

ASSESSING GROUNDWATER STRESS

An approach of measuring groundwater stress based on sub-national statistical data



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Understanding and managing water resources can be a challenging task for decision makers and others without a professional background in water studies. Concepts like the blue water footprint aim to make water quantity related issues easier to understand by calculating a water stress index. For groundwater management similar problems exist. Existing global models use grid-based approaches to estimate (ground)water withdrawal and use. While giving a fair overview about water stress on a global-scale, the grid approach gives the impression of a homogeneous data density. Regionally and locally high-resolution statistical data are available, bearing potentials for management and policy-making as well as for refinement and validation of existing global water models.

This study presents a scheme on how to process sub-national water withdrawal and use datasets, specified by source and sectoral use, for (ground)water stress calculations at various scales. The scheme was applied on a dataset for federal states and sub-watersheds in Germany and the respective groundwater stress value was calculated. The groundwater stress calculations indicate high groundwater stress for federal states exceeding 100 %, whereas sub-watersheds show moderate values up to 85 % stress. Sub-watersheds therefore appear as a more suitable spatial unit compared to federal states. The amount of used water with determinable source in a spatial unit highly depends on water import dependence of the respective spatial unit. Information on the spatial unit of origin of transferred waters will lead to a higher accuracy in the estimation of a spatial unit's groundwater stress based on groundwater use.

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1 BACKGROUND

The dynamics in the global freshwater systems have highly increased with growing human population and demands. Additionally, climatic patterns are changing. To meet human demands for crop and energy production as well as domestic uses, freshwater reserves are under increasing stress. In recent years, different attempts have been undertaken in order to assess the pressure on global freshwater resources.

Wada et al. (2010) estimated global groundwater depletion by subtracting groundwater withdrawals from groundwater recharge. Total Groundwater withdrawal information based on country-scale data (IGRAC) were downscaled to a $0.5^\circ \times 0.5^\circ$ grid relative to local surface water deficit or total water demand (depending on the country). The grid-based PCR-GLOBWB hydrological model was used for groundwater recharge estimates. Return flows and environmental flows were neglected.

Döll et al. (2012) assessed the impact of source-differentiated withdrawals on the different water storage reservoirs by using WaterGAP global hydrological model (WGHM, resolution: $0.5^\circ \times 0.5^\circ$ grid). By assigning source-preferences (withdrawal from surface water or groundwater) for different uses (irrigation, household, manufacturing, cooling of thermal power plants and water for livestock) reservoir changes could be analysed separately for surface water and groundwater. The assignments were based on national statistical data, estimates on irrigation water use efficiency, livestock number and type specific water requirements. Recharge and river discharge were computed with WGHM. Return flows from different compartments were accounted for.

Hoekstra et al. (2012) assessed global *blue water scarcity* on watershed level. *Blue water scarcity* is defined as the ratio of *total blue water footprint* by means of total consumptive use (total withdrawal from surface and groundwater - return flows, resolution: $5' \times 5'$) and *blue water availability* (available surface water and groundwater). Total consumptive use inputs were derived from country level annual values weighted with population density maps. Monthly blue water availability per watershed was calculated as natural runoff minus environmental flow requirements. The natural runoff is the sum of the actual runoff (from Composite Runoff V1.0 database, calibrated with time dependent runoff measurements, resolution: $30' \times 30'$) and the total blue water footprint within the river basin. Environmental flow and return flows were accounted for as fixed ratios.

Gleeson et al. (2012) focused on groundwater. The groundwater footprint was introduced as an index displaying the intensity of groundwater resources usage of big aquifer systems worldwide. The groundwater footprint was defined as the area-averaged annual abstraction of groundwater divided by the recharge rate minus the groundwater contribution to environmental streamflow. For groundwater abstraction, return flows (artificial recharge) from irrigation, and recharge, Gleeson et al. (2012) used inputs from Wada et al. (2010) and Wada et al. (2012). Environmental flow requirements were computed per basin as the monthly streamflow (at the basin outlet) that is exceeded in 90 % of the of the simulation period. The outputs of the grid-based groundwater footprint calculations were then summarised and compared to the area of the respective aquifers.

