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# Determining regional limits and sectoral constraints for water use under climate change

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## Abstract

Water is an essential input to the majority of human activities. Often, access to sufficient water resources is limited by quality and infrastructure aspects, rather than by resource availability alone, and each activity has different requirements regarding the nature of these aspects. This paper develops an integrated approach to assess the adequacy of water resources for the three major water users, the domestic, agricultural and industrial sectors. Additionally, we include environmental water requirements. We first outline the main determinants of water adequacy for each sector. Subsequently, we present an integrated approach using fuzzy logic, with allows assessing sector-specific as well as overall water adequacy. We implement the approach in two case study settings to exemplify the main features of the approach. Using results from two climate models and two forcing RCPs (Representative Concentration Pathways) as well as population projections, we further assess the impacts of climate change and population growth on the adequacy of water resources. The results provide an important step forward in determining the most relevant factors, impeding adequate access to water, which remains an important challenge in many regions of the world. The methodology allows to directly identify those factors most decisive in determining the adequacy of water in each region, pointing towards the most efficient intervention points to improve conditions. Our findings underline the fact that in addition to water volumes, water quality is a limitation for all sectors and especially for the environmental sector, high levels of pollution are a threat to water adequacy.

## 1 Introduction

Water is a critical resource for human livelihoods and is needed for the majority of human activities. Pressure on water resources is increasing due to consumption as well as pollution, leading to situations of water scarcity in many regions of the world. Much knowledge exists regarding the single determinants of water scarcity, making clear that





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water shortages are often due to quality or access, rather than due to physical water shortages (Finlayson et al., 2012; WHO/UNICEF, 2000; WWAP, 2012; Sullivan, 2002). For example, assessments of human water requirements (e.g. Falkenmark, 1997; Falkenmark and Rockström, 2004) show, that the share of domestic water needs is comparably small. Nonetheless, domestic water scarcity prevails in many (developing) countries, mainly due to inadequate water quality and access (Rijsberman, 2006). Other important water users are the industrial and agricultural sectors, which each have distinct requirements regarding quantity, quality and access (Flörke et al., 2012; Falkenmark, 1997). Approaches such as the Water Poverty Index (Sullivan, 2002) and the Climate Vulnerability Index (Sullivan and Meigh, 2005) are important starting points to understand and integrate the multiple aspects of water scarcity and water poverty. Already today, human activities impact water availability and projected development pathways indicate further increases of these pressures deriving from population and economic growth (Bates et al., 2008). Additionally, climate change is expected to alter temperature and precipitation patters (Kirtman et al., 2013; Collins et al., 2013), potentially reducing available water resources and adding to existing situation of water scarcity.

The majority of societal activities require water and each sector has individual requirements. Planners and decision-makers require tools, which allow to view the multiple determinants in conjunction, to identify where potential limitations are most efficiently eliminated, also taking into account potential future changes. Existing approaches to assess water scarcity usually focus on single aspects of the topic, for example on human water requirements (e.g. Falkenmark, 1997), the relationship between water use and availability (e.g. Alcamo et al., 2003), water consumption (e.g. Hoekstra and Chapagain, 2006), threats to water quality (e.g. Vörösmarty et al., 2010a) or physical scarcity and drought (for comprehensive reviews see Eriyagama et al., 2009; Brown and Matlock, 2011). Focussing on peoples' daily realities, development oriented assessments of water access often address the aspect of water infrastructure (UN, 2012). It is also clear, that sufficient water needs to be retained for functioning





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ecosystems (Smakhtin et al., 2004), also with regard to the long-term adequacy of human livelihood conditions, however environmental aspects are seldom considered in assessments of human water scarcity.

This paper proposes a framework to assess the *adequacy* of water resources, integrating the various aspects which determine sectoral water security. Adequacy for the purpose of this analysis refers to a situation, in which the quantity, quality and access to water resources is sufficient to meet needs, but is not necessarily abundant or ideal. While knowledge on the single important aspects for the main sectoral water users is available, so far an integrated approach to account for sector-specific determinants of water adequacy is missing. The proposed method allows to distinguish between anthropogenic and physical causes of water scarcity, for example due to management or infrastructure problems (economic and social water scarcity; Brown and Matlock, 2011) or due to actual resource scarcity.

To retain important information regarding the most relevant determinants and to include context specific cause-and-effect relationships between variables, we propose the use of fuzzy logic. This method has been used in water resources research for example to assess issues of water quality (Gharibi et al., 2012) or wastewater reuse potentials (Almeida et al., 2013) and could be shown as a useful tool for integrating determinants of human-environmental systems (Kropp et al., 2001; Lissner et al., 2012). By identifying those factors most limiting to adequate water access, the results obtained through the proposed approach can directly inform decision-makers on how to most effectively improve access to water, extending the approaches put forward by Sullivan (2002) and Sullivan and Meigh (2005).

The objective is thus to integrate determinants of sectoral water adequacy into an overall measure of water adequacy, allowing to identify regional limitations as well as sectoral constraints to human water security. The analysis follows two subsequent steps. Initially, we identify criteria, which determine the adequacy of water resources for the main water using sectors and translate the identified determinants and their relationships into a methodological framework. We then apply the framework in two





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countries, Indonesia and South Africa, taking into account several scenarios of climate change, to outline where climate and population change may lead to additional water stress.

The analysis steps produce an integrated overview of the adequacy of water resources, while the applied methodology allows retaining important cause-and-effect chains which can point towards policy-relevant information. The following Sect. 2 gives an overview of the example countries, outlines the analysis approach and introduces the methodological concept of the framework. We present the results in Sect. 3 and discuss them in Sect. 4, followed by some general conclusions.

