range of methodologies have been proposed for the evaluation of the water use impacts of products or services (Berger and Finkbeiner, 2010; Kounina et al., 2013). These include indicators focusing on multiple areas of protection (Frischknecht et al., 2006; Pfister et al., 2009; Ridoutt and Pfister, 2010) as well as indicators focusing on specific impacts of freshwater use, such as potential damage to human health (Boulay et al., 2011) or ecosystem quality (van Zelm et al., 2011). The methodologies have mainly been applied at the river basin or regional scale (aggregating several river basins).

Impacts on freshwater resources depend on both the location of water withdrawal and the river basin scale (Jeswani and Azapagic, 2011; Loubet et al., 2013). Hence, in contrast to greenhouse gas emissions, which have effects at the global level, water use impacts are highly dependent on local sensitivity towards freshwater abstraction. Geographical scale therefore becomes a critical issue when evaluating the impacts of freshwater use, and an assessment at the national level may mask the impacts that occur at the local level.

Recently, a few studies have specifically addressed the freshwater impacts of local water supplies (Stoeglehner et al., 2011; Godskesen et al., 2013). While an optimal level of spatial resolution has not yet been identified, there are rising concerns that national-level and sometimes even basin-level assessments are insufficient (Tendall et al., 2013), although to the best of our knowledge there has been no assessment of how the delineation of local water supply abstraction affects the quantification of freshwater impacts.

Therefore, in order to provide a new insight into this field, we evaluate the effect of increasing the spatial resolution from the regional (sub-national) level to the basin level, and then further to the groundwater body level. Two indicators form the basis of widespread freshwater impact assessment methods (Jeswani and Azapagic, 2011): the Withdrawal-To-Availability (*WTA*) and Water Stress Indicator (*WSI*), which represent impacts with (*WSI*) and without (*WTA*) being water stress weighted. Through the analysis of three Danish water supplies, the challenges of comparing different cases of water abstraction are highlighted. The final aim of the study is to show the strengths and shortcomings of selected indicators and their potential use in individual water supply systems.

There are two reasons why Denmark provides a good case study for analysis of impacts on the groundwater resource and the importance of spatial scale: 1) Danish drinking water supply is entirely dependent on groundwater aquifers (IWA, 2014) and 2) Danish groundwater resources are well described with a national groundwater model covering the entire country (Henriksen et al., 2008, 2003) and datasets covering the entire country at the sub-river basin level (DNA, 2014).

2. Material and methods

2.1. Methods for quantifying freshwater impacts of groundwater abstraction

The *WTA* ratio is commonly used as an indicator of water scarcity (Berger and Finkbeiner, 2010), and it is defined as the ratio of annual freshwater withdrawal to long-term annual water availability (Pfister et al., 2009):

$$WTA = WU / WR \tag{1}$$

where WU is annual freshwater withdrawal [m^3/yr] and WR is the total available water resource per year [m^3/yr]. Both parameters were estimated based on the data provided in local EU-WFD plans (DNA, 2014). Based on the WTA indicator, the degree of water stress can be assessed (**Table 1**) for the entire river basin. If the index value is above 1, it indicates that the freshwater resource is being utilized at an unsustainable rate, as withdrawals exceed the annually available resource. While the WTA relates water use to availability, it does not include any consideration of the water required to sustain the good quality of the resource and the functioning of freshwater-dependent ecosystems, and therefore it must be considered as only a rough indication of possible overexploitation.

Table 1. Interpretation categories for the two indicators WTA (Alcamo and Henrichs, 2002) and WSI (Smakhtin et al., 2004).

WTA	Interpretation	WSI	Interpretation
0 – 0.2	Low water stress	0 – 0.3	No water stress
0.2 – 0.4	Medium water stress	0.3 – 0.6	Moderate env. water stress
0.4 – 1	Severe water stress	0.6 – 1	Env. water stress
		> 1	Env. water scarcity

