



Towards indicators for water security - A global hydro-economic classification of water challenges

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Interim Report

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Towards indicators for water security - A global hydro-economic classification of water challenges

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Abstract

Following a risk-science perspective IIASA's Water Futures and Solutions Initiative has developed a novel indicator for measuring water security and water challenges. A hydro-economic classification depicts countries and/or watersheds in a two-dimensional space using normalized indicators of economic-institutional coping capacity and hydrological complexity. Lacking adequate data on institutional capacity that was acceptable to stakeholders, we use in a first attempt GDP per capita as proxy for economic-institutional coping capacity. Hydrological complexity is measured by an weighted indicator based on four component indicators: i) total renewable water resources per capita; ii) intensity of water use; iii) runoff variability; and (iv) dependency of external water resources. Indicators were selected to provide global data coverage and future projections using the results from global hydrological and water use models. Here we create a hydro-economic classification of countries for the year 2000 Using data from the Food and Agriculture Organization AQUASTAT database and ISI-MIP hydrological model results.

Acknowledgments

The Water Futures and Solutions Initiative is a broad-based international consortium with the long term goal of providing the systems analytical frameworks and tools to identify and assess sustainable, robust, no-regret portfolios of options, which are coherent across sectors and management scales, for the purpose of improving human well-being through enhanced water security, under the range of possible futures and uncertainties faced by society. Broad-based participation of the water community, and the communities of related sectors, is critical for not only advancing knowledge and science, but also for providing consistent messages on which decision makers across sectors and scales of management can act to produce consistent implementation of portfolios of solutions. We therefore would like to acknowledge and thank the partners that helped launch the initiative: IIASA, UN-Water/UNESCO, the World Water Council (WWC), the International Water Association (IWA), and the Ministry of Land, Infrastructure and Transport (MOLIT) of the Republic of Korea. We also thank the many organizations that have contributed as part of the consortium (see blue-box below).

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Professor DI Günther Fischer is a senior researcher in land use systems of the Food and Water thematic area at IIASA. He also holds the position of adjunct professor in the Department of Geography at the University of Maryland, USA. His main fields of research are mathematical modeling of ecological-economic systems, econometrics, optimization, applied multi-criteria decision analysis, integrated systems and policy analysis, spatial agro-ecosystems modeling, and climate change impacts and adaptation. He participated in the development of IIASA's world food systems model and was a key contributor to several major food and agricultural studies: On welfare implications of trade liberalization in agriculture; on poverty and hunger; on biofuels and food security; on the climate-water-food-energy-ecosystem nexus; and on climate change and world agriculture. He is collaborating with the United Nations Food and Agriculture Organization (FAO) on the development and application of the Agro-Ecological Zones methodology and has contributed to major FAO agricultural perspective studies, to IPCC assessment reports, the Millennium Ecosystem Assessment, WSSD Johannesburg Report Climate Change and Agricultural Vulnerability.

Professor Fischer is recognized as one of 23 IIASA scientists that have contributed to the large body of IPCC reports. The Nobel Peace Prize (2007) was awarded to the Intergovernmental Panel on Climate Change (IPCC) and Al Gore for "their efforts to build up and disseminate greater knowledge about man-made climate change, and to lay the foundations for the measures that are needed to counteract such change."

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Her responsibilities as a land use and GIS expert have included the development of large spatial databases serving the modeling and analysis needs in the areas of food-environment-bioenergy-water linkages, food-system analysis, land use and water scenarios and environmental transition. She was involved in Agro-Ecological Zones Methodology assessments for agricultural development planning, worked on several assessments of biofuels and food security, and the mobilization of resources for the bio-economy. In sustainable consumption research she has been a principal investigator in analysis tracing embodied land use and deforestation in agricultural and forestry products from primary production to final utilization. The geographic focus of her research has been both global and regional (e.g. Europe, China, and Brazil).

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Towards indicators for water security - A global hydro-economic classification of hydrological challenges and socio-economic coping capacity

Günther Fischer, Eva Hizsnyik, Sylvia Tramberend, David Wiberg

1 Introduction

1.1 Background

One of the primary tasks of the Water Futures and Solutions (WFaS) initiative is to develop global scenarios of water potentials and stressors and their interdependencies across the different water sectors, the climate-water-food-energy-ecosystem nexus, and the impacts on human wellbeing and earth ecosystems and the services they provide. A global assessment is essential in view of the increasing importance of global drivers such as climate change, population growth and rapid urbanization, economic globalization or safeguarding biodiversity. Maintaining a global perspective and providing the necessary regional detail to identify future pathways and solutions is key for water scenario development. Against this background, WFaS aims for its quantitative scenario assessment not only a high level of regional detail (typically at the grid-cell level) but also to go beyond globally uniform assumptions of important scenario drivers. This requires developing a system of classification for countries and watersheds describing different conditions pertaining to water security (or its reverse water challenges). We start from a general discussion on water security indicators leading to the novel concept of hydro-economic classification. Then we propose a compound indicator based methodology for the classification of countries (and watersheds) into a two-dimensional hydro-economic space. In this way, countries and/or watersheds can assume varying scenario drivers (e.g. technological change rates) for defined categories of hydro-economic development challenges.

1.2 Indicators of water security

The concept of water security (and its reverse water scarcity) is complex to define because it means different dimensions or facets. First, security needs to be understood as a relative concept, i.e., an imbalance between “supply” and “demand” that varies according to local conditions. Second, water security and water scarcity are fundamentally dynamic. For example, water scarcity intensifies with increasing demand by users and with the decreasing quantity and quality of the resource. It can further decrease when the right response options are put in place.

A widely used simple indicator in the context of population growth and finite water resources is the water crowding indicator (Falkenmark, et al., 2007). Its reverse, the per

capita available renewable water resources, are referred to as “Falkenmark Water Stress Indicator” (Falkenmark, 1989). Both relate the maximum theoretical yearly amount of water available for a country to population. Defining thresholds related to water scarcity for these indicators is complex as it involves assumptions on water use and its efficiency. Human use of available water resources includes agriculture (irrigation), energy generation, other industry (mainly manufacturing), and households. In addition some water should be reserved as ‘environmental flows’ (Smakhtin, 2008) (Pastor, et al., 2014) required for protecting aquatic ecosystems.

The intensity of human uses of finite water resources generally measures water use to availability ratio. It describes demand-driven scarcity and is often referred to as water stress (Kummu & Varis, 2011). The United Nations (UN, 1997) has set the withdrawal of 40% as the threshold for situations of high water stress. Almost 2 billion people live in countries where water use exceeds 40% of availability including India where the 40% threshold has just been reached. In many of these countries the majority of water use is for agriculture.

The International Water Management Institute (IWMI) introduced the concept of physical and economic water scarcity (Molden, 2007). The former is used to define situations where insufficient water is available to meet all demands including water needed for maintaining aquatic ecosystem services. Economic water scarcity is caused by lacking capacity for infrastructure development to use available water resources.

Recently frameworks focus on defining water security rather than water scarcity and include consideration of societies’ adaptation or coping capacity to water related challenges. (Grey, et al., 2013) perceived water security from a risk-science perspective and categorized countries and regions into four quadrants in terms of i) complexity and risk of the hydrological system and ii) the level of investment for water risk reduction.

Following the risk-science perspective IIASA’s WFaS Initiative has developed for its scenario analysis a hydro-economic classification determined by a combination of economic-institutional coping capacity and hydrological complexity.

1.3 Aims and objectives

The primary aim is to produce a hydro-economic classification of countries for use in the WFaS scenario approach. As watersheds and their inherent water challenges extend beyond national boundaries the hydro-economic classification should also be applicable to the geographic entity of watersheds. To be useful in WFaS the classification approach must meet three basic principles:

- (i) Produce a small number of distinct classes that differentiate countries in terms of (current and future) water challenges and the means they have to act and the urgency and priorities they are likely to assign to finding water solutions;
- (ii) Use variables/indicators that are not only available for past years but can also be computed for future periods and scenarios;
- (iii) Apply an approach that is flexible, transparent and can be refined/tailored to reflect stakeholder priorities and needs.

2 Methodology and data for hydro-economic classification

2.1 Conceptual approach and overview

The hydro-economic classification consists of two broad dimensions representing respectively

- (i) a country's/region's economic and institutional capacity to address water challenges; i.e. the economic institutional capacity (y-dimension)
- (ii) a country's/region's magnitude / complexity of challenges related to the management of available water resources; i.e. hydrological challenge/complexity (x-dimension)

For the classification, each major dimension is measured by a normalized composite index, which is computed from a set of relevant indicators. In this way countries/regions will be located in a two-dimensional space representing different human-natural water development challenges and levels of water security.