All these models used grid-based approaches giving the impression of a homogeneous data availability. However locally and regionally high resolution data exist with the potential for grid-refinement in many areas of the world. This bears a great potential for water management and policymakers as an increasing number of countries is making these data publically available.

This work aims to maximise the accuracy of quantitative global water use models by making full use of the publically available data. Apart from the relatively high reliability of ground-measured data based models, high data densities can be used as training values for model calibration or for their validation.

2 METHODOLOGY

To show the potential of high-resolution data we came up with an approach for processing sub-national (ground)water withdrawal and use data to calculate the groundwater stress for Germany by federal state and sub-watersheds (river basin sub-districts). The Groundwater Stress index of a spatial unit 'x' used in this study is defined as:

$$\text{Groundwater Stress} = \frac{W(x) \text{ or } U(x) - RF(x)}{R(x) - EF(x)} \quad (2.1)$$

with

$W(x)$ or $U(x)$ = Withdrawal or Use of groundwater within the areal extent of x [1000 m³]

$RF(x)$ = Return flow to groundwater due to leakage or irrigation within x [1000 m³]

$R(x)$ = Groundwater recharge within x [1000 m³]

$EF(x)$ = Groundwater contribution to environmental flow within x

2.1 GROUNDWATER WITHDRAWAL AND USE

The processed withdrawal data are based on statistical evaluations provided by the responsible agency of respective states. In order to identify the amount of groundwater abstracted within a subnational unit and its sectoral use, internal and external water transfers with the respective water sources (groundwater, surface water) have to be considered. The question is: which supplier delivers how much groundwater and to whom?

The following box scheme (Figure 1) explains schematically the water transfers within the water infrastructure. Applying this scheme presuming sufficient data availability, the transferred water volumes of the different water types (GW, SW, Undetermined Source) can be calculated and the destination in terms of sector of use (agriculture, industrial, domestic, Undetermined Use) can be identified.

The scheme consists of three boxes in horizontal order representing the observed spatial unit (middle), the imports to (left) and the exports from (right) the respective unit. Vertically, it is structured in the levels of water producers/extractors (top), water suppliers (middle) and water consumer (bottom) groups. Each level is further distinguished in public, non-public and external system elements as well as for imports and exports by location of the external system element in major units (watershed, national unit) and minor subunit (sub-watershed, subnational unit). The difference between units and subunits has to be made in order to calculate national/watershed balances. Water transfers between watersheds or national units need to be known. All data types represented by a system element category are listed in the appendix (0). The expression is representing the number of system elements from this category. The arrows are showing the interlinkages between the box elements.

We assume that the water entering a system element (producer, supplier or consumer group unit) is homogeneously mixed (weighted mean between all inputs) before redistribution. Additionally, we assume that exported water to other suppliers has the same composition of GW, SW, Undetermined Source like the own production. That is due to the assumption that only producers with a water production surplus will export water. External procurements of the public/non-public sector from non-public/public are assumed to come from the same subunit and therefore their composition is known. In the case of Germany, the source of water for imports is unknown. The producer level distinguishes the water sources as withdrawals from groundwater, from surface water or from unknown source. Herewith it is possible to account for the determinable share of each water type in each use category at consumer group level. The supplier level distinguishes between own production and external procurements {1-x} and the consumer group level between the type of use (agricultural, industrial, domestic and undermined use).

The amount of water from undetermined source is displaying for how much of the used water the source cannot be identified with our assumptions. Assuming we cannot estimate the composition of water transferred between systems we can determine the maximum error by assuming all imported water is of unknown source. Assuming our assumptions for water transfers are right, a minimum error can be determined. The actual error will be in the range between the min and the max error.

The numbers for use and supplied water do not match. This can be due to water transfers and/or difference between reported use and withdrawals due to reporting duty regulations to the German Statistical Office (for instance 10.000 m³/year for external procurements). The sum of water produced/used/transferred not considered in the statistics due to the reporting duty limit can hardly be estimated. As the task of statistical offices is to provide representative numbers for transparency and as a basis of political regulations, the reporting duty limit will likely be chosen in a way that the major part of the water market will be covered by the study. However, to understand the numbers presented in this report, this should be considered. The relative difference between supplied and used water per subunit was calculated as a percentage.