## 2 Methods and materials

### 2.1 Case study regions

The two case study countries are presented in Fig. 1, showing the major cities as well as regional population densities. Both countries currently are at a intermediate human development (HDI) stage. The 2012 HDI value for Indonesia is 0.629, with a rather strong increase from 0.422 since 1980. Like Indonesia, South Africa has a 2012 HDI value of 0.629, which is quite high above the average for Sub-Saharan Africa of 0.475 (UNDP, 2013). A higher development status is usually associated with increasing per capita water use. Both countries have positive population growth rates, and this trend is expected to continue. Both, development and increasing water use will likely increase the total water withdrawal.

Indonesia is generally quite water abundant and currently withdraws 5.6 % of total renewable resources and per capita use is rather low at 531 $m^3\,cap^{-1}\,yr^{-1}$. The highest share of water goes towards agricultural use (82 %) and 6.5 and 10 % are withdrawn for industrial and domestic use, respectively (FAO, 2011). Current per capita water use in South Africa is even lower at 284 $m^3\,cap^{-1}\,yr^{-1}$, however about 25 % of total renewable resources are currently withdrawn. This implies increasing pressure, as living standards rise and population increases. The distribution between sectors in South Africa is rather different with a relatively high fraction of domestic use at 31 %. 63 % go towards agricultural production and 6 % are used by industries (FAO, 2005).

### 2.2 Determinants and indicators to measure the sectoral adequacy of water

The most important sectors of human water use are the municipal (domestic), agricultural, energy production and industrial sectors (Flörke et al., 2012; WWAP, 2012; Falkenmark, 1997; Chenoweth, 2008). Sectoral attribution is sometimes ambiguous: the definitions of e.g. municipal and domestic water use overlap or are used interchangeably (Chenoweth, 2008; FAO, 2013; Flörke et al., 2012). Some accounts of water use and needs for agriculture include livestock production (FAO, 2013), while others account for them separately (Flörke et al., 2012). Further, water needs for energy and industrial production are often added up (Flörke et al., 2012) and are much more dependant on development status and country-specific conditions than other sectors (Chenoweth, 2008; Sullivan, 2002) (see Table 1 for details). For the purpose of the analysis, we distinguish the three sectors municipal, agricultural (including livestock) and industrial (including energy production), as this is the most common and applicable differentiation. An additional important aspect we take into account is the environment as a distinct water user, as functioning (aquatic) ecosystems and biodiversity are essential for healthy and sustainable living conditions and long-term water security (Smakhtin et al., 2004; Molle et al., 2010).

For an assessment of water adequacy, first sector-specific water resource needs have to be identified. Table 1 gives an overview of relevant literature sources that identify user/sector specific water needs, all converted to annual per capita water needs in $m^3$ ($m^3\,cap^{-1}\,yr^{-1}$). Rather than the actual current water use, the table gives an overview of what has been identified as (minimum) sectoral needs. As the large differences suggest, accounts of water needs differ in their assumptions, and usually do not take into account external (imported) water. Chenoweth (2008) for example derives a rather low level of water needs, generalizing the current water use in the Netherlands.

It is important to note, however, that imports of water through goods produced outside of the country are not taken into account here. The most detailed analyses are the ones presented by Falkenmark (1997) and Falkenmark and Rockström (2004), which are amongst the most widely used indicators of water scarcity for global analysis. Here, water needs are assessed assuming all needs are met within country-boundaries. Further important accounts of municipal water needs include an analysis by Gleick (1998), who calculates a minimum domestic water requirement of 18 $m^3 cap^{-1} yr^{-1}$, as well as a report by the Howard and Bartram (2003), where a range of 7.2–36 $m^3 cap^{-1} yr^{-1}$ is identified. Accounts of generalizable environmental water requirements (EWR) have mainly been put forward by Smakhtin et al. (2004), who derive basin-specific EWR as a fraction of overall run-off. Values range between 20 and 50 % of total available resources.

Additional to the availability of water resources in sufficient quantity, also quality and access determine water adequacy. Relatively little water is needed for the municipal sector. Here, access infrastructure as well as water quality are often a more important limitation to water adequacy (Rijsberman, 2006; Sullivan, 2002). Rather than looking at resource availability, access to an improved water source is central to the Millennium Development Goals (MDG), for example (UN, 2012). Water quality aspects are also of utmost importance for the municipal sector, as low quality of drinking water has direct consequences for human health (Howard and Bartram, 2003) and may render water non-potable without prior purification (Finlayson et al., 2012). In their assessment of the main threats to global water security Vörösmarty et al. (2010b) identify several relevant pollutants with direct negative health effects, including nitrogen, phosphorus, pesticides, mercury as well as organic matter and high sediment loads[1].

Water needs of the industrial and energy sectors are diverse. Water is eventually needed at some stage of the production process, but quantity, quality and other requirements depend strongly on the specific process (Graedel and van der Voet, 2010;

[1] For details on the background of all indicators of water quality used throughout this paper see Vörösmarty et al. (2010b).

WWAP, 2012). A common denominator is the need for cooling water, which is generally needed in production processes, for which some general requirements can be identified (Morrison et al., 2009). Low water quality can increase costs, as water has to be prepared for use. Especially high quantities of suspended sediments can damage turbines (Graedel and van der Voet, 2010; Vörösmarty et al., 2010b; Morrison et al., 2009). Higher water temperature may also reduce the availability and usability of water for cooling purposes (Graedel and van der Voet, 2010; Vörösmarty et al., 2010b). Though low water quality does affect industrial production, it is more often a cause of water pollution itself.

About 70 % of withdrawn water goes towards agricultural production (WWAP, 2012) and overall resource availability is the most critical factor for the adequacy of agricultural water. Seasonal variability and short-term shortages may be buffered through water storage (dams) as well as through the availability of irrigation infrastructure. While dams may have negative ecological effects for ecosystems, they can increase human water security, both through water storage for situations of shortages, as well as through potential buffering during flooding events (Vörösmarty et al., 2010b; Finlayson et al., 2012). Agricultural production in general may be less dependant on water quality, rather the sector contributes strongly to water pollution. Quality factors which may reduce yields are mainly related to potential salinisation (Vörösmarty et al., 2010b).