For example, for the estimation of qualitative and quantification assumptions of critical water dimensions (e.g. technological change rates) in the WFaS 'fast-track' scenario assessment we assign different values depending on the country's location in one of four quadrants in the two-dimensional space (Figure 1).

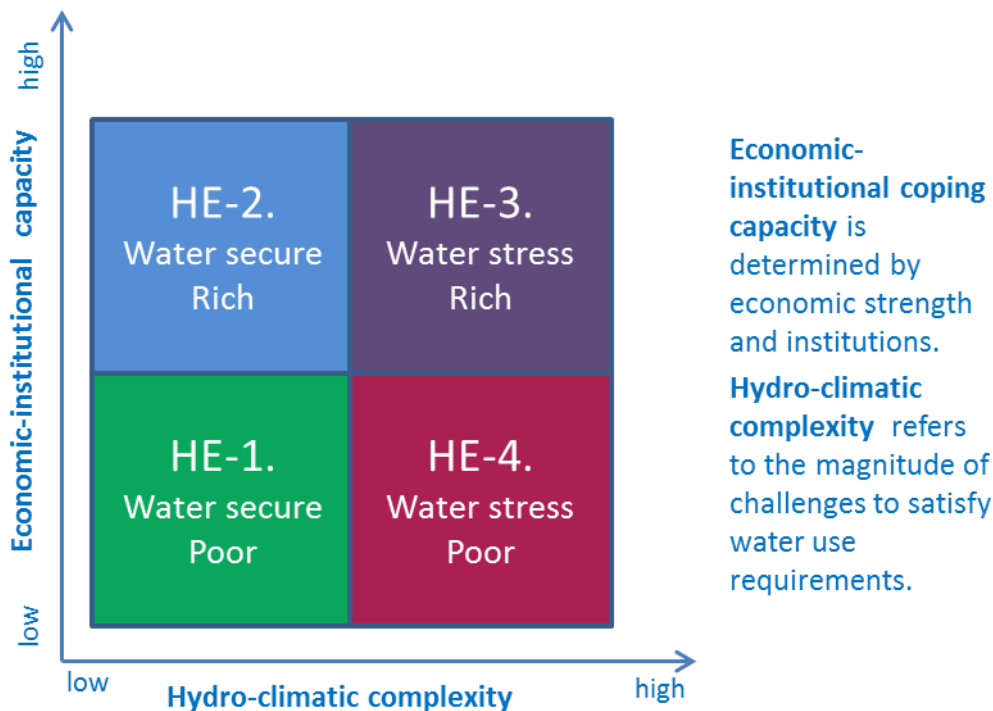


Figure 1. Conceptual framework for allocation of hydro-economic classification to four quadrants of water security

For the y-dimension, we've selected one indicator, namely GDP per caput (in constant PPP dollars per caput) as a measure of economic strength and financial resources available for investing in risk management.

Another indicator initially discussed was the Corruption Perception Index (CPI) (Transparency International¹). In a first attempt the CPI was included in the compound indicator for economic-institutional capacity based on the assumption that lower corruption may indicate higher coping capacity to water related risks and vice versa. However, in response to disapproval of this indicator by a workshop of WFaS stakeholders, the CPI was excluded from the composite indicator. Moreover for determining hydro-economic classes in different future scenarios, an estimation of the CPI would be required using formal methods or expert judgments based on the information available in the scenario narratives.

For the x-dimension of water challenge complexity, we use four component indicators:

- (i) Total renewable water resources per capita (in m³/person/yr) as a measure for water availability;
- (ii) The ratio of annual water withdrawal to total renewable water resources (scalar fraction) as a proxy for relative intensity of water use;
- (iii) Runoff variability expressed by the coefficient of variation of simulated monthly runoff for a 30-year period as proxy for both inter- and intra-annual variability of water resources;
- (iv) The share of external (from outside national boundaries) to total renewable water resources as a measure for the dependency of external water resources.

2.2 Methodology for indicator calculation

After selecting relevant indicator variables and data sources for X- and Y-dimensions of the hydro-economic classification scheme the classification process proceeds as follows:

- 1) For each indicator variable, define 5 classes along relevant scale (decide on linear or log scale as appropriate). Typical class names would be, for instance, 'very low', 'low', 'medium', 'high', 'very high' (or similar).
- 2) Map each indicator/variable V_i for $i=1, \dots, n$ to a normalized index value X_i by:
 - a. Determining the interval (broad class) $v \in [V_j, V_{j+1}]$ into which the indicator value v_i of a country/region falls;
 - b. Calculate the normalized index value $X_i(v_i)$ according to
$$X_i(v) = X_i(V_j) + \max(0, \min\left(1, \frac{v - V_j}{V_{j+1} - V_j}\right))(X_i(V_{j+1}) - X_i(V_j))$$
- 3) Determine an appropriate weight w_i for each sub-index. We follow the method proposed in WRI-Aqueduct (WRI, 2013) to set weights in a non-linear way according to a few classes of perceived importance of the criteria, for instance:

¹ See www.transparency.org

Importance	Weight
Very low	1
Low	2
Medium	4
High	8
Very high	16

- 4) Calculate the composite index I as weighted sum of normalized sub-indexes X_i :

$$I(V) = \frac{\sum_{i=1}^n w_i X_i(v_i)}{\sum_{i=1}^n w_i}$$

where $V=(v_1, \dots, v_n)$ is the vector of observed (or simulated) indicator variables for each country/region.

- 5) Make sure when combining sub-indexes X_i that all have the same orientation, i.e., a low value indicates respectively a low economic-institutional capacity or a low hydrological challenge and a high value indicates a high challenge. The orientation of a sub-index can be reversed by using an index X' instead of X according to:

$$X' = 1 - X$$

- 6) Do above calculations separately for X- and Y-axis and map a country's/region's position in the resulting two-dimensional plane. This will produce a scattergram of normalized index values in the interval of [0,1] in both dimensions, which is easy to divide into a convenient number (say four or nine) of mutually exclusive hydro-economic classes.

2.3 Quantifying 'economic-institutional capacity'

As discussed above we currently apply one variable as proxy for 'economic-institutional coping capacity', namely GDP (in PPP terms) per capita.

Estimates of GDP (in PPP terms using constant 2005 US dollars) per caput (**GDPC; US\$/cap/yr**) are taken from World Bank. Note, country estimates of this indicator are also part of the quantified SSP variables and projections are available for future periods by country and different five different SSP scenarios. Five classes are used for the normalized sub-index function:

Very low:	CL1 ... 3000 > GDPC > 250
Low:	CL2 ... 10000 > GDPC > 3000
Medium:	CL3 ... 10000 > GDPC > 20000
High:	CL4 ... 35000 > GDPC > 20000
Very high:	CL5 ... 90000 > GDPC > 35000

The range values are set with consideration of the significant GDP per capita increase in future projection. The index function ranges from 0 to 0.2 for values of GDPC in class 1, 0.2 to 0.4 for values in class 2, etc. For $GDPC > 90000$ US\$₂₀₀₅/cap/yr the index function is set to 1, for $GDPC < 250$ US\$₂₀₀₅/cap/yr an index function value of 0 is used. An index

function value of zero indicates a very low economic capacity, an index value of 1 means a rather high economic capacity. Figure 2 presents the normalized component index function $f_y^1(GDPC)$ used to express the dimension of income along the Y-axis of economic coping capacity.