The WSI was developed by Smakhtin et al. (2004) and is a more sophisticated version of the WTA . The WSI also considers water withdrawal in relation to the available resource, but it additionally takes into account environmental water requirements (EWR). The WSI is calculated as follows:

$$WSI = WU / (WR - EWR) \quad (2)$$

where EWR is environmental water requirement in m^3/yr . Estimating EWR is a complex task, requiring a full understanding of local hydrogeological conditions and interactions between groundwater, surface water, and ecosystem services. In this work, a rough simplification was used that assumes that 65% of the natural groundwater recharge must be available for fulfilling environmental water requirements. 65% was specified by the Danish EPA as a precautionary decision (DNA, 2014). The choice of 65% is largely based on

considerations for “indicator 1” in Henriksen et al. (2008), who emphasize that a more appropriate value would be based on monitoring data, although it can be used for “overall mapping purposes”. With no monitoring data available at the river basin or sub-river basin scale, we chose to follow the practice set forth by the Danish Nature Agency (DNA, 2014) and applied the same EWR value at all scales. Although this may be imprecise, it nevertheless recognizes that a marked portion of the groundwater recharge is needed to sustain ecosystems and maintain good groundwater quality. A *WSI* value above 1 indicates “environmental water scarcity,” in the sense that human water abstraction is making it harder to meet environmental needs. Interpretations of indicator values are typically graduated from low/no water stress to severe water stress (**Table 1**). The *WSI* was developed for use at the river basin scale, and the suggested method for estimating *EWR* is based on river flow regimes (Smakhtin et al., 2004).

2.2. Application of different geographical scales

In order to investigate the implications of spatial resolution, assessments were carried out on different geographical scales that we defined as the groundwater body level, the river basin level, and the regional level for Denmark (Figure 1):

- Level 1: The groundwater body scale, referring to distinct volumes of groundwater within an aquifer or aquifers. This has a typical extent in the 100m to 1 km scale.
- Level 2: The river basin scale (Level 2) delineated by the land area drained by a river and its tributaries. A typical extent lies in the 10-100 km scale.
- Regional scale: All groundwater bodies in a region, normally comprising several river basins (in our study Sjælland and Jylland each comprise one region). Typically this extends over a scale of >100 km.

Figure 1. Map showing Level 1, i.e. groundwater body level, Level 2, i.e. river basin level, and the regional level (full map extended) for Esbjerg Water Supply (DNA, 2014).

2.2.1. Level 1: Groundwater body

Denmark is divided into 23 river basins that are further divided into a number of groundwater bodies; these fall into three different types: surface-near, regional, and lower groundwater. Surface-near groundwater bodies are in direct hydraulic contact with streams at the surface; regional groundwater bodies have only limited contact with streams at the surface; whereas lower groundwater bodies are made up of deep chalk and sand aquifers as well as buried valleys, without any contact with surface streams.

At the groundwater body level, the two indicators were calculated using the following method:

- All groundwater bodies influenced by the water supply's groundwater abstraction were identified on the basis of estimations made by professionals in the utility company.
- For each of these groundwater bodies, the rates WU , WR , and EWR were determined and the two indicators (WTA and WSI) were calculated.
- The final values were obtained by calculating a weighted average of the indicators determined for each of the affected groundwater bodies:

$$WSI_{\text{final}} = f_1 * WSI_1 + f_2 * WSI_2 + \dots + f_n * WSI_n \quad (3)$$

where WSI_n is the indicator value determined for groundwater body n and f_n is the weighting factor assigned to groundwater body n . The weighting was based on the distribution of the water supply's abstraction:

$$f_n = (\text{share of annual abstraction originating from well field } n) / (\text{total annual abstraction of the water supply}) \quad (4)$$

In the case study of Aarhus Water, owing to the way groundwater bodies are demarcated within this district, there exists no quantification of the available resource at the level of single groundwater bodies. Instead, the resource and the total abstraction were quantified for each of the sub-districts (i.e. larger areas within which several groundwater bodies have been aggregated) defined within the relevant river basin.

2.2.2. Level 2: River basin

At the river basin scale, the boundaries were expanded so that all groundwater bodies located in the river basin were included. River basins are divided based on natural drainage areas. The two indicators were calculated for the relevant river basin, based on the following method:

- The rates WU , WR , and EWR were determined for all groundwater bodies within the river basin, except for the near-surface bodies, as the RBMPs provide no data for these.
- The parameters were then sequentially summarized for all the groundwater bodies. In this way, total annual water use (WU) within the entire river basin was determined, along with the total available resource (WR) and the environmental water requirement (EWR).
- The final indicator values were calculated based on the summarized values for WU , WR , and EWR .