The input values for sources and uses were merged from more detailed classifications from the statistical office of Germany.

Water Balance for Production and Use in a Spatial Unit

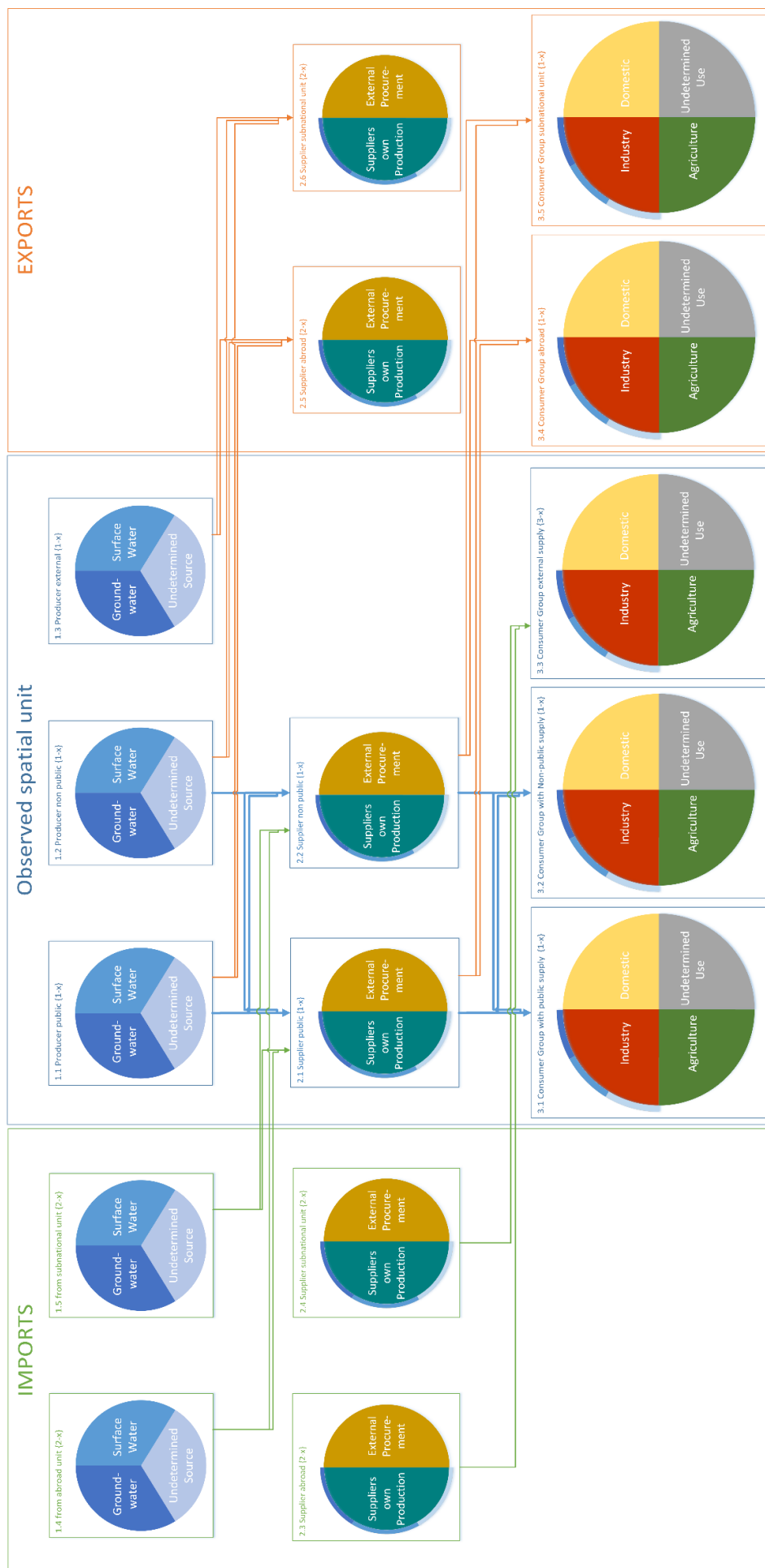


Figure 1: Description of inflows and outflows of observed consumption of provided water by source and sector

2.2 RETURN FLOWS

Return flows after the initial abstraction lead to induced groundwater recharge. For accurate consideration of return flows from pipe leakage, irrigation discharges from industrially and domestically used water have to be quantified and the corresponding recharged reservoir has to be determined. As the amount of irrigated water and the probability for leakage within Germany is low compared to the recharge, return flows will be neglected in the first step. However, for future studies with a more holistic claim these factors should be considered.