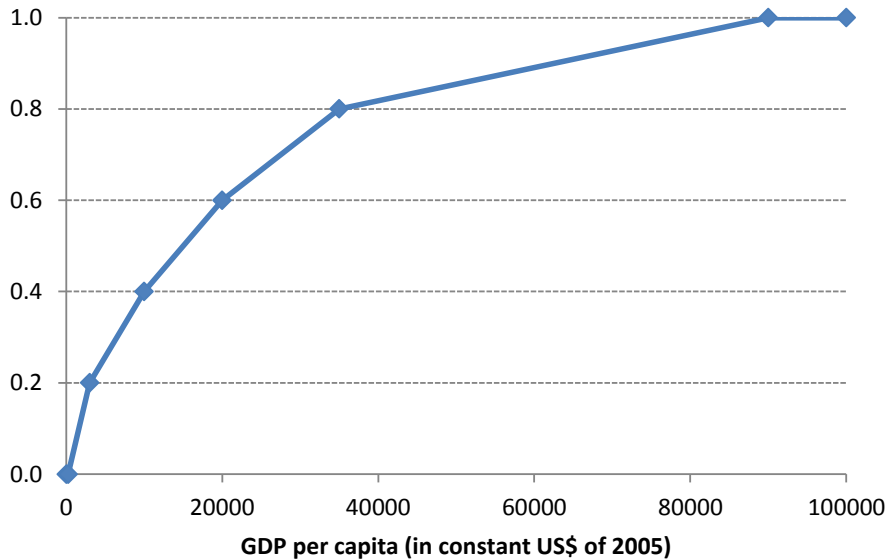


Figure 2. Index function for rating economic capacity for indicator of GDP (in constant PPP \$ of 2005) per caput

2.4 Quantifying ‘hydrological complexity’

Next we present the approach applied for computing normalized index functions for a range of indicator values aimed at measuring the hydrological complexity of a spatial assessment unit, which is used here as the X-dimension for a hydro-economic classification of countries/regions. This X-dimension refers to a country’s/regions’s perceived magnitude of water challenges, which is computed from four indicators: (1) total renewable water resources per capita; (2) the ratio of annual water withdrawal to total renewable water resources; (3) variability of monthly runoff; and (4) a country’s share of (actual) external to total renewable water resources.

Total renewable water resources per capita

Estimates of this indicator **TWRC (m3/cap/y)** are available in the national statistics of AQUASTAT². The statistical indicator for ‘actual total renewable water resources’ is calculated by adding an estimate of a country’s internal renewable water resources and the inflow from neighboring countries (and a part of the resources of shared lakes and border rivers) adjusted for the part of the flow that is secured/committed through treaties and agreements (in upstream and downstream countries). As the classification approach and this indicator is also required for different future scenarios, we apply a simulation approach and use as a proxy of a country’s/region’s internal renewable resources the

² online database available at <http://www.fao.org/nr/water/aquastat/dbase/index.stm>

calculated mean annual runoff over a 30-year period averaged of a multi-model ensemble of hydrological and climate models (for current calculations the hydrological results have been used from six hydrological models and five GCMs, for the historical period 1971-2000 and for three future 30-year periods (2011-2040, 2041-2070, 2070-2099) available for four RCPs (RCP2p6, RCP4p5, RCP6.0, RCP8p5). To this we add the AQUASTAT estimate of (actual) external renewable water resources (adjustments of this term, both due to climate change and possible changes in secured/committed flows, for future periods are still under discussion). For the base period we use population of 2000 to compute per capita water resources availability. Range values are based on (Shiklomanov, 2000). Five classes are used for the normalized sub-index function:

- Very high: CL1 ... 20000 > TWRC > 10000
- High: CL2 ... 10000 > TWRC > 5000
- Medium: CL3 ... 5000 > TWRC > 2000
- Low: CL4 ... 2000 > TWRC > 1000
- Very low: CL5 ... 1000 > TWRC > 100

The resulting normalized index function ranges from 0 to 0.2 for values of TWRC in class 1 (i.e. TWRC > 10000 m³/cap/yr), 0.2 to 0.4 for values in class 2, etc. For TWRC > 20000 m³/cap/yr the index function is set to 0; for TWRC < 100 m³/cap/yr an index function value of 1 is assigned. An index value of zero indicates a low hydrological complexity (in this case a large volume of per capita water resources available), an index value of 1 means an extreme low availability of water resources per capita (and thus a high challenge).

Figure 3 shows the normalized component index function $f_x^1(TWRC)$ used to express the dimension of water resources availability along the X-axis of hydrological complexity.

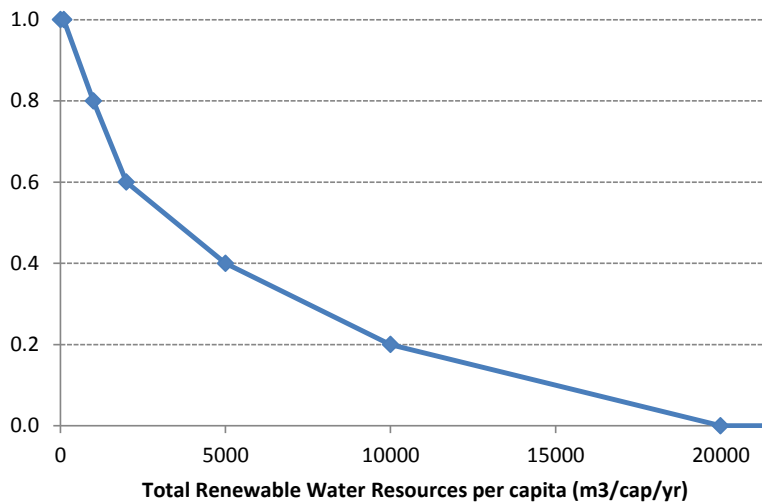


Figure 3. Index function for rating hydrological complexity for sub-indicator of water availability per caput (m³/cap/yr)

Intensity of water use

We apply the ratio of total water withdrawal to total renewable water resources (**TWD/TWR; scalar**) as proxy for intensity of water use. Again, estimates of this indicator can be compiled (for most countries) for the base year from AQUASTAT. As an alternative, and for applying the classification in future scenario periods, we use water withdrawals estimated by participating water demand models and total renewable water resources based on average annual runoff plus (actual) external water resources estimated by participating hydrological models to compute the respective future scenario-specific sub-indicator variables. Note that the ratio can exceed 1 due to use of non-renewable water sources, such as aquifers with ‘fossil’ water but also water from desalination plants, due to over-exploitation of renewable groundwater resources, or due to re-use of water (i.e. return flows of non-consumptive use).

Five classes are used for this normalized component index function:

Very low:	CL1 ...	$0.01 < \text{TWD/TWR} < 0.05$
Low:	CL2 ...	$0.05 < \text{TWD/TWR} < 0.15$
Medium:	CL3 ...	$0.15 < \text{TWD/TWR} < 0.30$
High:	CL4 ...	$0.30 < \text{TWD/TWR} < 0.60$
Very high:	CL5 ...	$0.60 < \text{TWD/TWR} < 1.00$

The normalized component index function $f_x^2(\text{TWD/TWR})$ ranges from 0 to 0.2 for values of TWD/TWR in class 1 (i.e. $\text{TWD/TWR} < 0.05$), 0.2 to 0.4 for values in class 2, etc. For $\text{TWD/TWR} > 1$ the index function is set to 1, for $\text{TWD/TWR} < 0.01$ an index function value of 0 is used (Figure 4). Again, an index value of zero indicates a very low complexity (in this case a low withdrawal ration relative to water resources availability), an index value of 1 means that annual water withdrawals exceed annual water resources.

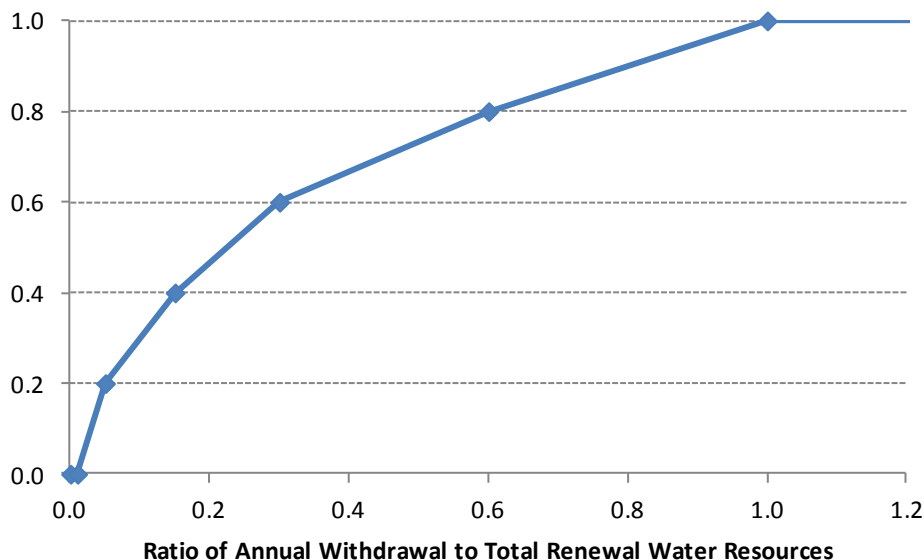


Figure 4. Index function for rating hydrological complexity for sub-indicator of water withdrawal to renewable water resources

Variability of monthly runoff

For this indicator (**CVTWR; CV %**) we use simulated 30-year time series of total monthly runoff averaged across participating hydrological models to compute the respective coefficient of variation (i.e. standard deviation divided by mean) for each country and river basin for respectively 1971-2000, 2011-2040, 2041-2070 and 2070-2099. Note this CV captures both inter- and intra-annual variability of runoff.

