

A Metric Model on Identifying the National Water Scarcity Management Ability

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Abstract Our planet is getting thirstier and thirstier. Water scarcity has become an increasingly hard but urgent problem. The world's water situation engenders little optimism. About one quarter of the world's population is experiencing water scarcity. Moreover, water resources are unevenly distributed and extremely scarce in Africa and the Middle East. Water scarcity further incurs many international issues such as international conflicts, environmental refugees and disease caused by water pollution, which have made a more unstable world. To make contributions to solve the water problems, this study proposed a metric model to identify the ability of each country to manage water scarcity, and offered solutions to a country considered water over-loaded. In this paper, we developed our metric, Total Scarcity Metric, and divided it into Physical Scarcity Metric (affected by environmental factors and population) and Economic Scarcity Metric (affected by social factors other than population) by the two causes of water scarcity. This paper made some adjustments to an indicator we found widely-used in the literatures, and determine Physical Scarcity Metric based on it. Based on that result, Pakistan was chose as a sample region for further analysis, and Pakistan still has a long way to go. This model will prove to be advantageous for a region's authoritative figures to consult with when in pursuit of obtaining a higher level of water resources allocation. It also can serve as a public rationale to support certain superficially incomprehensive judgments made by the administration.

Keywords Water scarcity · Total scarcity metric · Physical scarcity metric · Economic scarcity metric · Grey relational analysis · Pakistan · Water situation forecasting · Grey forecasting model · Regression analysis · Sample plan

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1 Introduction

There is much talk of national water scarcity, of which the most obvious situation is that nearly two-thirds countries and 1.6 billion people face the scarcity (WHO 2003). The access to safe and affordable water for domestic use is lack in all of these countries and individuals. Due to the rapid population rise, improved standards of living, urbanization and industrial growth in a country, the demand, competition and conflicts water use sectors have increased. Therefore, solving this problem and the rational allocation of water resources have always been urgent problems to every government. As a matter of fact, we hypothesize that an understanding of water scarcity is important since it affects the views of users and policymakers on the urgency, which can address the water crisis. What's more, they can concentrate on the most effective policies to address water scarcity as well.

However, before solving the problem of water shortage, the assessment of national water supply capacity, is in need. The capacity of a country on providing clean water to meet the need of its citizens plays an important role in development. Moreover, measuring the level of water scarcity in a country is an essential factor for the policymakers to make a water resources management plan.

In recent years, all kinds of researches have been put forward in this field. First of all, the Falkenmark indicator was most widely used in this kind of problems which proposed by Malin Falkenmark in 1989 (Falkenmark et al. 1989). The indicator was defined as total annual renewable water resources per capita, which can be a measure of water scarcity. In addition, the study of Falkenmark firstly introduced the concept of classification on water scarcity stress. Moreover, it provided a theoretical basis for the assessment of water scarcity. But, as time goes on, the model of Falkenmark could not meet the growing needs of water scarcity analysis, and the factors are less sufficient. Then, in 1991, Shiklomanov presented a Water Resources Vulnerability Index to give an accurate assessment of the demand for water, which have taken fixed requirements per person as a proxy on a national scale (Shiklomanov 1991). Just after that, much more indexes had been put forward, such as Physical and Economic Scarcity Indicators and Water Poverty Index (Seckler et al. 1998; Sullivan and Meigh 2003; Rijsberman 2006). Although these indicators were more and more comprehensive, they still cannot assess the water supply capacity under the conditions of water scarcity. More than that, neither can they provide a basis for the forecasting of the situation. The linkages between water supply and water demand were not established. Henceforth, in 2013, according to the study of Collet et al., a modeling framework was raised at a 10-day time step to assess whether water resources have been able to meet water demands over the last 50 years (Collet et al. 2013). They offered us a good example to analyze the water supply capacity, but the scarcity of water was not considered as a specific condition. In addition, it still could not measure the level of regional water scarcity in quantized way. In 2014, Boithias provided a spatially explicit metric, named S:D ratio with gave measure index on water supply and demand under water scarcity (Boithias et al. 2014). The global change (i.e. both climate and population changes) were taken into account. Thus, it can be used for the prediction of regional water scarcity in the next few years.