2.3 GROUNDWATER RECHARGE

The amount of groundwater recharge was extracted from a raster dataset produced by BGR for Germany with a resolution of 1 km*1 km displaying the long-term annual mean groundwater recharge given in mm*m⁻²*year⁻¹ for the observation period 1961-1990. We derived the mean annual groundwater recharge per subnational unit/sub-watershed. The obtained recharge value was multiplied with the area of the observed spatial unit.

2.4 ENVIRONMENTAL FLOW

As the groundwater contribution to environmental flow is not the main focus of our study, it was in the first step assumed to be constant over Germany. In order to compute its impact on the show case study of Germany we calculated the groundwater footprint assuming a conservative value by setting environmental flow as 40 % of recharge and an abstraction favoring value of 10 % of recharge after Ponce (2007).

3 RESULTS & DISCUSSION

Comparing the results for groundwater stress of federal states (see appendix: 7.2) and sub-watersheds, we identify city states as points of high groundwater withdrawal and use, exceeding the groundwater recharge observed in that respective area by up to 350 % (depending on the calculation). In contrast, the calculated groundwater stress calculated for sub-watersheds does never exceed 90 %. As groundwater availability is driven by the groundwater recharge observed in the whole sub-watershed, the sub-watershed unit seems to be more suitable to quantify scarcity.

The amount of used water with undetermined source highly varies between the different sub-watersheds (Table 1). It is a direct indicator for the amount of imported water to a sub-watershed as the spatial unit of origin is unknown and therefore the water source cannot be specified.

The highest total groundwater use is observed in the sub-watersheds Niederrhein, Havel and Danube. The Niederrhein is located in Nordrhein-Westfalen, the most densely populated area in Germany and with the biggest industrial sector. The Spree sub-watershed receives a relatively small groundwater recharge due to less precipitation compared in the rest of Germany. However, it is the most densely settled sub-watershed in eastern Germany with the cities of Berlin and Potsdam located in its center resulting in a high water demand and thus a high groundwater stress. Apart from being the biggest sub-watershed, the Danube region being located close to the Alps shows by far the highest groundwater recharge rates in Germany. Thus, despite the high total groundwater use, the groundwater stress is relatively low.

For a more detailed look on whether groundwater stress is recharge- or use-driven, an in-depth analysis should be undertaken.