Five classes of CV ranges are used for the normalized sub-index function:

- Very low: CL1 ... $0 < CVTWR < 30$
- Low: CL2 ... $30 < CVTWR < 60$
- Medium: CL3 ... $60 < CVTWR < 100$
- High: CL4 ... $100 < CVTWR < 150$
- Very high: CL5 ... $150 < CVTWR < 225$

The normalized index function $f_x^3(CVTWR)$ ranges from 0 to 0.2 for values of CVTWR in class 1, 0.2 to 0.4 for values in class 2, etc. For $CVTWR > 225\%$ the index function is set to 1 (Figure 5). As before, an index value of zero indicates a very low complexity in terms of variability of monthly runoff, an index value of 1 means that the standard deviation of monthly runoff is more than twice the 30-year mean, which suggests a substantial challenge for managing month-by-month variations of water resources.

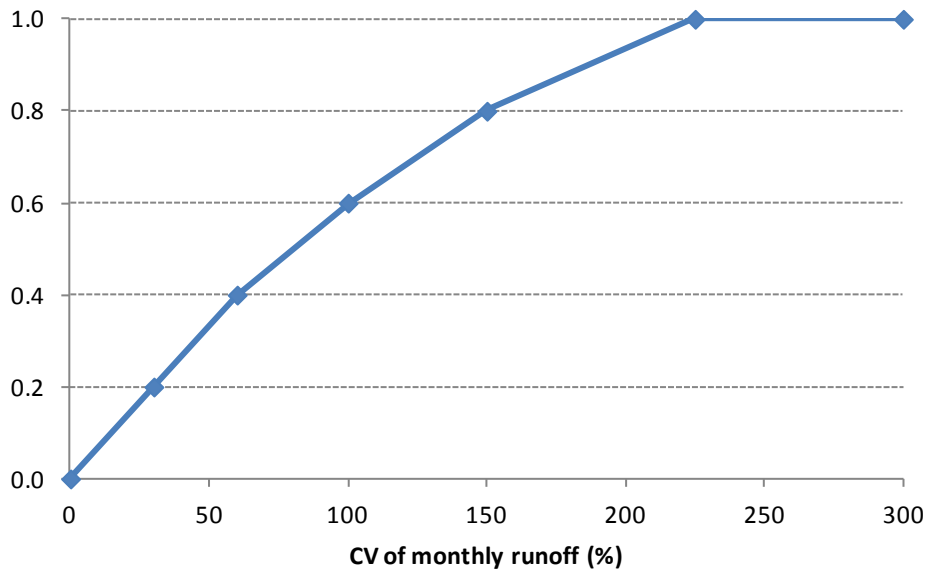


Figure 5. Index function for rating hydrological complexity for sub-indicator of variability of total monthly runoff

Dependency share of external to total renewable water resources

For this indicator (**DPC; scalar**) we use the ratio of (actual) external water resources to estimated (actual) total renewable water resources as indicator variable. Figure 9 shows the S-shaped form of the normalized sub-index function $f_x^4(DPC)$:

Very low:	CL1 ...	$0.05 < DPC < 0.30$
Low:	CL2 ...	$0.30 < DPC < 0.45$
Medium:	CL3 ...	$0.45 < DPC < 0.55$
High:	CL4 ...	$0.55 < DPC < 0.70$
Very high:	CL5 ...	$0.70 < DPC < 0.95$

The normalized index function ranges from 0 to 0.2 for values of DPC in class 1 (i.e. a dependency share of 0.05 to 0.30), 0.2 to 0.4 for values in class 2, etc. For $DPC > 0.95$, i.e. when only 5% of a country's water resources originate internally, the index function is set to 1 (Figure 6). An index value close to zero indicates that only a small fraction of total water resources comes from neighboring countries; an index value of 1 means that nearly all renewable water resources originate from outside a country, as inflow from upstream countries or from shared bordering lakes or rivers. Such dependency on upstream neighboring countries may increase the complexity of water challenges and management. Countries with very high dependency on external resources include for example Bangladesh, Egypt and Hungary.

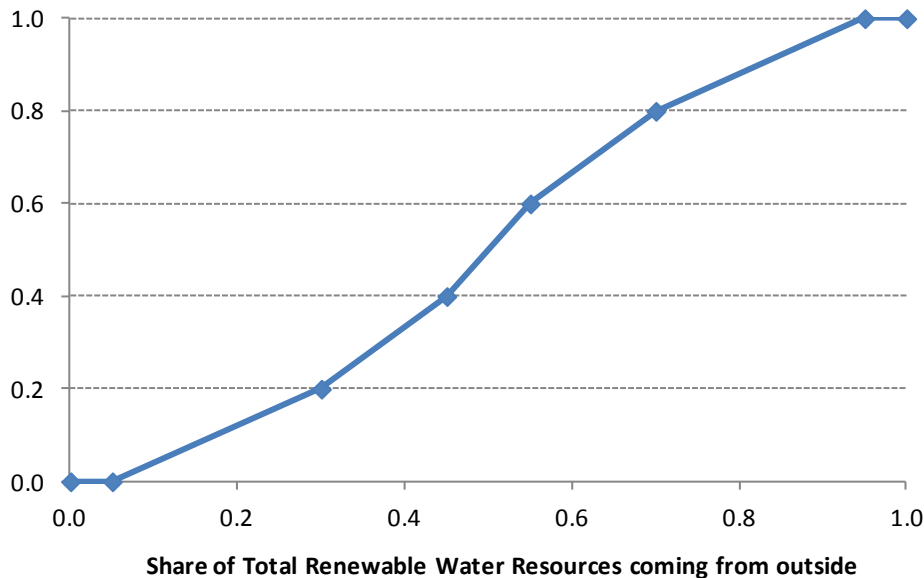


Figure 6. Index function for rating hydrological complexity according to dependency on (actual) external water resources

2.5 Assigning weights to all indicators

We propose to assign a ‘high’ importance (i.e. weight is 8) to three of the above criteria, for respectively total renewable water resources per caput, for share of annual water withdrawals to total annual renewable water resources and for variability of monthly runoff, and to use ‘medium’ importance for dependency on external water resources. Note, the relative importance of different component indicators is expressed by weights w_i and could be set according to stakeholder priorities.

2.6 Example for quantification of X-dimension

Below is a worked example of the classification procedure for quantifying the X-dimension of the hydro-economic classification, which intends to quantify a country’s/region’s position with regard to its hydrological challenges and complexity.

Indicator variables are calculated as averages of outputs of global simulations on 0.5 degree global grids from six hydrological models and using outputs from five different climate models for the period 1971-2000. Quantifications of water withdrawals were taken from AQUASTAT. Table 1 presents indicator values, values of individual index functions for the five criteria and the resulting compound index function values.

Table 1: Example quantification of X-dimension of hydro-economic classification

Country	Component Variable				Component Index Function				X-Ind I_x
	V_1	V_2	V_3	V_4	X_1	X_2	X_3	X_4	
<i>Weight</i>					8	8	8	4	
Austria	9706	0.047	24.2	0.292	0.212	0.185	0.161	0.194	0.187
Spain	2768	0.323	65.4	0.003	0.549	0.615	0.427	0.000	0.455
Ukraine	2854	0.186	43.4	0.619	0.543	0.448	0.289	0.693	0.465
China	2188	0.195	58.0	0.010	0.587	0.460	0.386	0.000	0.410
Israel	296	1.029	118.2	0.579	0.956	1.000	0.673	0.638	0.842
Argentina	22041	0.040	23.7	0.661	0.000	0.150	0.158	0.748	0.195
Brazil	47201	0.007	52.9	0.342	0.000	0.000	0.353	0.256	0.137
Algeria	382	0.490	73.1	0.036	0.937	0.727	0.466	0.000	0.609
Nigeria	2314	0.036	87.6	0.228	0.579	0.130	0.538	0.142	0.377
Tanzania	2828	0.054	84.1	0.127	0.545	0.208	0.520	0.062	0.372
S. Africa	1148	0.243	40.0	0.128	0.770	0.524	0.267	0.063	0.455

Note: V_1 =Renewable water resources per capita; V_2 =Ratio of total water withdrawals to total renewable water resources; V_3 =CV of 30-year variability of monthly total runoff; and V_4 =dependency on external water resources.