Environmental water requirements (EWR) refer to the fraction of water, which should remain within aquatic ecosystems to ensure adequate long-term ecosystem health and sustainability. Basin-specific EWR depend on prevailing regional climate conditions and vegetation (Smakhtin et al., 2004). Water pollution is an additional critical determinant of ecosystem health and multiple sources of human activities affect water quality and pollution levels, threatening biodiversity (Vörösmarty et al., 2010b).

Summarizing the determinants of sectoral water adequacy, Table 2 gives an overview of the proposed indicators for the subsequent analysis. Column 2 specifies the indicator name, as used in the remainder of the paper. Columns 3 and 4 summarize the





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variables and data sources, which are used to quantify each indicator. The data are also discussed in more detail in the following Sect. 2.3.

## 2.3 Fuzzy logic approach to measuring water adequacy

A fuzzy logic approach is developed to translate the sector-specific determinants into an integrated measure of water adequacy. Fuzzy logic allows converting qualitative or inherently fuzzy concepts into mathematical representations, by defining linguistic categories and translating the input values into degrees of membership ($\mu_{zi}$). For the process of fuzzification, upper and lower thresholds $\iota_1$ and $\iota_2$ are defined which determine the degree of membership of values to the respective linguistic categories. Further, the shape of the function (e.g. linear, exponential) determine the degree of membership of each element. The fuzzified variables take continuous values between 0 and 1, representing the degree of membership to the respective concept (see e.g. Lissner et al., 2012; Kropp et al., 2001, for details). For the purpose of the present analysis, we want to calculate the *adequacy* of the determinants of water availability, quality and access to derive an integrated measure of water adequacy, where values near 1 indicate highly adequate conditions and values near 0 indicate inadequacy of the respective component. Equation (1) describes the process of fuzzification for linear membership functions, as used for the purpose of the present analysis.

$$\mu_{zi}(\iota) = \begin{cases} 0, & \iota \leq \iota_1 \\ \frac{\iota - \iota_1}{\iota_2 - \iota_1}, & \iota_1 < \iota < \iota_2 \\ 1, & \iota_2 \leq \iota \end{cases} \qquad (1)$$

Following the process of fuzzification, the variables can then be aggregated using context-specific decision rules, which allow to account for relationships between variables. Decision rules should be chosen according to the specific properties of the variables and the analysis. Operators include strict minimum (AND) and maximum (OR) operators as well as averages such as as harmonic, geometric and arithmetic mean





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(Mayer et al., 1993). Fuzzy logic further offers the possibility to include the compensating element $\gamma$, which allows using fuzzyAND (Eq. 2) and fuzzyOR operators by taking into account the arithmetic mean to the extent of $\gamma$, with $\gamma$ values near 1 resulting in a strict application of the operator and values near 0 actually calculating the arithmetic mean (Kropp et al., 2001).

$$\mu(z_1 \wedge z_2 \wedge \ldots \wedge z_n) = \gamma * \min(\mu_{z1}, \mu_{z2}, \ldots, \mu_{zn}) + (1-\gamma) * \frac{1}{N} \sum_{i=1}^{N} \mu_{zi} \qquad (2)$$

Figure 2 outlines the aggregation process, showing current values for South Africa. The aggregation for Indonesia follows the same procedure. For each sector, two main aspects are considered: these include the fuzzified determinants of access and quality (middle column, Fig. 2) as well as the fuzzified adequacy of water availability (right column). We first calculate individual sector adequacy and subsequently aggregate all values to an integrated measure of water adequacy. Each step of fuzzification and aggregation follows a context-specific reasoning-process.

### 2.3.1 Fuzzy reasoning-process and data preparation

In the case of municipal water adequacy, water quality plays a prominent role. Contaminated drinking water either renders the water non-usable or threatens human health. Various aspects determine municipal drinking water quality (m_quality) (see Sect. 2.2). Vörösmarty et al. (2010a) provide a comprehensive global database of water quality indicators, which we use to represent the individual indicators of water quality for each sector. Where data from this source is used, it was prepared as follows: data are provided as values between 0 and 1, where values near 0 indicate low threat intensity and values near 1 indicate severe threats to water security. We calculated the mean threat intensity for the administrative regions of the two case study countries and invert these values, so that values near 1 indicate adequate water quality (low pollution threat) and values near 0 indicate low water quality (high pollution threat).





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Therefore, no further fuzzification is required for these values. In terms of access, improved and unimproved water sources are differentiated (Howard and Bartram, 2003; ICF, 2013). The MEASURE Demographic and Health surveys (ICF, 2013) provide access to detailed indicators, aggregated to administrative regions. To represent the adequacy of access to drinking water (m_access), we weight the different types of access according to their adequacy (adapted from Howard and Bartram, 2003, Table 6). Water piped onto the premises has a weight of 1, access through a well has weight of 0.5, while all other types of access have a weight of 0.2. The sum of the weighted access types returns values between 0 and 1, where values near 1 indicate highly adequate m_access (i.e. a very high proportion of population with water piped onto premises), whereas values near 0 indicate inadequate m_access. High quality water infrastructure (m_access) plays an important role in mitigating potential negative effects of low water quality in the municipal sector (m_quality). For the aggregation of the municipal determinants of access and quality (m_factors), this translates into the fuzzy reasoning process as a fuzzyAND operator, where both aspects have to be sufficiently available for adequacy to be high. However, as highly adequate access infrastructure can reduce contaminants, a $\gamma$ value of 0.6 is introduced, allowing to compensate to some extent (Fig. 2, column 3). While comparatively little water is needed to fulfil municipal water needs (m_water), nonetheless water availability is obviously essential and a strict fuzzyAND is applied to aggregate the overall measure of municipal water adequacy (m_adequacy) to account for this fact (Fig. 2, column 4).