2.2.3. Regional scale

At the regional scale, groundwater bodies for the entire region were summarized, so that an indicator value describing the aggregated groundwater resource within the whole region (Jylland for Esbjerg and Aarhus and Sjælland for Copenhagen) could be established. It should be noted that, again, near-surface groundwater bodies were not included, as no data were available for these in the RBMPs. Finally, the WTA and the WSI were also calculated for the entire country.

2.3. Uncertainty in parameter estimation and sensitivity analysis

In order to investigate the uncertainty of WR , results were generated based on groundwater recharge rates estimated by Troldborg and Henriksen (2006) for HOFOR, the Greater Copenhagen utility. A variation in groundwater recharge corresponding to between 78% and 118 % of the recharge modeled for the year 2000 was found based on model results for the period 1991-2000. In order to investigate the effect of this time-dependent variation in WR , a new WSI was calculated for HOFOR at Level 1 (groundwater body scale) using WR ranges corresponding to between 78% and 118% of the WR used in the original Level 1 HOFOR assessment.

Uncertainty related to possible variations in *EW*R was assessed by applying *EW*R results estimated on the basis of four ensemble resource indicators developed by Henriksen et al. (2008). Ensemble resource indicators build on a multifaceted interpretation of the *EW*R concept, incorporating both the consideration of groundwater quality and the preservation of surface water flows. While two of the indicators are linked to groundwater recharge, the other two are linked to stream flow. The four ensemble resource indicators were calculated for different catchment areas approximately overlaying HOFOR's capture zones (Troldborg and Henriksen, 2006). The results from their study illustrate that the sustainable yield varies significantly (accounting for 2 to 35% of the groundwater recharge) from one catchment to another when determined based on the indicator with the most critical estimate of the sustainable yield. This corresponds to *EW*R values of 65 to 98% of *WR*. In order to investigate the effect of the described variation in *EW*R, a new *WSI* was calculated for HOFOR at Level 1, using an *EW*R value corresponding to 98% of *WR*.

2.4. Case study descriptions

Three Danish water supplies were selected as case studies for this paper: (a) Esbjerg Water Supply, (b) Aarhus Water, and (c) HOFOR (Copenhagen's water supply). The three case studies represent three different situations in terms of water availability and demand. While Esbjerg Water Supply has relatively low drinking water demand and relatively large reserves of groundwater, HOFOR represents the opposite situation, with the largest urban water demand in the country and a relatively limited resource. Aarhus Water was selected as an "intermediate" case study, as the water demand there is higher than in Esbjerg, while the groundwater resource is generally believed to be available in sufficient quantities. An overview of the three utilities is given in **Table 2**.

Table 2. Overview of groundwater abstraction in the three water supplies, data from 2011. *Data for Aarhus do not exist at the GW body level.

Water supply	No. of wells	No. of well fields	Total vol. abstracted in 2011	Total no. of people supplied	Area of	Area of
					affected river basins [km ²]	GW body [km ²]
Case A: Esbjerg Water Supply	36	5	5.9 Mm ³	72 000	4400	825
Case B: Aarhus Water	98	21	16 Mm ³	250 000	772	N/A*
Case C: HOFOR (Copenhagen)	470	48	54 Mm ³	1 000 000	7235	3995

Drinking water delivered to consumers in Esbjerg is abstracted from a few well fields located close to the town and two well fields located in the central part of Jylland. The affected aquifers consist of sand deposits.

In Aarhus, the main part of the groundwater is abstracted from so-called “buried valley aquifers,” which are ancient river valleys that have subsequently been filled with newer sand and gravel sediments.

In Copenhagen, the water supply is based on groundwater which is abstracted from an area covering large parts of north- and mid-eastern Sjælland. The water is mainly withdrawn from pre-quaternary chalk deposits.

Based on impact assessment of data for the period 2001 to 2011 (Supporting Information) it was decided to use 2011 as reference year for water demand and water availability. It is the latest data available and does not deviate markedly from the period 2001-2011. Complete data sets with example calculations are included in supporting information Appendices D to J.

3. Results and discussion

3.1. Freshwater impacts of three Danish water supplies

The environmental impacts of each water supply's groundwater abstraction were assessed using the two different indicator approaches described above, each calculated at the groundwater body scale (Level 1), at the river basin scale (Level 2) and at the regional scale. The assessment of the three water supplies revealed markedly lower impacts per abstracted cubic meter of groundwater for Esbjerg Water Supply than for the two other water supplies (**Figure 2**). The *WSI* values for Esbjerg Water Supply were in the range 0.24-0.81, whereas the corresponding ranges were 0.24-1.64 and 1.38-1.75 for Aarhus Water and HOFOR, respectively. The evaluation based on the *WTA* indicator showed the same overall picture.