Accordingly, a comprehensive model and a specific system are in need to measure the national water supply capacity and water scarcity extent. Also, the future situation of the water scarcity in a country can be forecasted by the comprehensive model. In addition, how the plan changes water scarcity can be evaluated by the system. Benefit from that, the targeted programs can be made by government, and the plans can be adjusted at any time according

to actual conditions. The development and application of mathematical model, which provide a good insight into the intricacies of various problems related to proper water scarcity, is therefore necessary.

The current water shortage should be blamed on excessive activities of the human beings: (a) human's demand on water resources is larger and larger with the increasing world population; (b) the over-exploitation on water resources speed up the depletion; (c) the water contamination worsens the water quality; (d) the excessive emission of greenhouse gas results in a warmer world and the frequent occurrence of extreme water. Historically, people had taken many measures to alleviate water shortage. Sprinkler irrigation and drip irrigation technology can greatly improve the use efficiency of water. More than that, some contributions were made by people to exploit potential water resources. But still, many countries face severe water scarcity.

In this paper, an evaluation system was developed to measure each country's ability to provide clean water to meet the need of its citizens. It is consistent with the ability of managing the water scarcity, which is affected by environmental and social drivers. The study tried to find these drivers and provide effective water strategy for countries based on them.

Next, a metric, named Total Scarcity Metric (TSM) was established to measure water scarcity for each country. To set an example, Pakistan was selected as a sample country to handle its serious water situation. In the TSM model, water scarcity was divided into physical water scarcity and economic water scarcity, and corresponding metrics were developed by different approaches. Moreover, a research was made to explain how and why water is scarce in Pakistan, and then the future situation was forecasted. To forecast the water situation in 2030 by the metric, the paper determined the predicted value of influential factors on the basis of Grey Forecasting Model and Regression Analysis. It can be found that its total water scarcity will be alleviated. Based on that, a sample plan was designed for Pakistan and its performance was predicted.

In this paper, the general assumptions are listed in section 2, while some hypotheses for specific model are in section 4 and 5. Moreover, the TSM model and its verification were discussed in section 3. In addition, in section 4, the paper analyzed current and future water situation in Pakistan qualitatively and synthetically. Our intervention sample plan is discussed in section 5, including its statement and future performance.

2 General Assumptions and Variable Description

2.1 General Assumptions

The collected data from online databases is accurate, reliable and mutually consistent. Because the data sources are all websites of international organizations, it's reasonable to assume the high quality of their data.

In model verification, the indicator data from countries that the paper neglects has little impact on the calculation of the weights and the results.

Pakistan's development will follow the numerous trends in worldwide development of countries based on various factors. This assumption enables this research to predict Pakistan's development by using the result of relationship quantization among influential factors, and all these factors are determined by worldwide data.

In the coming few years, Pakistan has a stable political environment. This assumption implies the minimal impact of political situation, terrorist activities and diplomatic disputes on the development of Pakistan and the implementation of the sample plan. What's more, a stable trend of the influential factor of water scarcity was forecast.

The total water withdrawal is made up of water withdrawal for agriculture, industrial and municipal use, since the water withdrawal for environmental use is insignificant compared to that for the other three sectors, and the corresponding data is lacking. Under this assumption, the value of water withdrawal can be added for the three sectors to get the total water withdrawal value.

For TSM model (model in section 3), time factor is not taken into consideration. Thus the model can be verified by using the data available in the latest year. But time is an important factor in the forecasting (Table 1). The abbreviation of the variable descriptions in this paper are shown in Table 1.

Besides these general assumptions, there are also hypotheses we make for the specific models. They will be presented and discussed in section 4 and 5.

2.2 Variable Description

3 Total Scarcity Metric Model

In this section, this paper constructed a metric incorporating of a country's ability to provide improved water to meet the needs, named Total Scarcity Metric (TSM). The metric measures the ability to manage water scarcity for a country. A larger TSM implies a weaker ability for a country to handle the balance between improved water supply and demand, and a harder work for it to solve its water problem.