The common denominator to assess industrial water adequacy is the availability of cooling water of sufficient quality, which can be represented by the sediment load as well as water temperature (thermal alteration) (Vörösmarty et al., 2010b). Both, the quality (i_quality) as well as sufficient water availability (i_water) determine the adequacy of industrial water resources (i_adequacy), however, low water quality does not completely inhibit cooling water extraction. We therefore use of fuzzyAND with a $\gamma$ value of 0.8 aggregate the indicators for the overall measure of industrial water adequacy (i_adequacy).





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For the agricultural sector as the highest water user, sufficient water availability (a_water) is most important. Infrastructure to buffer potential shortages can reduce the risk of inadequate water supply. Both the availability of dams as well as irrigation infrastructure can provide such infrastructure. As either of these two indicators may increase water security, these are aggregated using a fuzzyOR. Dam density is included in the river threat database (Vörösmarty et al., 2010b) and prepared as described. Similarly, data on areas equipped for irrigation is provided in percentage values and is averaged over the administrative regions. Infrastructure to ensure the security of supply of water for agriculture (a_sec_supply) is especially important in regions where available water resources are close to or below thresholds of water needs. To account for this, we introduce an if-clause into the analysis: only if water availability is below the threshold of adequacy, supply infrastructure becomes relevant for the analysis. Where water availability is limited, the security of supply indicator plays an important role. As slight shortages in water availability can be compensated in this way, a $\gamma$ value of 0.6 is introduced to combine adequacy of access and quality (a_factors) with water availability (a_water) for the agricultural sector.

Environmental water requirements (EWR) are prioritized in our analysis in the following way: we assume that sufficient water is retained for ecosystems by deducting EWR from the overall water resources, before assessing water availability for other sectors. Smakhtin et al. (2004) calculate basin-specific EWR as a percentage of overall run-off, ranging between 20 and 50 % of total available resources. We average these values over the administrative regions of the case study countries and subtract the respective fraction from the overall water available in the respective region. The remaining water is then available for human use in three sectors, while keeping water availability within sustainable environmental boundaries. Environmental water quality is represented by an integrated indicator of biodiversity threat (biod_threat), representing relevant pollution and disturbance factors (Vörösmarty et al., 2010b).





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### 2.3.2 Scenarios of water availability

To measure water availability and calculate future scenarios of climate change impacts, we use output from the Lund–Potsdam–Jena managed Land (LPJmL) model, a dynamic global vegetation and water balance model (Bondeau et al., 2007). Similar to the preparation of water quality data, we calculated values for the administrative regions, summing up the cell values to derive yearly values of water availability. Calculations are based on two Representative Concentration Pathways (RCP) as forcings for the two employed Global Climate Models (GCM) (van Vuuren et al., 2011). We calculate mean annual water availability for a baseline (1981–2010) and a short term (2011–2040) scenario, based on the GCMs HadGEM2-ES and GFDL-ESM2M, using RCP2.6 and RCP8.5, further referred to as: HADbase, HAD2.6, HAD8.5, GDFLbase, GDFL2.6 and GDFL8.5. To assess per capita availability, we rely on regionalized population projections from the National Statistical Offices for the case study regions and divide the total available water resource by the population (Indonesia: BAPPENAS, 2005, South Africa: van Aardt, 2007[2]).

In order to assess the adequacy of available water resources using fuzzy values, (m_water, i_water, a_water and all_water), we use the rounded lower and upper ranges as identified in Table 1 (column "Thresholds") for the process of fuzzification. Here, the lower identified threshold refers to the minimum water need identified in the literature and the upper threshold denotes a situation of adequacy. We assess the adequacy of resource availability separately for each sector and sum all sectoral needs to assess the cumulative adequacy of overall water resources (all_water).

To finally derive an integrated indicator of overall water adequacy (all_adequacy), sectoral quality and access aspects are combined with the overall water needs across sectors. For the purpose of exemplifying the approach, we use a MEAN operator to aggregate all sectoral determinants of access and quality (all_factors), but combine

[2]Available subnational projections for South Africa exist up to the year 2021; we applied the national available growth rates to the projected data for 2021 to derive values for 2025.





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this indicators with the overall water availability (all_water) using a strict MIN operator, reflecting the fact that sufficient resource availability is a prerequisite.

## 3 Results

The overall adequacy of water is a function of all factors which affect the quantity, quality and access to water of relevant sectors. Besides outlining the aggregation procedure, Fig. 2 also presents results in the form of maps, representing the fuzzified and aggregated values for South Africa for each analysis step for current conditions of water availability (HADbase). The analysis is conducted calculating the degree of membership to the linguistic category "conditions are adequate", which translates into results of water adequacy ranging from very high (0.8–1), high (0.6–0.8), intermediate (0.4–0.6), low (0.2–0.4) to very low (0–0.2). As generally visible, access factors critically determine the resulting values of water adequacy: while the adequacy of available water resources is (very) high in terms of quantity for most sectors, access and quality have a strong influence on the results.

Water quality plays an especially important role for the adequacy of municipal water resources in South Africa. Though the adequacy of access (m_access) is high to very high, municipal water quality (m_quality) is (very) low and leads to inadequate municipal adequacy of access and quality (m_factors). For the industrial sector, available resources suffice to meet needs, but alterations of quality reduce its adequacy in all regions. Due to the high agricultural water needs (a_water), limitations are faced in some regions of South Africa. Both, the areas equipped for irrigation as well as the dam density are rather low, thus the security of supply is often insufficient to buffer potential shortages. Nonetheless, agricultural adequacy (a_adequacy) is intermediate to high all over South Africa. The integrated indicator depicting regional biodiversity threat shows that water quality pressure on the environment is high, negatively affecting the environmental water adequacy (env_adequacy). The mean adequacy of determinants of access and quality as a combination of all sectoral determinants (all_factors) is low to intermediate. The sum of sectoral water requirements (all_water) shows limitations in resource availability, especially in densely populated areas, hinting at potential competition between sectors. The overall result depicting water adequacy (all_adequacy) is an aggregate of all input factors and cumulative water requirements of all sectors, mainly reflecting the limitations in access and quality factors across regions.