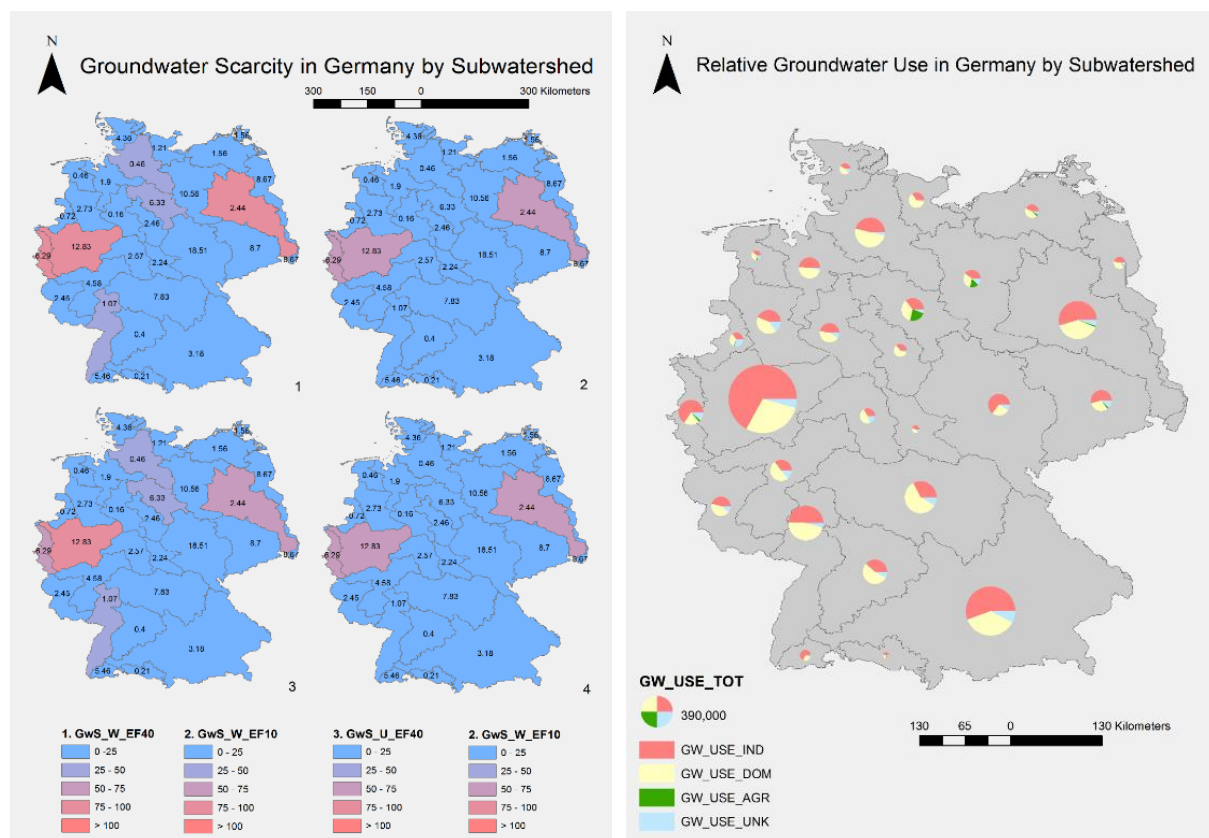


Figure 2: **Map 1** (left) shows the calculated Groundwater Stress per sub-watershed with four different input value combinations Blue (0-25 %) to red (>100 %). 1. For groundwater withdrawals (W) and an environmental flow requirement (EF) of 40 %, 2. for W and EF of 10 %, 3. for groundwater use (U) and EF of 40 % and 4. for U and EF of 10 %. The displayed numbers inside the sub-watersheds represent the percentage of used water with undetermined source. **Map 2** (right) shows the calculated groundwater use per sub-watershed for the four sectors (red = industrial use, yellow = domestic use, green = agricultural use, light blue = undetermined use) with the size of the pie diagram indicating the total amount of used groundwater in 1000 m³.

Table 1: Total water consumption per watershed (including water transfers) as calculated according to the taken assumptions. Relative total consumption for undetermined source without our assumptions regarding water transfers (column 10). Column 11 is showing the relative difference between total supplied water (calculated) and total consumed water (from statistics).