Table 1 Variable description

Abbreviation	Full Name	First appearing page
TSM	Total Scarcity Metric	2
PWS	Physical Water Scarcity	3
EWS	Economic Water Scarcity	3
PSM	Physical Scarcity Metric	3
ESM	Economic Scarcity Metric	3
HDI	Human Development Index	4
CR	Criticality Ratio	4
CI	Criticality Index	4
TRWR	Total Renewable Water Resources	4
IRWR	Internal Renewable Water Resources	6
CF	Climate Factor	6
WRI	World Resources Institute	6
IV	Interannual Variability	6
SV	Seasonal Variability	6
FO	Flood Occurrence	6
GRA	Grey Relational Analysis	6
ACR	Adjusted CR	6
WAPC	Water Availability per Capita	6
GRA	Grey Relational Analysis	6
GFM	Grey Forecasting Model	7

The definition of water scarcity was firstly taken into consideration in this section. Intuitively, water scarcity is the lack of sufficient available water resources to meet the needs in a region. On the basis of its cause, water scarcity can be categorized into physical water scarcity and economic water scarcity. On the one hand, Physical water scarcity (PWS) is the result of inadequate water resources to satisfy the demand or use of a country or a region which are conditioned on the full use efficiency of these resources. On the other hand, Economic water scarcity (EWS) is the scarcity rising from the incomplete use of water in a country or a region (wikipedia 2015). By these definitions, we think that EWS depends more on social factors incorporating the ability to fully utilize water, while some other social factors (e.g. population) and environmental factors (such as climate or topography), mainly affect PWS. Therefore, it's natural to divide the metric into two components. The Physical Scarcity Metric (PSM) and Economic Scarcity Metric (ESM) were named, respectively. Meanwhile, the increasing values of PSM and ESM were hypothesized the meaning of worse scarcity situation.

3.1 Review of Literatures

Literatures provide a wide range of indicators measuring water scarcity. So before we conduct the construction of PSM and ESM, we go through these indicators. Then, this study chose three indicators that are most commonly used and related to the objectives and themes of this paper, to analyze their strengths and limitations (Chenoweth 2008; Naf 2008).

3.1.1 The Falkenmark Indicator and its Improved Version

The Falkenmark Indicator (Falkenmark et al. 1989) was defined as total annual renewable water resources per capita, which can be a measure of water scarcity. Table 2 shows the partition of water scarcity based on this indicator. The first and second column of the table show the two difference thresholds (Perveen and James 2011). Among of them, the second thresholds are more frequently used.

Due to its extreme simplicity and the easy access to the data, the Falkenmark Indicator becomes the most widespread metric of water scarcity (Brown and Matlock 2011). However, its main limitations are obvious: (a) it fails to take enough environmental and social factors into account, thus it's not convincing even as an indicator of physical scarcity; (b) the identification of the thresholds is too arbitrary.

As an improvement on the Falkenmark Indicator, Ohlsson (2000) incorporated some social factors into his new index, the Social Water Stress Index (Ohlsson 2000). The study of Ohlsson considered wealth, health and education level. Thus, it used Human Development Index(HDI) as a weight of the Falkenmark Indicator.

Table 2 The Falkenmark indicator

Original thresholds	Adapted thresholds	The state of water scarcity
>2000	>1700	Water Sufficiency
1000–2000	1000–1700	Water Stress
600–1000	500–1000	Water Scarcity
<600	<500	Water Absolute Scarcity

3.1.2 Criticality Ratio and Criticality Index

The Criticality Ratio (CR) determined "the ratio of water use to water availability in a watershed or country" (Alcamo et al. 1997), or equivalently, "the ratio of water withdrawals for human use to total renewable water resources" (Alcamo et al. 2000), i.e.

$$CR = \frac{\text{Total Water Withdrawal}}{\text{Total Renewable Water Resources (TRWR)}} \quad (1)$$

The numerator of Eq. (1) is the withdrawal from surface water or groundwater for agricultural, industrial and municipal use. Besides, the denominator includes surface runoff and groundwater recharge (Naf 2008). The threshold value of 0.4 is commonly used to determine the boundary of water stress. The larger CR value implies the more severe water situation.

As the Falkenmark Indicator, the intuition and calculation of CR are simple enough so that it can be demonstrated to the public. Furthermore, compared to the Falkenmark Indicator, it applies not only the water availability, but also the water use, which is determined by the water demands. Considering its drawbacks, (a) this ratio uses the more objective indicator, the water withdrawals, rather than the more subjective indicator, the water demands, so it may lose some power in measuring the water demands; (b) according to the definition of "water use", the ratio neglects the return flow of water, which is an important source of "actual" water use; (c) some other factors, such as population, are not incorporated, at least directly incorporated in it. Also there are literatures (e.g. Dow et al. 2005) criticizing the setting of the threshold of 0.4.