Figure 3 shows the integrated water adequacy (all_adequacy) for South Africa and Indonesia for current conditions, as well as future changes where applicable. In both countries, regions of lowest adequacy are those with the highest population density (depicted in Fig. 1). Projected changes in water availability do not affect the overall adequacy of water for human use in most regions, as quality and access play such an important role, however changes are apparent in some regions. Here, also differences between the two applied models become visible. Population density plays a crucial role in determining the adequacy of water availability (all_water). A large number of users may lead to overall scarcity, either due to resource limitations or quality restrictions. In the example countries, regions with high population density are currently close to the thresholds of water scarcity and population growth is likely to aggravate the situation.

In South Africa, mean overall adequacy (all_adequacy) is intermediate to low (GDFLbase: 0.41, HADbase: 0.4) and the highest values of adequacy also remain at intermediate levels with values between 0.51 and 0.55 in the regions of Eastern Cape, Mpumalanga and Limpopo. The water adequacy is most severely limited in Gauteng, with a very low adequacy of 0. Though generally resource availability under the current climate is very adequate in the regions of South Africa, municipal and industrial water quality are low to very low in many areas.

In Indonesia, water resources are generally abundant, but the metropolitan region of Jakarta faces some water limitation and projections of water availability show further reductions in the region. Though overall water availability is projected to increase in most regions, population growth in already populous areas of the country is also projected to increase significantly, keeping constant or diminishing per capita water availability. The island of Java, for example, is home to the largest cities and shows the lowest values





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of water adequacy and a decrease in adequacy over the coming decades. Mean adequacy under current conditions in Indonesia is intermediate, with lowest values in the densely populated regions of Bali with intermediate to low water adequacy. Similarly, the regions of Central, East and West Java as well as Yogyakarta display low to very low values. Where adequacy is low under current conditions in Indonesia, further changes are projected, leading to additional reductions in water adequacy. Conditions are best in Maluku Islands, East Kalimantan and Papua, with high values across models and scenarios. Generally, access to an improved water source (m_access) is low to intermediate, leading to an overall reduced adequacy (m_adequacy). Water quality in Indonesia for all users is intermediate to high and water availability is high, except for the densely populated regions. As measures to increase the security of supply of water for irrigation purposes are relevant mainly where water shortages are to be expected, agricultural adequacy (a_adequacy) is high, despite a lack in irrigation equipment and low dam density in many regions. The security of supply indicator performs best in those regions, where water availability is below the scarcity threshold, allowing to buffer potential shortages in water resources.

### Sectoral priorities of water adequacy

While an overall aggregate indicator of water adequacy gives important information on the overall situation of water security, a sectoral differentiation allows prioritizing especially stressed sectors to most efficiently improve water adequacy. Comparing the sectoral adequacy, it is apparent that the municipal as well as environmental water adequacy are lowest, in both South Africa and Indonesia, also showing the lowest spread between regions (Fig. 4). In Indonesia, municipal water adequacy is lowest in rural regions, where especially the access to an improved water sources is limited. In several regions, environmental water quality dominates the result. In the most densely populated regions of Bali as well as East and West Java, the overall water availability proves to be a limitation under future conditions.





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Agricultural water adequacy shows the highest spread across regions in both countries. While the mean adequacy is intermediate to high in both countries, some regions are severely water constrained. When looking at the overall adequacy of the three different sectors municipal, industrial and agricultural, the analysis shows that for the municipal and industrial sectors the main impediment are water quality and access factors, rather than the availability of water resources. This also holds for short term future scenarios. In the case of agricultural water resources, however, the availability of sufficient irrigation water plays a role in some regions of the case study countries.

Identifying the sectors and factors most relevant for each region in determining the adequacy of water resources provides important information to improve the quality of water resources and access in an efficient way. Figure 5 shows which sectors most severely constrains water adequacy in each region. Where this factor changes over time, this is indicated by a box in the respective colour. In the case of South Africa, environmental water adequacy is a severe constraint for all regions and has the strongest influence on the overall result. The map therefore shows the second-most limiting factor. Environmental water conditions for the regions of Indonesia are also often low and follow as second-most limiting factors for all regions.

In the case of South Africa, the results in the majority of regions are dominated by limitations in municipal water adequacy, when environmental constraints are not taken into account, except for the region of Gauteng, where water resources limit the results. However here, municipal water quality plays a much more important role than access. Similar to the findings in Indonesia, high population density (see Fig. 1), leads to limitations in water resources availability (all_water), in South Africa, especially under future conditions. The regions of Western Cape and KwaZulu-Natal are water limited under all scenarios, and water limitations are expected in Northern Cape, Free State and Limpopo in the future. The largest province of Northern Cape is a sparsely populated region, where mining is a predominant activity. Here, the industrial water quality is the most decisive factor for adequacy under current conditions.





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## 4 Discussion

Our results highlight that sector-specific water needs are diverse and that several distinct factors determine whether the quality, quantity and access to resources are adequate. Calculating water adequacy for two case study countries, the present work exemplifies how such an integrated approach can be applied. Changing resource availability as well as population increases have an impact on the patterns of water adequacy. For effective and informed decision-making it is essential to provide detailed and applicable information on the sectoral differences which affect the adequacy of water resources.