Figure 2. The *WTA* and the *WSI* calculated at the groundwater body scale (Level 1), the river basin scale (Level 2) and the regional scale for each of the three water supplies included in the study. When calculated at the national scale, values of 0.10 and 0.29 are obtained for the *WTA* and the *WSI*, respectively. Datasets are available as Supporting Information.

HOFOR has the highest impact when assessed at Level 1. However, the indicator values calculated for Aarhus Water are almost as high as for HOFOR, and when assessed at Level 2, Aarhus Water yields slightly higher index values. This indicates that the impact per abstracted cubic meter of groundwater is approximately the same for Aarhus Water and HOFOR. The result for Aarhus Water is somewhat surprising, as this utility is located in an area which is generally considered to have access to sufficient groundwater resources.

3.2. Implications of spatial resolution

For all three case studies, spatial resolution markedly affects the estimated freshwater impact. For Esbjerg Water Supply, the indicator values calculated at Level 1 are 53% higher than those calculated at Level 2. For Aarhus Water, the assessments at Level 1 and Level 2 include the same data, but the weighting applied at Level 1 results in 10% higher *WTA* and *WSI* values compared to those obtained at Level 2. Scale-dependent variations are also observed for HOFOR, where the *WTA* and *WSI* values obtained at Level 1 are 22% higher than at Level 2. In conclusion, enlarging the scale from groundwater body level (Level 1) to river basin level (Level 2) has a significant effect on indicator values, with more critical results obtained at Level 1.

It should be noted that differences in the results of the two types of assessments are not only due to differences in scale – an important difference between the two approaches is the weighting of the individual groundwater bodies. While the assessment at Level 1 applies weighting factors according to the distribution of the water supply's total abstraction, the assessment at Level 2 simply aggregates *WU*, *WR*, and *EWR* for all groundwater bodies. The influence of this methodological difference is dependent on how the abstraction is distributed between the groundwater bodies. If, for example, a large proportion of the water supply's total abstraction originates from a relatively stressed groundwater body, this will have a negative effect on the result of the Level 1 assessment. In contrast, if the majority of the water supply's abstraction originates from a groundwater body with no water stress, this will have a positive effect on the overall result from the Level 1 assessment. Hence, the weighting feature includes the effects of the ways in which individual well fields

are prioritized, and in this way the Level 1 approach offers a management tool which can help the water supplier in selecting the most sustainable abstraction strategy.

In addition to Level 1 and Level 2, the impact assessment was also carried out at the regional scale. In the case of Esbjerg Water Supply and Aarhus Water, the regional assessment incorporates all groundwater bodies within Jylland, and for HOFOR it incorporates all groundwater bodies within Sjælland. When evaluated at the regional level, large-scale variations within Denmark as a whole become apparent: while Jylland ($WTA = 0.09$ and $WSI = 0.24$) has enough groundwater to support both human demand and environmental requirements, Sjælland ($WTA = 0.48$ and $WSI = 1.38$) represents an area with a relatively stressed groundwater resource (**Figure 2**).

These results further highlight the importance of the choice of scale when assessing the impacts of water abstraction in different parts of the country. For Esbjerg Water Supply, the indicator values obtained at Levels 1 and 2 are several times higher than the results obtained at the regional level, and for Aarhus Water the difference is even greater. For HOFOR, the difference between the assessment at Level 2 and the regional assessment is very small, which is explained by the fact that only two additional river basins are added in the regional assessment, and the total result is therefore only influenced to a limited degree, as the assessment at Level 2 already contains four out of the total six river basins on Sjælland.

In general, all results at the two smallest scales (Levels 1 and 2) indicate much more critical situations (WSI ranging from 0.50 to 1.75) than the evaluations at the regional and national levels (WSI for Denmark was 0.29).