In the example of Table 1, total water resources per capita (variable V_1 in $m^3/cap/yr$) range from 296 m^3/cap for Israel to 47,201 m^3/cap for Brazil. The respective component index function values are respectively 0.937 and 0.000. A component index function value of 0.5 is attained for a water resource level of 3,500 m^3/cap . As for the share of water withdrawal in total water resources (variable V_2), the lowest value of 0.007 is shown for Brazil, the highest for Israel ($V_2=1.029$). The normalized index function results

in values of respectively 0.000 and 1.000. The last column in Table 2 applies the weights for the individual component indicators and shows the compound index value of 'hydrological complexity'. The lowest value, hence the least complexity, is computed for Brazil, the highest value for Israel.

2.7 Hydro-economic classification diagram

The previous descriptions and worked examples explain the quantification of X- and Y-dimensions used for hydro-economic classification, namely of 'hydrological complexity' (X-dimension) and 'economic-institutional capacity' (Y-dimension). All data are available for the base period and can be calculated for future periods, which allows each country to be displayed in a 2-dimensional hydro-economic classification diagram. In the following section we show a calculated example for all countries of the world for the year 2000 (Figure 7).

In this diagram, both dimensions range from 0 to 1, which makes it particularly easy to classify by quadrants (4 classes), or to use any other and more detailed number of classes (e.g. 9 classes) that may help to account for transition phases in development.

The rating of component indicators described in this note is fairly simple, flexible and easy to present to stakeholders. Combining the component indicators into compound X- and Y-dimensions is transparent. The effect of assigning different priorities and selecting different criteria weights can easily be assessed, and stakeholders can be consulted when setting priorities and associated criteria weights.

From a risk-science point of view, the diagram helps identify regions/countries with higher or lower development challenges for water management. For example, an economic-institutional capacity (countries depicted in the upper area of the diagram) may support solutions for water management even in regions of high hydrological complexity (right area of the diagram). Development challenges are highest in the lower right corner of the diagram where countries face a high degree of hydrological complexity but have little economic-institutional capacity for responding to these challenges.

3. A hydro-economic classification of countries

A hydro-economic classification can be calculated at different geographic scales (e.g. for countries or watersheds) and for different time periods. Over time countries will shift their relative position in the scatter plot because of their demographic and economic development but also because water resources may be affected by climate change.

Here we present an example for the year 2000 calculated at the country level using data summarized in Table 2 and the specification of the compound indicators described in section 2.

Table 2: Data sources for the calculation of the compound indicators

Variable	Unit	Data source
GDP per capita, PPP	Constant 2005 international \$	Worldbank
Population	Number of people	United Nations
Total renewable water resources Total water withdrawal External water resources	Km ³ /year	AQUASTAT Database of the United Nations Food and Agriculture Organization (FAO)
Coefficient of variation of monthly river runoff		Model-ensemble of six hydrological models calculated from ISI-MIP (Warszawski, 2014)

Figure 7 presents a scatter plot of the two compound indicators calculated for 160 countries of the world for the year 2000. Different colors are used for countries in different broad (continental) regions, e.g. red for countries in North Africa and the Middle East, blue for countries in Europe. Defined areas can be delineated for grouping countries according to their hydro-economic classification. In the example presented we've assigned countries to four major groups. These are referred to as hydro-economic class 1 (HE-1) to 4 (HE-4).

In our example the indicator on the y-axis comprises only one indicator, GDP per capita. Therefore we can readily indicate the level of GDP per capita in each of the four HE groups. In contrast hydrological complexity is a compound indicator using four sub-indices related to hydrological complexity and challenges. An increasing indicator denotes an increasing level of hydro-climatic challenges and complexity. Although a strong simplification, we may designate countries located in HE-1 and HE-2 as regions exposed to 'low' hydrological challenges and countries in HE-3 and HE-4 exposed to 'high' hydrological complexity/challenges (Table 3).

Table 3. Definition of four major groups in the hydro-economic classification

	HE-1	HE-2	HE-3	HE-4
Economic capacity (y-axis)	Low (poor)	High (rich)	High (rich)	Low (poor)
GDP per capita	< 15,000 Int\$	< 15,000 Int\$	> 15,000 Int\$	> 15,000 Int\$
Hydrological complexity (x-axis)	Low (Water secure)	Low (Water secure)	High (Water stress)	High (Water stress)

Countries with highest hydro-economic development challenges are located towards the lower right corner of the scatter plot (quadrant HE-4). In these countries the economic-institutional coping capacity is low and at the same time hydrological complexity is high. The classification maps countries in Northern Africa (Egypt, Algeria), the Middle East (Iraq, Syria, Yemen, Jordan), Sub-Saharan Africa (Niger, Somalia, Sudan) and Asia (e.g. Pakistan) into this sphere of high hydro-economic development challenges.

Relatively few countries appear in the upper right corner (quadrant HE-3), representing high economic capacity and high hydrologic challenges, in this case mainly the very dry climate (e.g. Saudi Arabia, Israel, United Arab Emirates).

Hydro-economic development challenges tend to be lower the more a country is located towards the upper left corner of the diagram. Here countries have a high economic-institutional coping capacity and are exposed to relatively low hydrological complexity. Many industrialized countries in Europe (e.g. Germany, United Kingdom, Italy, France), North America (USA, Canada) and Asia (Japan) are mapped here (quadrant HE-2).

Countries across the globe appear in the lower left quadrant (HE-1) characterized by low economic coping capacity to respond to hydrological challenges. However at the same time these challenges are comparatively low.

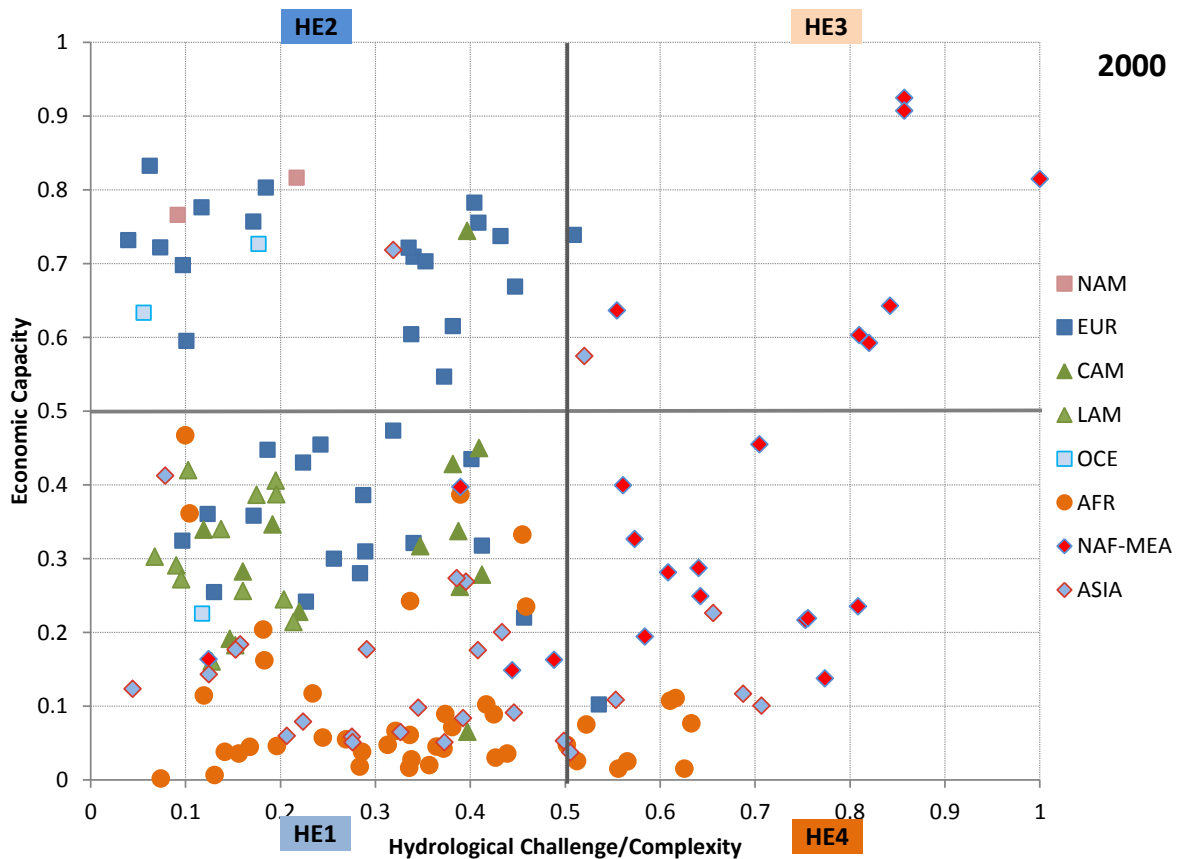


Figure 7. Hydro-economic classification of countries according to their level of hydrological complexity (X-axis) and their economic capacity (Y-axis) for the year 2000

Table 4 summarizes the number of people living in countries assigned to the four major hydro-economic classifications. In addition the table shows detailed results for the index values of economic capacity (Indicator Y-Axis) and hydrologic complexity and challenges (Indicator X-Axis) for selected countries (sorted by their population numbers). Annex I provides the indicators for all the 160 countries which were included in the calculations considering size and data availability and covering 99.5% of the world's population and area.