Spatial Unit	Spatial Subunit	TOTAL CONSUMPTION (with water transfers)							Undeter mined Source Without Water Transfers	relative difference between total supply and total consumption
		Total	by source							
			Surface Water	Groundwater	Undeter mined Source	Surface Water	Ground water	Undeter mined Source		
1000 m³				%						
Donau	Same RBD	3221214	2162286	956479	102448	67.1	29.7	3.2	11.4	2.0
Rhein	Alpenrhein/Bodensee	75827	61828	13837	161	81.5	18.2	0.2	21.0	0.8
Rhein	Hochrhein	124501	73786	43915	6801	59.3	35.3	5.5	35.1	8.3
Rhein	Oberrhein	4779714	4251392	477137	51185	88.9	10.0	1.1	4.1	2.6
Rhein	Neckar	1080542	844651	231587	4303	78.2	21.4	0.4	48.0	7.2
Rhein	Main	1172674	678805	402078	91791	57.9	34.3	7.8	24.7	2.1
Rhein	Mosel/Saar	286987	134589	145370	7028	46.9	50.7	2.4	23.1	7.9
Rhein	Mittelrhein	248064	58114	178600	11349	23.4	72.0	4.6	48.0	14.8
Rhein	Niederrhein	4639972	2212675	1831965	595333	47.7	39.5	12.8	27.2	5.9
Rhein	Deltarhein	81644	7199	73860	586	8.8	90.5	0.7	75.5	38.5
Ems	Obere Ems, Ems/Nordradd e,	316778	83271	224875	8633	26.3	71.0	2.7	42.0	16.1
Ems	Hase Leda-Jaemme, Untere Ems, Ems-Aestuar	37442	2118	35151	173	5.7	93.9	0.5	25.6	43.3
Weser	Werra	129251	105090	21271	2891	81.3	16.5	2.2	32.3	11.0
Weser	Fulda/Diemel	148665	54764	90086	3814	36.8	60.6	2.6	92.6	38.3
Weser	Weser	1692223	1541836	147614	2772	91.1	8.7	0.2	7.3	4.4
Weser	Aller	277998	60105	200301	17592	21.6	72.1	6.3	21.5	2.0
Weser	Leine	175886	105983	65583	4319	60.3	37.3	2.5	17.0	18.9
Weser	Tide-Weser	1982055	1769969	174444	37642	89.3	8.8	1.9	4.6	1.6
Elbe	Mulde-Elbe, Schwarze Elster	328671	128950	171143	28578	39.2	52.1	8.7	55.5	7.7
Elbe	Saale, Obere Moldau, Berounka, Eger, Untere Elbe	585762	293297	184016	108450	50.1	31.4	18.5	45.2	0.7
Elbe	Mittelbe, Elde	167147	32382	117115	17650	19.4	70.1	10.6	27.6	20.5
Elbe	Havel	875176	288812	565020	21343	33.0	64.6	2.4	6.7	0.3
Elbe	Tide-Elbe	3131957	2772864	344553	14539	88.5	11.0	0.5	2.0	0.3
Oder	Oder	89256	27975	53539	7742	31.3	60.0	8.7	25.3	14.1
Maas	Same RBD	346507	83631	241097	21778	24.1	69.6	6.3	35.9	8.3
Eider	Same RBD	50039	1130	46726	2182	2.3	93.4	4.4	25.2	29.6
Schlei/Trave	Same RBD	248767	152602	93154	3010	61.3	37.4	1.2	7.5	3.9
Warnow/Peene	Same RBD	108797	34679	72417	1701	31.9	66.6	1.6	11.1	6.7
Germany	All RBD	26403515	17691665	7460505	1251346	67.0	28.3	4.7	15.2	0.1

4 RECOMMENDATIONS

From our first application of the developed data processing methodology for the calculation of groundwater stress based on subnational data we can derive prerequisites and recommendations for the subnational data evaluation performed by the state authorities.

The statistical office of Germany surveys the water supply in Germany separately for the public and the non-public sector. The evaluation of water production, supply, transfers and water use was performed for the spatial units of sub-watersheds (sub river basin districts) and federal states. Due to the observed advantages regarding the groundwater stress calculations we recommend the statistical evaluation of the mentioned water terms for (sub-)watersheds rather than federal states.

The evaluation of water production is categorised in groundwater, spring water, bank-filtrated groundwater, enriched groundwater, lake and reservoir water and river water. We conclude that for our purpose a distinction of groundwater and surface water is sufficient.

On water supplier level the survey distinguishes between own production and external procurements. Not included in the published surveys is information about the spatial subunit (federal state / sub-watershed) or medial source of origin (surface water or groundwater) of transferred waters between subunits as a part of external procurements. However, this information is crucial to correctly calculate the water-use-based water stress. In Germany the resulting amount of water with undetermined source makes up for 5 – 15 % of the total used water volume. As a rough estimate the amount of imported groundwater could be quantified based on the percentage range of groundwater produced in the surrounding sub-watersheds. We highly recommend to also include information on spatial origin (and destination) and the media of origin in the survey. Additionally, we recommend to report on system losses due to leakage of piping systems as it can be a significant source of recharge to ground- and surface water.

The water use is evaluated by sector and spatial unit of application. As information on return flows is highly important for (ground)water stress calculations and watershed management, we recommend to further subdivide the main water use sectors.