The Criticality Index (CI) was proposed based on the work of Kulshreshtha (1993), where he provided a metric table concerning Use-Availability ratio (%) and supply per capita (m^3). In CI, the former is CR value and the latter is the water availability per capita (measured by the internal renewable water resources (IRWR) per capita). Table 3 displays the Kulshreshtha's table adapted for CI, where the four different values show four different levels of water scarcity (Naf 2008).

CI provides a similarly simple but more accurate estimation of water scarcity than CR, because it considers water scarcity from both supply pressure and usage pressure of water. In addition, the population factor is added into the analysis. But other main drawbacks of CR still remain in CI.

3.1.3 IWMI Analysis

The IWMI Analysis is conducted by the International Water Management Institute. It is a comprehensive analysis including the identification and forecast of water scarcity based on

Table 3 CI value

Per capita water availability [m^3]	CR Value			
	<0.4	0.4-0.6	0.6-0.8	>0.8
<2000	2	3	4	4
2000-10,000	1	2	3	4
>10,000	1	1	2	4

Comments: 1-water surplus; 2-marginally vulnerable; 3-water stress; 4-water scarcity. Source: (Naf 2008)

water supply and demand situation of a country. Meanwhile, it has divided these countries into different groups by their abilities to deal with water scarcity. To forecast the future, IWMI developed two scenarios only different in the water use in agricultural sector, and then several settings regarding projected water use in three sectors are made on the basis of scenarios. IWMI chose CR to discriminate physical scarcity, and the growth of total water withdrawal was used to differentiate several levels of economic scarcity (Seckler et al. 1998).

This method contains an integrated analysis framework for forecasting the water scarcity by water supply and demand. Therefore, its analysis result, namely “World Scarcity Map”, is often quoted in different relevant literatures. However, this analysis is too intricate and complex to be understood and implemented. At the same time, it relies much on personal judgments (especially in the setting of the future scenarios) and the access of data.

3.2 Construction of PSM

Taken all these indicators into consideration, (a) the Falkenmark Indicator is too “naive” for the analysis, that is, the factors it involves are far less sufficient to meet our needs; (b) the Social Water Stress Index is not applicable to measure PWS because the components of HDI have more closer effects on EWS; (c) the IWMI analysis framework is too complicate to handle. We finally choose CR and CI as the starting point of our construction of PSM. Then we want to eliminate the drawbacks of CI as much as possible.

3.2.1 *Water Use = Water Demand*

The water demand was divided into two components, the “object” component and the “subject” component. On the one hand, the “object” component is people’s actual use of water, thus can be measured by water use of people. On the other hand, the “subject” component concerns about the “efficiency” of water, thus it is affected by social and economic factors, such as the relevant technology and infrastructures, and people’s awareness of water conservation. By combination of two components, the personal requirements were gotten in the paper to support their production and living, i.e. the water demand. Thus, this paper considered the “subject” component in the ESM, and remained the “object” component here. By this way, the water demand was completely incorporated in the model.

3.2.2 *The Neglect of Reused Water*

The return flow of water was still not be considered to involve, because (a) the quality of reused water varies by countries, some may be very poor; (b) it’s difficult to develop an indicator balancing between the correct expression of its meanings and the data availability. Besides, there exist literatures that neglected it but still performed well (e.g. Alcamo et al. 2000) [World Water in 2025].

3.2.3 *Insufficient Factors*

In this paper, an adjustment on CR is made to alleviate this limitation. Then, we develop a “climate factor”(CF) based on the linear combination of three indicators created by the World Resources Institute (WRI), Interannual Variability (IV), Seasonal Variability(SV) and Flood

Occurrence(FO). All three indicators ranges from 0 to 5.3 (Food and Agriculture Organization Database 2015; World Resources Institute Database 2015).