More than half of global population lives in countries grouped into HE-1. Their economic capacity for investments is low making them vulnerable to hydrologic complexity and challenges, which however are relatively low as well. As much as 98 countries throughout the world are located in the lower left quadrant of the major group HE-1.

The second largest group in terms of population is HE-4. In these countries economic coping capacity is low as in HE-1 but in addition hydrological complexity and challenges are high. About one fourth of global population in 28 countries (including India, Pakistan, Egypt, Iran) lives in these countries, which have a low adaptation capacity and are exposed to water high challenges. Except India, Pakistan and Uzbekistan countries of HE-4 are regionally concentrated in northern Africa and selected Sub-Saharan African countries. The most vulnerable countries with economic coping capacity indicators below 0.2 and hydrologic complexity indicators above 0.6 include Pakistan, Sudan, Niger, Somalia, Uzbekistan and Yemen.

It should be pointed out that the compound indicator for hydrologic complexity for China and India, the world's most populated countries, is 0.41 and 0.55 respectively. Both are thus close to our (arbitrarily) defined threshold of 0.5, which separates HE-1 from HE-4. This demonstrates the importance for a careful interpretation of countries located in 'water secure' (HE-1) or 'water stress' (HE-4) environments when the hydro-economic classification is divided into only four major groups.

The higher a country located in the hydro-economic diagram (i.e. increasing Y-Axis), the higher its economic strength and coping capacity. Only some 15% of global population lives in HE-2 and HE-3 pointing towards the current high level of global inequalities in economic potential. In HE-3 hydrological challenges are high but countries have high economic coping capacity. Less than 100 thousand people live in HE-3 including a number of countries in the Central East (Saudi Arabia, Israel).

Some 14% of global population is home to countries in HE-2 where (on aggregate average across the country area) water related risks are relatively low. This is due to low hydrological complexity combined with high economic coping capacity. The majority of industrialized countries are classified into HE-2 including the United States, Canada, Japan, Australia and many European countries.

Table 4: Hydro-economic classification, by countries, year 2000

Major Hydro-Economic Class Selected country	Population (million people)	Economic coping capacity (Indicator: Y-Axis)	Hydrologic complexity/challenge (Indicator: X-Axis)
HE-1: (Poor economies; Low hydrological complexity)			
Total in HE-1	3502 (57%)	n.a.	n.a.
<i>of which</i>			
China	1298	0.18	0.41
Indonesia	213	0.18	0.17
Brazil	174	0.34	0.14
Russian Federation	147	0.36	0.12
Bangladesh	130	0.05	0.39
Nigeria	124	0.09	0.38
Mexico	100	0.43	0.40
Viet Nam	79	0.10	0.36
Philippines	77	0.18	0.31
Ethiopia	66	0.02	0.36
Turkey	64	0.40	0.40
Thailand	63	0.27	0.41
HE-2: (Rich economies; Low hydrological complexity)			
Total in HE-2	852 (14%)	n.a.	n.a.
<i>of which</i>			
United States of America	282	0.82	0.23
Japan	126	0.72	0.33
Germany	82	0.74	0.43
United Kingdom	59	0.72	0.34
France	59	0.71	0.36
Italy	57	0.70	0.37
Spain	40	0.67	0.45
Canada	31	0.77	0.09
Australia	19	0.73	0.18
HE-3: (Rich economies; High hydrological complexity/challenges)			
Total in HE-1	91 (1.5%)	n.a.	n.a.
<i>of which</i>			
Korea Rep.	46	0.57	0.52
Saudi Arabia	20	0.60	0.81
Belgium	10	0.74	0.51
Israel	6	0.64	0.84
United Arab Emirates	3	0.92	0.86
HE-4: (Poor economies; High hydrological complexity/challenges)			
Total in HE-4	1658 (27%)	n.a.	n.a.
<i>of which</i>			
India	1054	0.11	0.55
Pakistan	145	0.12	0.69
Egypt	68	0.24	0.81
Iran, Islamic Rep.	65	0.33	0.57
Sudan (former)	34	0.08	0.63
Kenya	31	0.08	0.52
Algeria	31	0.28	0.61
Morocco	29	0.19	0.58

Source: WFaS/IIASA

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Annex I. Hydro-economic classification, by country, year 2000

Country	Population (thousand people)	Hydrologic complexity (Indicator: X-Axis)	Economic capacity (Indicator: Y-Axis)	HE Class
Afghanistan	22,856	0.514	0.037	HE4
Albania	3,072	0.246	0.289	HE1
Algeria	30,534	0.609	0.317	HE4
Angola	13,926	0.198	0.162	HE1
Argentina	36,931	0.195	0.406	HE1
Armenia	3,076	0.449	0.149	HE1
Australia	19,164	0.177	0.727	HE2
Austria	8,005	0.187	0.757	HE2
Azerbaijan	8,111	0.506	0.163	HE4
Bahamas	298	0.397	0.744	HE2
Bangladesh	129,592	0.389	0.051	HE1
Belarus	10,058	0.300	0.316	HE1
Belgium	10,176	0.509	0.739	HE3
Belize	251	0.160	0.318	HE1
Benin	6,518	0.400	0.071	HE1
Bhutan	571	0.158	0.184	HE1
Bolivia	8,307	0.214	0.270	HE1
Bosnia and Herzegovina	3,694	0.145	0.298	HE1
Botswana	1,758	0.410	0.391	HE1
Brazil	174,425	0.137	0.358	HE1
Bulgaria	8,006	0.418	0.342	HE1
Burkina Faso	12,294	0.502	0.048	HE4
Burundi	6,374	0.336	0.016	HE1
Cambodia	12,447	0.275	0.059	HE1
Cameroon	15,678	0.130	0.114	HE1
Canada	30,667	0.092	0.766	HE2
Central African Republic	3,702	0.142	0.038	HE1
Chad	8,222	0.454	0.036	HE1
Chile	15,420	0.103	0.420	HE1
China	1,298,268	0.410	0.176	HE1
Colombia	39,764	0.068	0.332	HE1
Congo, Dem. Rep.	49,626	0.074	0.002	HE1
Congo, Rep.	3,136	0.182	0.263	HE1
Costa Rica	3,919	0.192	0.362	HE1
Côte d'Ivoire	16,582	0.249	0.117	HE1
Croatia	4,506	0.186	0.447	HE1
Cuba	11,104	0.401	0.356	HE1
Cyprus	943	0.554	0.636	HE3
Czech Republic	10,243	0.373	0.547	HE2

Country	Population (thousand people)	Hydrologic complexity (Indicator: X-Axis)	Economic capacity (Indicator: Y-Axis)	HE Class
Denmark	5,340	0.409	0.755	HE2
Djibouti	732	0.617	0.111	HE4
Dominican Republic	8,592	0.417	0.315	HE1
Ecuador	12,345	0.090	0.324	HE1
Egypt	67,648	0.809	0.285	HE4
El Salvador	5,940	0.407	0.303	HE1
Equatorial Guinea	520	0.104	0.373	HE1
Eritrea	3,668	0.513	0.025	HE4
Estonia	1,371	0.241	0.430	HE1
Ethiopia	65,578	0.357	0.020	HE1
Fiji	812	0.118	0.278	HE1
Finland	5,173	0.097	0.698	HE2
France	59,048	0.355	0.709	HE2
Gabon	1,235	0.100	0.467	HE1
Gambia	1,297	0.435	0.102	HE1
Georgia	4,746	0.143	0.164	HE1
Germany	82,349	0.432	0.737	HE2
Ghana	19,165	0.344	0.061	HE1
Greece	10,987	0.357	0.604	HE2
Guatemala	11,237	0.235	0.279	HE1
Guinea	8,344	0.168	0.045	HE1
Guinea-Bissau	1,241	0.269	0.055	HE1
Guyana	733	0.128	0.160	HE1
Haiti	8,645	0.397	0.065	HE1
Honduras	6,218	0.169	0.191	HE1
Hungary	10,211	0.334	0.473	HE1
Iceland	281	0.040	0.732	HE2
India	1,053,898	0.553	0.108	HE4
Indonesia	213,395	0.170	0.177	HE1
Iran, Islamic Rep.	65,342	0.574	0.349	HE4
Iraq	23,857	0.659	0.294	HE4
Ireland	3,804	0.136	0.776	HE2
Israel	6,015	0.842	0.643	HE3
Italy	56,986	0.366	0.703	HE2
Jamaica	2,582	0.363	0.342	HE1
Japan	125,720	0.332	0.719	HE2
Jordan	4,827	0.753	0.272	HE4
Kazakhstan	14,957	0.416	0.308	HE1
Kenya	31,254	0.522	0.075	HE4
Korea DPR	22,894	0.406	0.084	HE1
Korea Rep.	45,988	0.520	0.575	HE3