This significant difference is also found when the results from the two smallest scales are compared to previous studies where an indicator equivalent to WSI has been assessed based on internationally available datasets for freshwater resources (**Table 3**). In their study of the world's regional groundwater aquifers, Gleeson et al. (2012) found that the regional aquifer covering Jylland had a degree of water stress equivalent to a WSI of 0.44, which is 83% higher than our WSI calculations based on RBMP data. On the other hand, Gleeson et al. (2012) found that the regional aquifer covering Sjælland had a WSI of 0.86, which is 38% less

than our results indicate. Even larger differences are found when comparing our results with those from a study of the freshwater resources of the world by Smakhtin et al. (2004), who found that Scandinavia (as a whole) had no water stress ($WSI < 0.3$). Two important conclusions can be drawn from this comparison of WSI calculations: 1) the choice of underlying datasets and scales of assessment markedly influence the results and conclusions on water scarcity levels and 2) an assessment at the national or regional level can underestimate the environmental impact of freshwater withdrawal at the local level.

Table 3. Comparing assessments of Water Stress Indicators based on different datasets and scales.

Area	Our assessment	Gleeson et al. (2012)	Smakhtin et al. (2004)
Jylland	0.24	0.44 (+83%)	-
Sjælland	1.38	0.86 (-38%)	-
Denmark	0.29	-	-
Scandinavia	-	-	<0.3

3.3. Strengths and shortcomings of the two indicators

WTA and WSI represent different approaches to the task of quantifying freshwater impacts of groundwater abstraction. While the WTA provides a simple and easily applicable tool that relates water abstraction to water availability, it does not include the consideration of environmental water requirements. This aspect has been pointed out by others (Smakhtin et al., 2004; Gleeson et al., 2012) as a crucial component in the analysis of impact on freshwater resources. The water stress thresholds suggested for the WTA differ significantly from the thresholds suggested for the WSI (Table 1). While medium and severe water stress occurs at relatively low values (0.2 and 0.4, respectively) for the WTA , the limits for water stress and water scarcity are considerably higher (0.6 and 1, respectively) when it comes to the WSI . These differences in qualitative interpretation are linked to the different nature of the indicators – since the WSI subtracts EWR from the total available resource, the index value becomes critical as it approaches 1 and water scarcity

occurs at values above 1. The *WTA*, on the other hand, does not include environmental requirements, and any indication of water stress therefore occurs at much lower index values.

It should be noted that the water stress values suggested for the *WTA* and the *WSI* are based on studies of surface water, and it is not obvious that the same threshold values apply when the indicators are used to assess the impacts of groundwater abstraction. In the groundwater footprint study by Gleeson et al. (2012), where the ratio of groundwater footprint to aquifer area is presented as being equivalent to the *WSI*, groundwater abstraction is assessed as unsustainable for index values above 1. This threshold value, which corresponds to the category of environmental water scarcity for the *WSI*, is quite intuitive, as an index value of 1 indicates that the annual volume of water available for human abstraction is being exceeded. However, setting additional categories for various degrees of water stress is less straightforward. The qualitative interpretation of the indicators is an important part of the impact assessment, as a quantitative evaluation of the sustainability of abstraction in water supplies has very limited value if the values cannot be translated into directly comprehensible water stress categories.

3.4. Methodological challenges

3.4.1. Inconsistencies in scale

The Level 1 assessment could not be carried out using a single consistent approach for all three case studies. This is largely due to differences in the demarcations of groundwater bodies across the country, which we speculate are even more pronounced when comparing groundwater bodies at the global scale, as the following example will demonstrate. According to the guidelines developed by the European Commission in connection with the implementation of the Water Framework Directive (European Commission, 2003), the demarcation of a groundwater body must be made in a way that enables an accurate description of its qualitative and quantitative status. This means that a groundwater body as defined by the European Commission (2003) is not necessarily equal to a groundwater aquifer – it can be part of an aquifer and it can include more groundwater than is contained within one aquifer. Neither is it identical to a capture zone, i.e. a zone with boundaries based on modeled flow lines which are dependent on the abstraction of groundwater.

In other words, groundwater bodies are not geologically or hydrologically separated entities but rather administrative entities which can vary significantly in size and shape. This variation is exemplified by the different demarcations of groundwater bodies included in the Level 1 assessments of Esbjerg Water Supply, Aarhus Water, and HOFOR, respectively (**Figure 3**).