The reporting duty limit for entities in Germany was set to 10.000 m³ annually. This limit should be chosen according to the total available water and the total used water. To adequately determine the reporting duty limit, a good knowledge about the water infrastructure including well-inventory (size, position), piping systems and connected entities is important. Especially in water scarce countries where efficient water management is required, high resolution data are highly beneficial.

5 NEXT STEPS

Our work offers a number of follow-up options:

5.1 REFINING THE GROUNDWATER STRESS TERMS

First, a watershed-dependent approach for computing environmental flow requirements should be introduced to the model instead of using a fixed percentage of recharge. Also the return flow term was neglected in the initial groundwater stress calculations notwithstanding return flows to either ground- or surface water do occur due to various processes (leakage from piping systems, irrigation-induced recharge, re-injection of used water from industry and domestic use).

5.2 VALIDATION

As mentioned before, various approaches related to global groundwater stress have been published in recent years which can be used for cross-validation (i.a. Gleeson et al 2012, Doll et al 2012). Watershed and groundwater models based on independent input data (i.e. groundwater level data) bear the potential to validate the presented approach on local or regional scale.

5.3 SPATIAL REPLICABILITY

The global applicability of the presented approach could be tested by applying it to other units with good data availability. A brief evaluation on publically available sub-national water withdrawal and use data of other countries revealed some promising datasets (i.e. EU, Mexico). Application of the developed data processing can bring up further issues which can be solved by adjusting the data processing scheme, making it applicable to a bigger variety of input datasets.

5.4 PROGRAMME CODING

The data processing scheme can be a basis of a broadly applicable policy instrument with a more holistic claim including also the surface water compartment of water stress within a watershed. Advancing in that direction would make coding a considerable alternative to the current excel-based data processing.

5.5 OPEN QUESTIONS

Several issues occur due to the way data are evaluated by the state authorities and distinct approaches among several states. Merging or comparing datasets from different states can therefore be very challenging. Additionally, it is questionable how representative the published data are. Germany for instance does not state how much of the abstracted water and use is actually evaluated as it is not clear how big the sum of withdrawals that is lower than the reporting duty value is. Solving this issue can provide a lead to the level of representativeness of the provided data.