Country	Population (thousand people)	Hydrologic complexity (Indicator: X-Axis)	Economic capacity (Indicator: Y-Axis)	HE Class
Kuwait	1,941	1.000	0.815	HE3
Kyrgyzstan	4,955	0.461	0.091	HE1
Lao PDR	5,317	0.224	0.079	HE1
Latvia	2,385	0.193	0.371	HE1
Lebanon	3,742	0.561	0.400	HE4
Lesotho	1,964	0.321	0.067	HE1
Liberia	2,847	0.131	0.006	HE1
Libyan Arab Jamahiriya	5,231	0.705	0.455	HE4
Lithuania	3,500	0.308	0.390	HE1
Macedonia, FYR	2,009	0.352	0.345	HE1
Madagascar	15,364	0.196	0.046	HE1
Malawi	11,229	0.427	0.030	HE1
Malaysia	23,415	0.079	0.412	HE1
Mali	11,295	0.391	0.043	HE1
Mauritania	2,643	0.628	0.107	HE4
Mexico	99,960	0.398	0.428	HE1
Moldova, Rep.	4,107	0.544	0.102	HE4
Mongolia	2,411	0.145	0.143	HE1
Montenegro	622	0.097	0.347	HE1
Morocco	28,793	0.584	0.194	HE4
Mozambique	18,201	0.301	0.018	HE1
Myanmar	44,958	0.207	0.060	HE1
Namibia	1,896	0.354	0.290	HE1
Nepal	24,401	0.296	0.051	HE1
Netherlands	15,863	0.421	0.783	HE2
New Zealand	3,858	0.056	0.633	HE2
Nicaragua	5,074	0.152	0.182	HE1
Niger	10,922	0.576	0.025	HE4
Nigeria	123,689	0.377	0.089	HE1
Norway	4,491	0.062	0.833	HE2
Oman	2,264	0.820	0.592	HE3
Pakistan	144,522	0.688	0.117	HE4
Panama	2,956	0.119	0.357	HE1
Papua New Guinea	5,379	0.044	0.124	HE1
Paraguay	5,344	0.204	0.291	HE1
Peru	25,862	0.095	0.310	HE1
Philippines	77,310	0.309	0.177	HE1
Poland	38,302	0.401	0.435	HE1
Portugal	10,336	0.401	0.615	HE2
Puerto Rico	3,814	0.409	0.450	HE1
Qatar	591	0.857	0.907	HE3

Country	Population (thousand people)	Hydrologic complexity (Indicator: X-Axis)	Economic capacity (Indicator: Y-Axis)	HE Class
Romania	22,192	0.306	0.337	HE1
Russian Federation	146,758	0.123	0.372	HE1
Rwanda	8,098	0.338	0.028	HE1
Saudi Arabia	20,045	0.810	0.603	HE3
Senegal	9,506	0.443	0.089	HE1
Serbia	10,145	0.279	0.330	HE1
Sierra Leone	4,143	0.156	0.036	HE1
Slovakia	5,405	0.260	0.455	HE1
Slovenia	1,985	0.123	0.595	HE2
Somalia	7,399	0.626	0.015	HE4
South Africa	44,760	0.455	0.353	HE1
Spain	40,288	0.455	0.669	HE2
Sri Lanka	18,745	0.441	0.260	HE1
Sudan (former)	34,188	0.633	0.077	HE4
Suriname	467	0.161	0.299	HE1
Swaziland	1,064	0.477	0.285	HE1
Sweden	8,860	0.076	0.722	HE2
Switzerland	7,168	0.206	0.803	HE2
Syrian Arab Republic	15,989	0.756	0.273	HE4
Tajikistan	6,173	0.513	0.053	HE4
Tanzania UR	34,038	0.373	0.045	HE1
Thailand	63,155	0.405	0.311	HE1
Timor-Leste	830	0.341	0.065	HE1
Togo	4,794	0.323	0.047	HE1
Tunisia	9,456	0.641	0.321	HE4
Turkey	63,628	0.402	0.398	HE1
Turkmenistan	4,501	0.672	0.278	HE4
Uganda	24,213	0.293	0.038	HE1
Ukraine	48,892	0.465	0.274	HE1
United Arab Emirates	3,033	0.857	0.925	HE3
United Kingdom	59,096	0.340	0.722	HE2
United States of America	282,496	0.233	0.817	HE2
Uruguay	3,319	0.196	0.391	HE1
Uzbekistan	24,776	0.707	0.101	HE4
Venezuela	24,348	0.175	0.391	HE1
Viet Nam	78,758	0.361	0.098	HE1
Yemen	17,723	0.774	0.138	HE4
Zambia	10,202	0.259	0.057	HE1
Zimbabwe	12,509	0.556	0.015	HE4

Annex II. Scatter plots of component index functions

The diagrams in Figures A1 to A4 below show scatter-plots of the different component index functions, for some 160 countries, against the Y-dimension of economic capacity. Both axes span an interval [0,1], where a high value along the Y-dimension indicates high income and coping capacity, a large value close to 1 along the X-dimension is an indication of a higher water related challenge. Different colors are used for countries in different broad (continental) regions, e.g. red for countries in North Africa and the Middle East, blue for countries in Europe

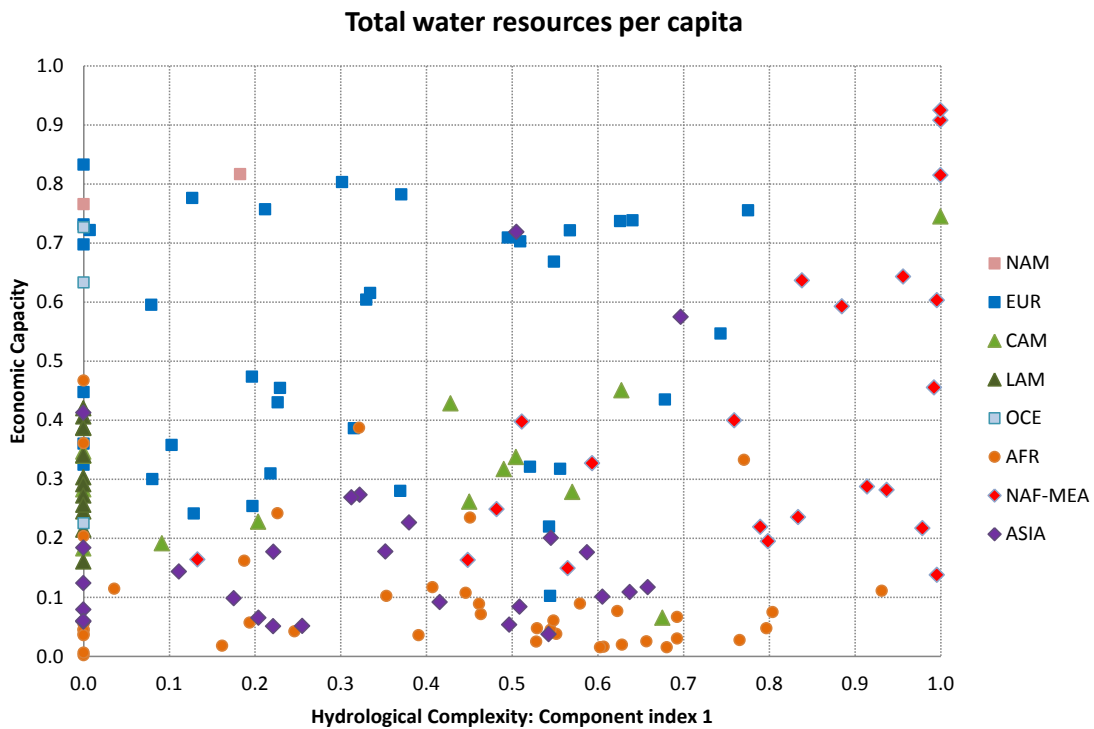


Figure A1: Scatter-plot showing value of sub-index $f_x^1(TWRC)$ of total renewable water resources per capita (along X-axis) against economic capacity index (Y-axis)