This variation led to significant difficulties in finding a consistent approach that could be applied across all three case studies. In the case of Aarhus Water, no quantification of the resource was available at the groundwater body level. Hence, aggregated quantities at the sub-district level were used instead (the three sub-districts are shown in **Figure 3**). In the case of HOFOR, rough estimations were made in cases where groundwater bodies overlapped, so well fields therefore affect several groundwater bodies. In these cases, the withdrawal rate from the well field in question was distributed equally between the relevant groundwater bodies. These necessary methodological modifications demonstrate the challenge of developing an operational, scale-consistent method that can be applied across different case studies.

Figure 3. Variations in the demarcation of the groundwater bodies. Datasets are available as Supporting Information.

3.4.2. Uncertainty in parameter estimation and sensitivity analysis

A limitation of the methodology was uncertainty in the estimation of the three parameters WU , WR , and EW . While WU should be relatively simple to estimate, the water withdrawal data registered in the Danish groundwater database Jupiter (GEUS, 2013) are often inadequate, in that abstractions from irrigation wells and other private wells are often missing (Thorling et al., 2012). To compensate for this shortfall, the abstraction data provided in the RBMPs are based partly on permitted withdrawal rates. However, actual water withdrawal rates are seldom equal to the permitted rates; in 2000, for example, the water withdrawn for irrigation purposes amounted to only one-third of permissions (Henriksen et al., 2008).

The total annually available groundwater resource (WR) is also subject to uncertainty. The estimated rates stated in the RBMPs are based on groundwater recharge rates modeled for the year 2000 with a national hydrological model for Denmark (Henriksen et al., 2003). Hence, groundwater recharge rates are no more precise than the accuracy of this model, while the rates stated in the RBMPs should only be seen as rough estimates (Henriksen et al., 2008). Apart from net precipitation, groundwater recharge is dependent on the geological composition of the upper layers and on the degree of interaction between groundwater and surface water. Nonetheless, groundwater recharge is also affected by the abstraction of water from the given aquifer: the higher the pumping rate, the greater the groundwater recharge. A sensitivity analysis was carried out based on the variation in WR corresponding to between 78 and 118% of the original WR value used in the original Level 1 assessment of HOFOR. This yielded a WSI between 1.16 and 2.24, corresponding to 66% and 128%, respectively, of the values obtained in the original assessment (1.75) (**Table 4**). This sensitivity analysis shows the potential effect of choosing WR data modeled for other years. Likewise, groundwater recharges modeled for other abstraction rates or in relation to deeper layers will significantly affect the outcome. These observations serve to highlight the importance of considering the background of the WR input when assessing the impacts of groundwater abstraction.

Table 3. Comparing assessments of Water Stress Indicators based on different datasets and scales. Datasets are available as Supporting Information.

Parameter	Determination method	Observed variation	Impact on final WSI
Total available resource (WR)	Data from the Danish RBMPs (year 2000)	78% – 118% ^a	Between 66% and 128% of the original result
Env. water requirements (EWR)	65% of WR (year 2000)	100% - 151% ^b	Between 100% and 17500% of the original result

^a For WR, the observed variation was obtained from a study by Troldborg and Henriksen (2006), in which the time-dependent variation in the groundwater recharge was modeled for the period 1990-1999; the percentages refer to the relative variation compared to the groundwater recharge in 2000.

^b For EWR, the observed variation was obtained from the same study by Troldborg and Henriksen (2006), in which the sustainable yield was estimated for 8 major catchments influenced by HOFOR's groundwater abstraction; the results showed that the sustainable yield varied from 2 to 35% of the groundwater recharge. Details on the methodology used by Troldborg and Henriksen (2006) can be found in Henriksen et al. (2008).

The most challenging of the parameters is the environmental water requirement (*EWR*). The assumption that *EWR* accounts for 65% of the natural groundwater recharge across the country makes no allowance for local conditions. In reality, groundwater required to support the environment will be dependent on local hydrogeological conditions as well as the site-specific relationship between surface water flow and ecological conditions. The concept of *EWR* has typically been used to describe the fraction of available freshwater that is required to sustain critical surface water flows, as suggested by Smakhtin et al. (2004). However, when focusing on groundwater abstraction, the resource available for sustainable abstraction (i.e. the sustainable yield) is limited by a range of environmental considerations addressing both the surface water environments and the groundwater resource itself (Henriksen et al., 2008; Navarro & Schmidt, 2012). Long-term annual average abstraction must not exceed groundwater recharge in the same period; it must not lead to a reduction in groundwater quality, unacceptable reductions in surface water flow or any significant damage to groundwater-dependent terrestrial ecosystems. In the sensitivity analysis carried out for HOFOR at Level 1, an *EWR* value corresponding to 98% of *WR* yielded a *WSI* of 30.6, which is 17.5 times higher