The results of the analysis clearly show that infrastructure (municipal access and security of supply) and quality aspects play an important role to determine water adequacy. Though insufficient water resources, also over the course of the next decades, have an impact in some regions, often the distribution of population plays an important role, as densely populated places face more severe water scarcity.

In some of the analysis regions, agricultural water is already limited. In Indonesia, for example, most agricultural production currently takes place on the densely populated island of Java. Here, water resources are already limited and population growth in this region may aggravate the problem. Reduced water availability in the future may affect domestic food security, if water resources available become insufficient in relevant growth phases and supply infrastructure is insufficient to meet additional demand. Even today, Indonesia is a net importer of food and malnutrition and stunting among children is present (WFP, 2012). With increasing development and higher demand lifestyles, the water-intensity of food consumption patterns may increase, further exacerbating the problem (Pradhan et al., 2013).

Our findings show that in Indonesia, the security of supply indicator is usually adequate in regions, where water availability is below the threshold, implying that awareness of shortages is present and potential scarcity can be buffered to some extent. Contrary to this, in South Africa buffering infrastructure in the from of irrigation



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equipment and dams is inadequate in the whole country, leading to low agricultural adequacy in some regions. Due to the current low per capita water use (284 $m^3\,cap^{-1}\,yr^{-1}$; FAO, 2005), water demand remains below available supply, therefore the overall water availability is currently not the main limitation to water access. Rather, inadequate supply infrastructure and lacking quality are an important impediment to adequate water (IRIN, 2009; Muller et al., 2009), which is also visible in our results. Though water is scarce in some regions, South Africa is currently a net food exporter. However with a trend towards more water intensive lifestyles, water demand is expected to overtake supply in the coming years, which may lead to competitions between sectors.

Currently, water use in both example countries is below the minimum requirement identified in the literature (Table 1) (Indonesia: 531 $m^3\,cap^{-1}\,yr^{-1}$; FAO, 2011, South Africa see above). Increasing development may lead to additional pressured here, as lifestyles adjust to prevailing patterns in highly developed countries and water use increases. Improved access to water resources for example, which is urgently needed in many regions of the case study countries, has been shown to increase water consumption, as more water is used e.g for hygiene purposes, an important improvement to heath status (Larson et al., 2006). Our results show, that water is a limiting factor in some densely populated regions already today. Here, growing water demand would indeed be critical. Especially in regions where high population growth and high development is expected, integrated water management schemes may therefore become increasingly important.

Limitations in water quality play a very decisive role in both countries and in all sectors. Especially the environmental water adequacy proves to be one of the most limiting factors for water security/adequacy, due to increasing threats to biodiversity from high pollution levels. Even when prioritizing environmental water needs, as has been done in the present approach by allocating environmental water needs before other sectors, water quality threatens environmental water sustainability. Where access to drinking water is not provided through improved sources, high pollution levels may also have





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direct health implications. Additionally, low quality water for agriculture may also lead to reduced yields or health effects due to contaminated foods (Toze, 2006).

Sustainable adaptation and development in the water sector should concentrate on improving water infrastructure and on improving the quality of accessible water in many regions. Improving infrastructure can also reduce the susceptibility to impacts of climate extremes, as contamination and disruption of water infrastructure then becomes less likely.

The presented approach was developed to be widely applicable in developing countries, enabling comparability between regions. It provides an overview of the main determinants and was applied in a first exemplary approach, using comparable data for two case study countries. In its present form, the approach has some limitations. By using global data sets for example, comparable results between countries are produced, however, regionally collected data may reflect regional to local conditions more accurately. A regional to local adjustment of the methodology could also take into account local characteristics, such as water intensive industries and energy production types. Further, seasonal variations in water availability play an important role at the local and regional scale, but have not been included in the present application. Additionally, the forecasting capacity of the results is limited so some extent, as the quality and infrastructural components could not be calculated with scenario values in a comparable way, as data were unavailable at present.

The fact that infrastructure, access and quality are often more important than water availability itself in determining adequate water availability, especially in developing countries, is widely recognized. However, quantifications to identify the most pressing factors on a sub-regional scale have so far been lacking. The presented approach outlines a novel way of providing comparable results across regions to identify, which aspects of water supply need to be improved most urgently. The approach can point towards adaptation strategies which allow prioritizing between different development goals and choosing strategies, which most efficiently improve water availability. The approach allows testing different allocation patterns for different water sectors and can





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show at which point overall water adequacy could be most efficiently increased by adjusting single factors of the analysis.

As water resources become scarce, either due to increasing population and demand, or through a reduction in resource availability, competition between different sectors to have access to sufficient water resource may arise. The present approach allows to identify needs of different users and make visible, which aspects are important in different regions. By taking into account sector-specific needs, the approach can provide management relevant information for decision-makers. It also allows identifying potential trade-offs and competitions between sectors.

## 5 Conclusions

This paper presents an integrated approach to determine how adequately important sectors are supplied with water resources. The applied fuzzy logic algorithm allows to identify regions of inadequate water supply in a comparable and transferable way. The approach also allows identifying those factors and sectors which are most important in a regional context, contributing to decision-making processes for sustainable development and integrated climate change adaptation. It is clear that water scarcity is essentially human made and population density, infrastructure and associated pollution determine whether available water is sufficient and in adequate form to be used. It is essential to increase knowledge of processes, as access to sufficient clean water is the most critical of human needs. Thus, improving access has high priority, especially in developing countries, where development and human well-being are often severely restricted by lacking water access. Applicable approaches, which combine a range of determinants of water adequacy and allow to prioritize interventions are urgently needed to advance sustainable development. The presented approach is an important contribution to improve knowledge and cope with the multiple challenges the water sector faces.