On the foundation of the Grey Relational Analysis (GRA)⁴, the weight of the three indicators are calculated on CF, to give the Eq. (2) as follow:

$$CF = \omega_1FO + \omega_2IV + \omega_3SV \tag{2}$$

Where ω_1 , ω_2 and ω_3 are the respective weight of three indicators, and their sum equals to 1. By Eq. (2), the increases in the values of IV, SV and FO, they lead to the larger value of CF, resulting in the worse and the more volatile climate condition for water supply. At the same time, larger value of CR implies more severe water resource situation. Therefore, CF can be multiple to the original CR and get the Eq. (3) for adjusted CR (ACR) can be got as follow.

$$ACR = CR \times CF = \frac{\text{Total Water Withdrawal}}{\text{TRWR}} \times CF \tag{3}$$

3.2.4 Adjustments for Alternative Water Sources

Some discussions are provided on two alternative water sources generated by human technology, rainfall harvesting technology, aquifers and desalination plants. In some countries, both of them have become an important provider of additional water resources. However, in most countries, the immature development of them restrains the application. Due to the data access limitation, we can only consider supply from desalination plants in this paper. Besides, the desalinated water produced is added to the total renewable water resources per capita in the denominator side, and then the Eq. (3) becomes

$$ACR = \frac{\text{Total Water Withdrawal}}{\text{TRWR} + \text{Desalination Water Produced}} \times CF \tag{4}$$

The value of CI is determined by the Table 4. Table 4 inherits the structure of Table 3, only changing the CR to ACR and the scales of corresponding thresholds. As shown in the table, countries with larger ACR values and lower water availability per capita (WAPC) values face severe physical scarcity, while those with lower ACR and larger WAPC values nearly have no water stress. It also can be seen that ACR is more dominant than WAPC because countries with larger ACR and WAPC values are regarded as water scarcity countries. However, those countries with lower ACR and WAPC values are only classified as marginally vulnerable countries or water stress countries.

Actually, it's hard to make a decision between ACR and CI. CI takes a comprehensive consideration on water scarcity, but it cannot have continuous values. Because of that, it may

Table 4 CI value

Per capita water availability [m ³]	ACR Value			
	<0.8	0.8–1.2	1.2–1.6	>1.6
<2000	2	3	4	4
2000–10,000	1	2	3	4
>10,000	1	1	2	4

Comments: 1-water surplus; 2-marginally vulnerable; 3-water stress; 4-water scarcity

be hard to compare the performance among the countries with the same CI value. For ACR, it is a continuous indicator, but some factors, such as population, fail to be directly incorporated. So this paper presented values of both indicators where the model was used. Particularly, using CI as a measure of PSM for the model verification is a better choice, while use ACR in the sensitivity analysis in section 4 and 5.

3.3 Construction of ESM

3.3.1 Influence Factors

There are many social and economic factors affecting EWS, most of which can be categorized into the development of water technology and infrastructure, along with people's attitude to water saving. As a result, a factor model with the weight determined by the Grey Relational Analysis (GRA) is built to develop the ESM for a country. Figure 1 shows a map of main factors that influence the EWS.

This research provides some definition for factors in Fig. 1 (According to World Bank [World Bank website]) and interprets them.

- (1) Urbanization rate is the rate of urban population (i.e. people living in urban areas) to total population. Due to the more awareness of the importance of water conservation and better water use that the habit urban people showed than rural people, the increase of this indicator shows a less economic scarcity.
- (2) Primary enrollment rate is total number of students enrolled for primary education in their theoretical age, divided by the total population in that age group. It estimates the degree of population receiving basic education, which contains the education for water and water conservation.
- (3) Access to improved water refers to the percentage of the population using an improved drinking water source. As a matter of fact, it shows a country's technology to transfer water resources to improved drinking water. It was also suggested by UN-Water to monitor the sustainable development of water.(UN-Water 2015)
- (4) Irrigation efficiency is the ratio of irrigation water requirement per year to irrigation water withdrawal per year. Accordingly, it's often referred to "water use efficiency"