than the value calculated when *EWR* was set to 65% of *WR* (**Table 3**). The sensitivity analysis shows the potential effect of basing the assessment on more site-specific estimations of *EWR*, and in this way it serves to highlight the importance of assessing environmental water requirements at the local scale, by taking into account site-specific geological, hydrological, and ecological conditions. Without reliable *EWR* estimations, it is recommended to base freshwater impact assessments on the *WTA* alone, since it is not affected by changes in *EWR*.

3.4.3. Identification of research needs

The knowledge gained in this study opens up several possibilities for further research that can pave the way for the development of a standard procedure for assessing the freshwater impacts of groundwater abstraction in water supplies. One research path should be the development of a scale-consistent methodology that can be applied across different case studies, thus providing comparable results. Owing to variations in the delineation of groundwater bodies and river basins, such consistency was not ensured by any of the methods presented in this paper. As such, additional downscaling to the capture zone of each well field is encouraged. However, this approach requires access to models that can estimate the necessary parameters at the level of the individual capture zone – a spatial resolution which, for the moment, may be impractical for global- or continent-wide assessments.

Research should also be directed to improve estimations of *EWR* at sub-river basin scale, in order to replace the generic value of 65% which is currently applied to all groundwater bodies in the Danish River Basin Management Plans. For the estimations to be of any relevance to the specific area affected by the water supply's abstraction, they must be based on analyses of local problems. This is, however, not the case in existing studies addressing *EWR*: while Smakhtin et al. (2004) based their estimations on stream flow requirements at the regional basin scale (e.g. Scandinavia), Gleeson et al. (2012) applied a method modified from Smakhtin et al. (2004) to assess *EWR* for the major regional aquifers of the world (e.g. Sjælland). Assessed at this broad scale, local variations in *EWR* are not taken into account. In the effort to ensure better *EWR* estimations, the involvement of experts and professionals from water suppliers is recommended, as this will both improve the knowledge base and raise the acceptance of stakeholders.

4. Conclusions

This study developed further existing methods for the evaluation of freshwater withdrawal impacts, by increasing the spatial resolution from the regional scale to the groundwater body scale, thus taking into account the local nature of freshwater problems. We applied two indicator approaches, Water-To-Availability and the Water Stress Index, to three Danish water supplies characterized by different situations in terms of groundwater availability and demand. The main findings of the study are as follows:

- Spatial resolution is an important determining factor for the outcome of impact assessments. For the three case studies, *WTA* and *WSI* were 27% to 583% higher at Level 1 and 4% to 521% higher at Level 2 than impacts calculated for the regional scale. Freshwater impact assessment on regional scale may dramatically underestimate local water scarcity.
- A clear advantage of the groundwater body level (Level 1) is that it accounts for freshwater impacts at the scale of the individual well field and can be used to optimize withdrawal from multiple well fields in large water supply systems.
- Copenhagen's water supply had the highest impact on the freshwater resource per cubic meter of water abstracted, with a *WSI* of 1.75 at Level 1. This is followed by Aarhus's water supply with a *WSI* of 1.64 at Level 1, while the lowest impact was found for Esbjerg's water supply (*WSI* = 0.81 at Level 1).
- The choice of geographic scales has a significant impact on the assessment, leading to ambiguous conclusions from the quantification of freshwater impacts at local, regional, and national levels.
- The two indicators (*WTA* and *WSI*) each have their strengths and limitations. The results obtained in this study demonstrate that the indicator with the highest environmental relevance, the *WSI*, is also the one with the highest level of uncertainty, as it requires the estimation of environmental water requirements. Previous studies found that *EWR* values varied from 65% to 98% of the groundwater recharge in the Copenhagen case study.
- A sensitivity analysis showed significant variations in the final indicator results, depending on the input parameters used. *EWR* especially, which is subject to a high degree of uncertainty, has a

significant influence on the results. Therefore, developing a methodology to obtain exact, site-specific, and hence more environmentally relevant *EW*R estimations should be prioritized. Without reliable *EW*R estimations, basing freshwater impact assessments solely on the *WTA* should be considered.

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Supporting Information

<http://findit.dtu.dk/en/catalog/241168682>

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