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**Table 1.** Overview of sectoral water needs according to different sources, all converted to $m^3\,cap^{-1}\,yr^{-1}$.

| | Chenoweth (2008) | Falkenmark (1997) | Shuval (1992) | **Range** | **Threshold** |
|---|---|---|---|---|---|
| municipal | 30.6 | 36 | 100 | 30.6–100 | 30–100 |
| industrial | 12.6 | 36–432 | – | 12.6–432 | 10–400 |
| agricultural | | 504–1584 | 25 | 25–1584 | 500–1500 |
| cumulative | | | | | **540–2000** |





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**Table 2.** Overview of data sources (variables) used to represent the indicators of water adequacy.

| Sector | Indicator | Variable | Source |
|---|---|---|---|
| Municipal | municipal water access (m_access) | Source of drinking water | ICF (2013) |
| | municipal water quality (m_quality) | Phosphorus loading<br>Nitrogen loading<br>Sediment loading<br>Organic loading<br>Mercury deposition<br>Pesticide loading | Vörösmarty et al. (2010b) |
| Agricultural | agricultural water quality (a_quality) | Soil salinisation | Vörösmarty et al. (2010b) |
| | security of supply (a_sec_supply) | Dam density | |
| | | Area equipped for irrigation | AQUAstat (FAO, 2013) |
| Industrial | industrial water quality (i_quality) | Sediment loading<br>Thermal alteration | Vörösmarty et al. (2010b) |
| Environmental | environmental water quality and biodiversity threat (biod_threat) | Biodiversity threat | Vörösmarty et al. (2010b) |
| Water availability | | Total runoff and discharge | LPJmL (Bondeau et al., 2007) |





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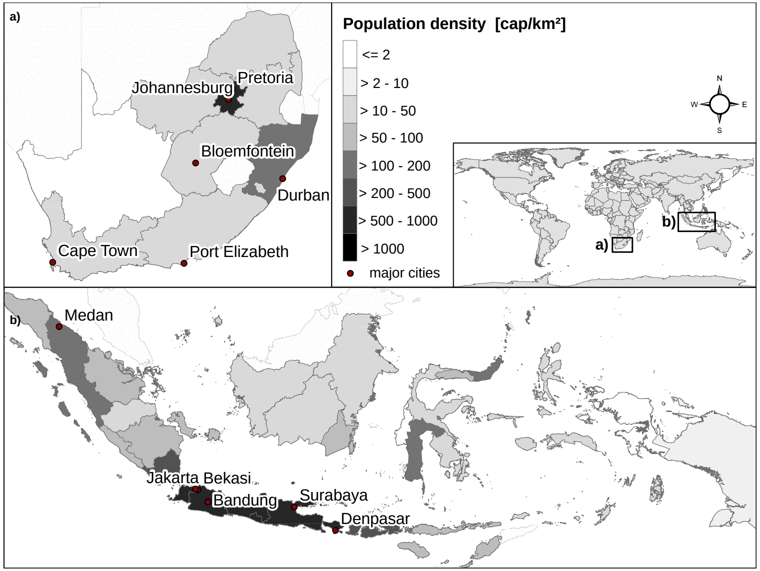


**Fig. 1.** Regional population densities and major cities of the example countries **(a)** South Africa and **(b)** Indonesia and their location on the world map.





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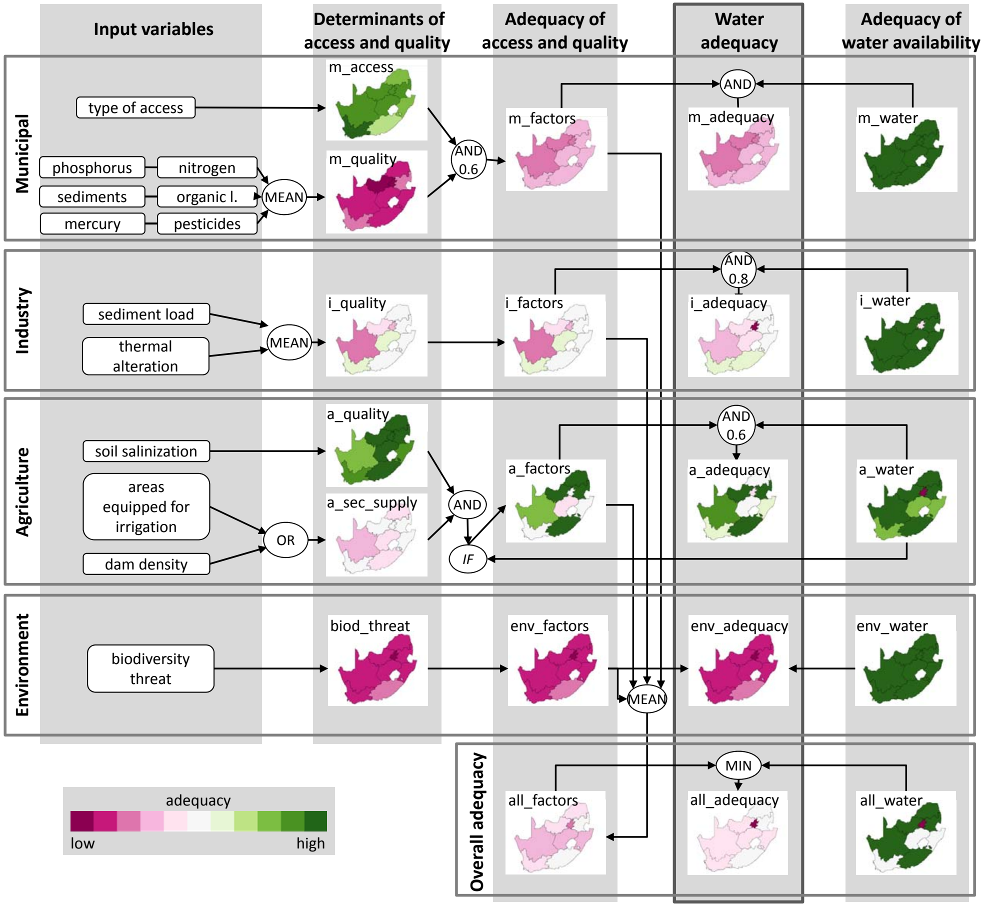


**Fig. 2.** Fuzzy aggregation tree to calculate the adequacy of available water resources. Maps show values for South Africa using water availability data from the GFDL-ESM2M model under current conditions (GDFLbase).