6 LITERATURE

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7 APPENDIX

7.1 ADDITIONAL FIGURES

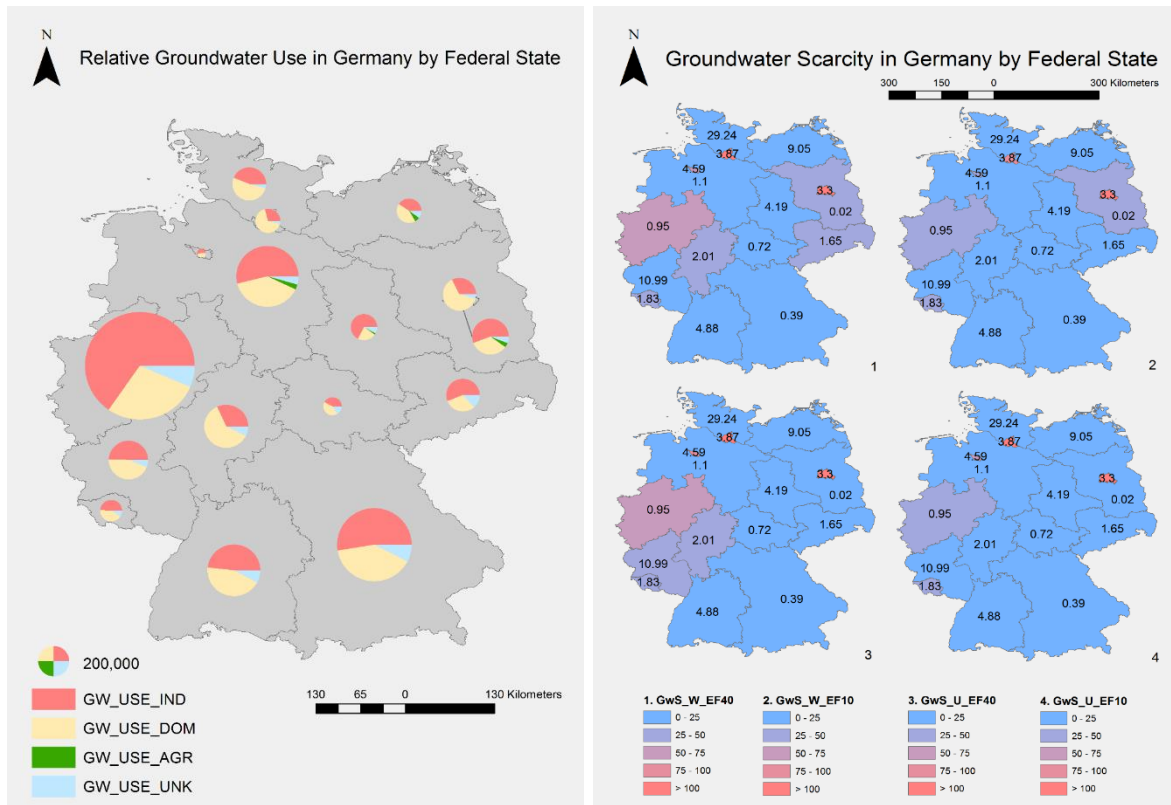


Figure 3: **Map 1** (left) shows the calculated Groundwater Stress per federal state with four different input value combinations Blue (0-25 %) to red (>100 %). 1. For groundwater withdrawals (W) and an environmental flow requirement (EF) of 40 %, 2. for W and EF of 10 %, 3. for groundwater use (U) and EF of 40 % and 4. for U and EF of 10 %. The displayed numbers inside the federal state represent the percentage of used water with undetermined source. **Map 2** (right) shows the calculated groundwater use per federal state for the four sectors (red = industrial use, yellow = domestic use, green = agricultural use, light blue = unterminated use) with the size of the pie diagram indicating the total amount of used groundwater in 1000 m³.

7.2 SUPPLEMENTARY INFORMATION ON BOX SCHEME

Imports

1.4 From abroad unit {2-x}

- Abroad public production
- Abroad Non-public production
- Abroad producer {1-x}:external procurement

1.5 From subnational unit {2-x}

- Public production
- Non-public production
- Producer {3-x} external procurement

2.3 From Supplier abroad {2-x}

- Water exchange between different public suppliers of the same spatial unit

2.4 From Supplier subnational unit {2-x}

- Water exchange between different public suppliers of the same spatial unit

Observed Spatial Unit

1.1 Producer public {1-x}

- Water exchange between different public suppliers in the same spatial unit

1.2 Producer non-public {1-x}

- Water exchange between different public suppliers in the same spatial unit

1.3 Producer external {1-x}

- Water exchange between different ext. producers in the same spatial unit

2.1 Supplier public {1-x}

- Water exchange between different public suppliers of the same spatial unit

2.2 Supplier non-public {1-x}

- Water exchange between different non-public suppliers of the same spatial unit

3.1 Consumer Group with public supply {1-x}

- Public own consumption

3.2 Consumer Group with Non-public supply {1-x}

- Non-public own consumption
- Third-party consumer groups

3.3 Consumer Group external supply {3-x}

- Public consumer groups supplied by supplier {1-x} from subnational unit {2-x}
- Public consumer groups supplied by supplier {1-x} from abroad unit {2-x}
- Non-public consumer groups supplied by supplier {1-x} from subnational unit {2-x}
- Non-public consumer groups supplied by supplier {1-x} from abroad unit {2-x}
- Third-party consumer groups supplied by supplier {1-x} from subnational unit {2-x}
- Third-party consumer groups supplied by supplier {1-x} from abroad unit {2-x}

Exports

2.5 To Supplier abroad {2-x}

- Water exchange between different suppliers of the same spatial unit

2.6 To Supplier subnational unit {2-x}

- Water exchange between different suppliers of the same spatial unit

3.4 To Consumer Group abroad {1-x}

- Public own consumption
- Non-public own consumption
- Third-party consumer groups

3.5 To Consumer Group subnational unit {1-x}

- Public own consumption
- Non-public own consumption
- Third-party consumer groups

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