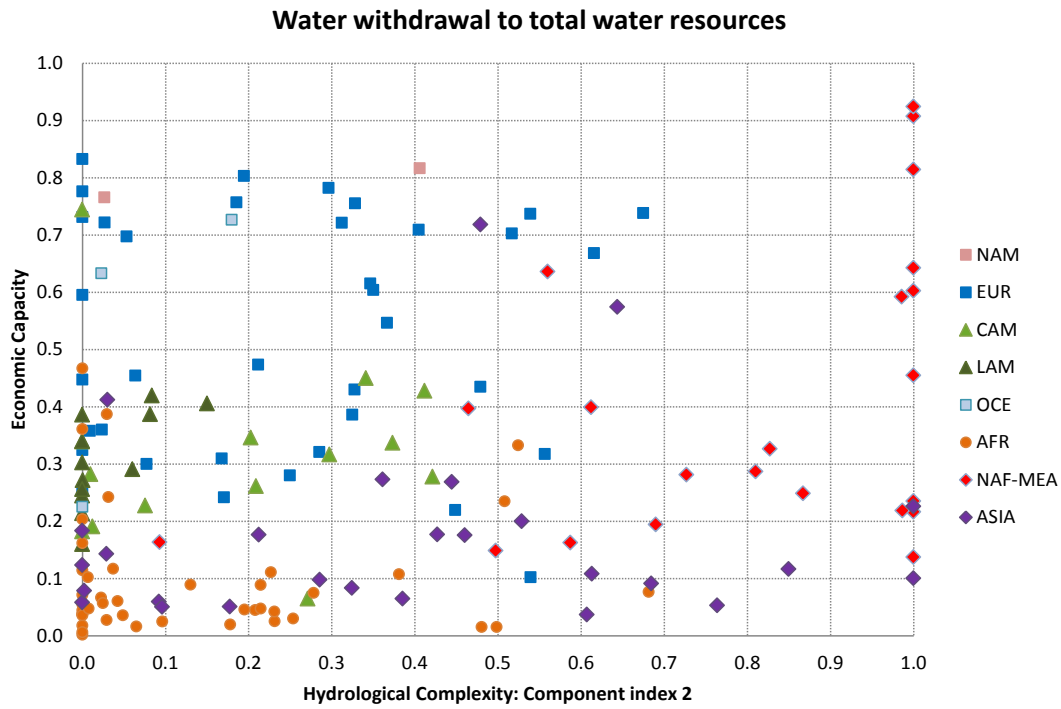


Figure A2: Scatter-plot showing value of sub-index f_x^2 (TWD/TWR) of share of water withdrawal to total renewable water resources per caput (along X-axis) against economic capacity index (Y-axis)

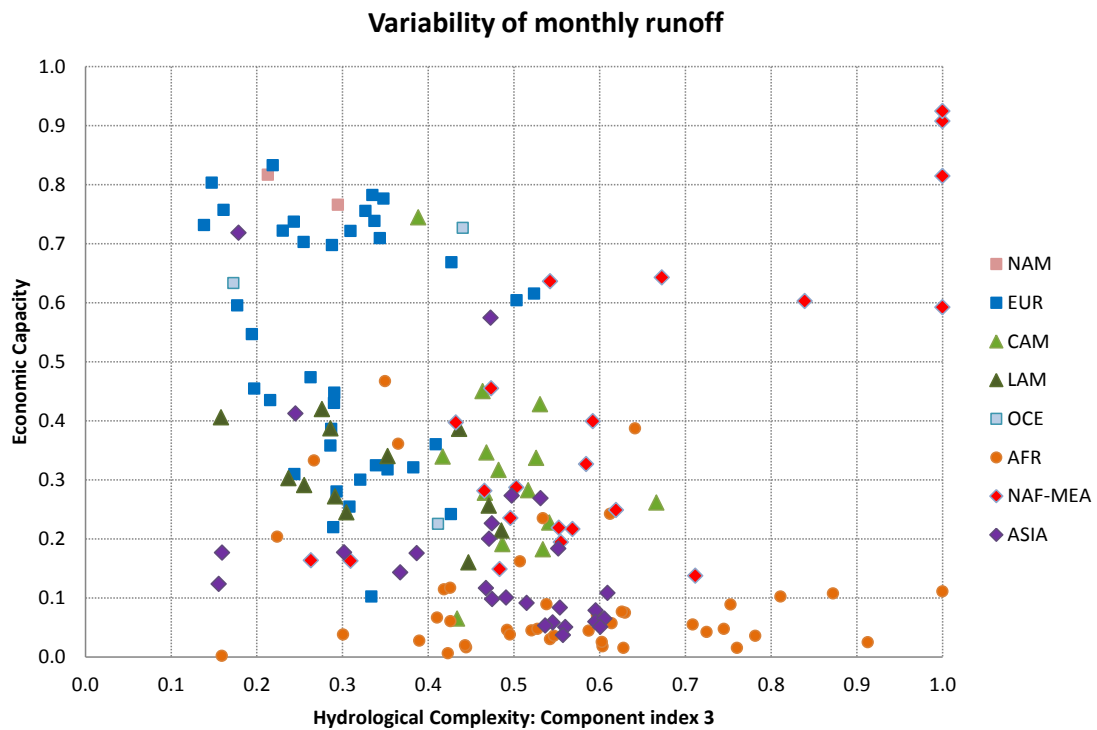


Figure A3: Scatter-plot showing value of sub-index f_x^3 ($CVTWR$) of variability of monthly runoff (along X-axis) against economic capacity index (Y-axis)

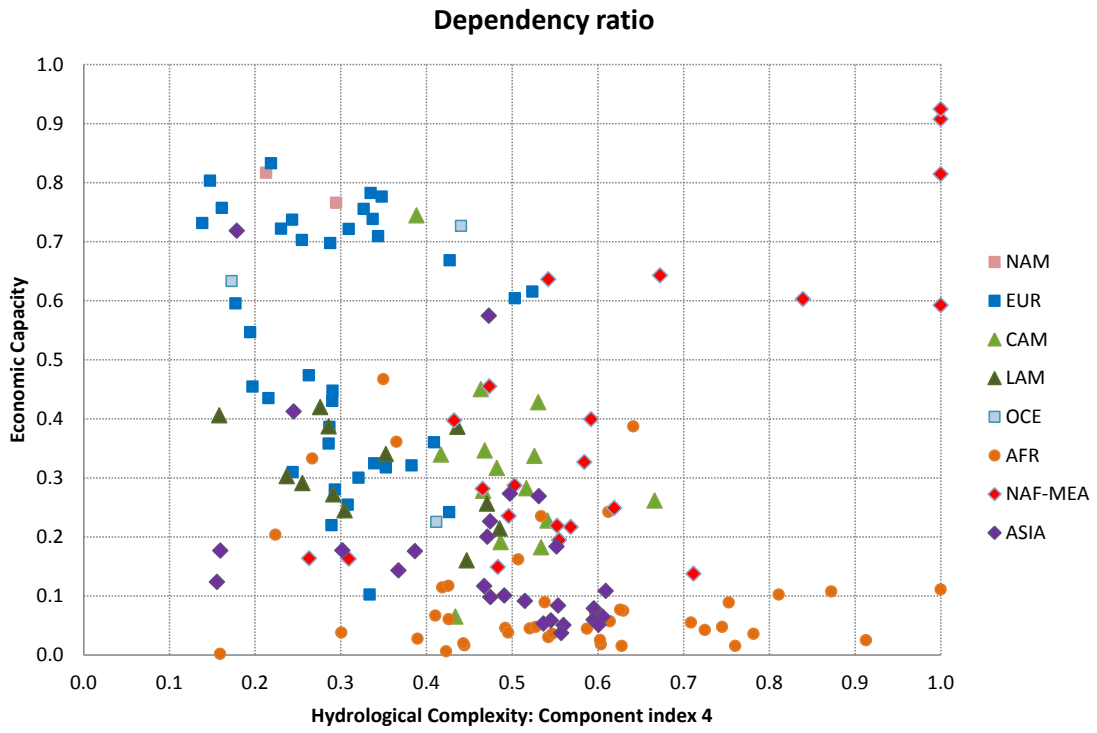


Figure A4: Scatter-plot showing value of sub-index f_x^4 (DPC) of dependency on external water resources (along X-axis) against economic capacity index (Y-axis)