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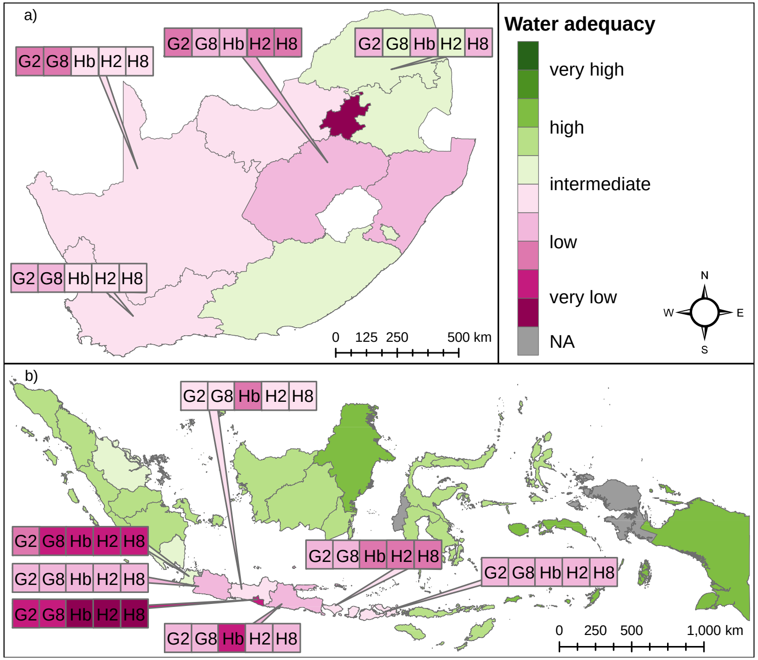


**Fig. 3.** The maps show the integrated measure of water adequacy under current conditions (GDFLbase) for **(a)** South Africa and **(b)** Indonesia. Colored boxes show changes in water adequacy where these occur, differentiating the models and RCPs. G2: GDFL2.6, G8: GDFL8.5, Hb: HADbase, H2: HAD2.6 and H8: HAD8.5.





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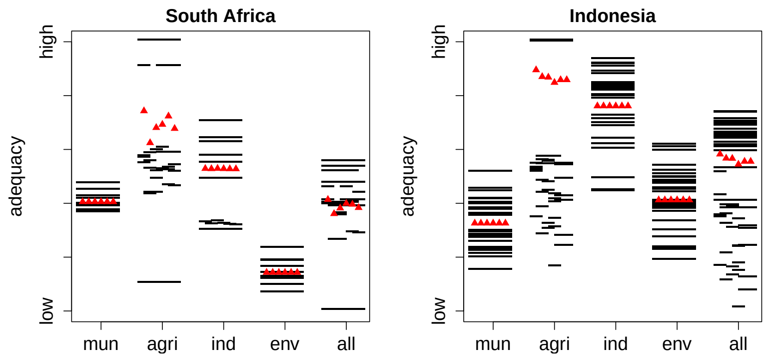


**Fig. 4.** Sectoral water adequacy in South Africa (left panel) and Indonesia (right panel), showing results for the individual sectors (mun = municipal, agri = agricultural, ind = industrial, env = environmental, all = overall). Black lines show results for the individual municipalities, red triangles show the country average for results across models and RCPs from left to right: GDFLbase, GDFL2.6, GDFL8.5, HADbase, HAD2.6, HAD8.5.





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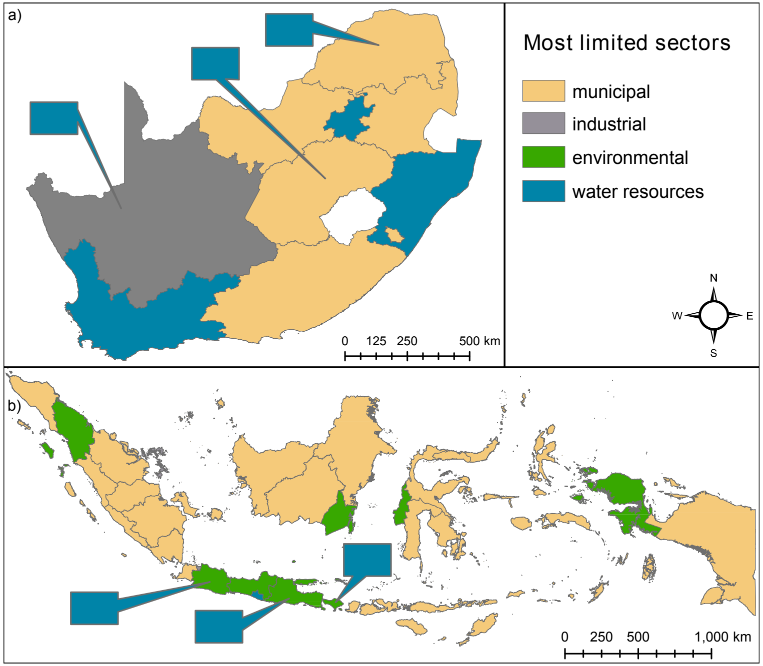


**Fig. 5.** Overview of the most limited sectoral adequacy for the regions of **(a)** South Africa and **(b)** Indonesia under current conditions (GDFLbase). Where changes occur across scenarios, these are indicated by a box in the respective colour. Note that the sectoral limitations shown for South Africa are the second-most important after the environmental sector.





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