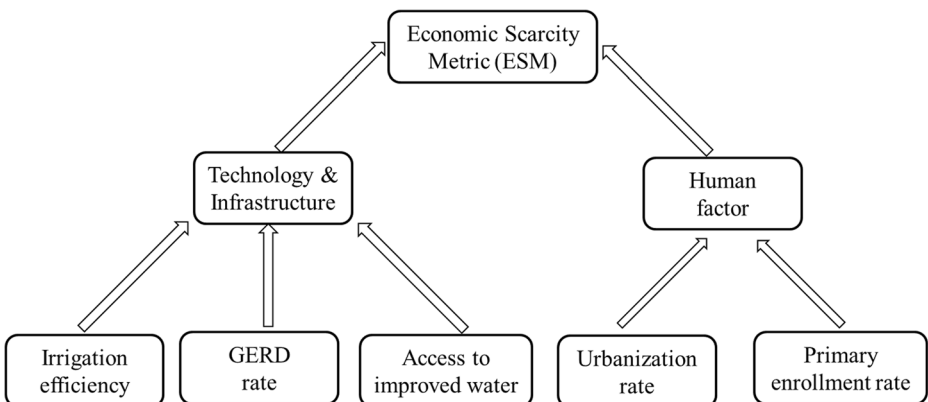


Fig. 1 Main factors of ESM

(Faurès 2012) in agriculture. Moreover, from the data of FAO (Food and Agriculture Organization Database 2015), agriculture water withdrawal accounts for 60% of total. In some countries such as Pakistan, this number is over 90%. So the importance of irrigation efficiency to the total use efficiency cannot be neglected.

- (5) GERD rate is the Gross domestic Expenditure on Research & Development (or GERD) as a percentage of GDP (Uneso Database 2015). It reflects the emphasis and development level on R&D, which can determine the technology and downstream infrastructure construction of water.

Recall that economic scarcity is a result of incomplete water use. So all these factor has a negative effect on ESM.

3.3.2 Application of GRA

The correlation between each factors above and ESM is sophisticated and uncertain. What’s more, these correlations are interacting. Therefore, it’s hard to analyze their effect on ESM if we consider approaches with perfect information. Grey Relational Analysis (GRA) is a branch of Grey System Theory which can capture the implied interactions among factors, also it can indicate the grey relational grade of each factor. Then the weight of each factor can be determined on the basis of the relative size of its grade. In this model, the paper follows the steps below to calculate the weight of each factor.

- Step 1: Normalization based on classification of factors. According to the goals and directions of their impact, factors can be divided into 3 types, namely “higher is better” factors, “lower is better” factors and “middle is better” factors. The previous analysis implies that all the considered factors are “higher is better” factors, so the observations of these factors can be normalized by

$$x_{ij} \leftarrow \frac{x_{ij} - m_j}{M_j - m_j} \tag{5}$$

where x_{ij} is the i th country observation on the j th factor and $M_j = \max_i x_{ij}, m_j = \min_i x_{ij}$

- Step 2: Choosing reference series. Reference series consist of optimal(best) value of each factor. Because all the factors are “higher is better” factors, so the reference series is

$$X_0 = \{x_{01}, x_{02}, \dots, x_{0k}\} \text{ with } x_{0j} = 1 \text{ for all factors } j = 1, 2, k$$

- Step 3: Computing grey rational coefficient ξ_{ij} (j) with respect to the i th country observation on the j th factor. The equation is

$$\xi_{ij} = \frac{\Delta_{\min} + \rho \Delta_{\max}}{\Delta_{ij} + \rho \Delta_{\max}} \tag{6}$$

where $\Delta_{ij} = x_{ij} - x_{0j}, \Delta_{\max} = \max_i \max_j \Delta_{ij}, \Delta_{\min} = \min_i \min_j \Delta_{ij}$ and resolution ratio ρ is set 0.5 to optimally improve the significance of the difference among rational coefficients.

Step 4: Calculating the rational grade of each factor on ESM by taking the average of its rational coefficient, that is

$$r_j = \frac{1}{n} \sum_{i=1}^n \xi_{ij} \tag{7}$$

where n is the number of countries.

Step 5: Computing the weight of each factor j by

$$\omega_j = \frac{r_j}{\sum_{j=1}^k r_j} \tag{8}$$

Finally, the value of ESM of a country p can be obtained by

$$ESM_p = \sum_{j=1}^k \omega_j x_{pj} \tag{9}$$

ranging from 0 to 1. Recall that we hypothesize that larger value of ESM indicates worse water problem, so a change need to made to Eq. (9), which is shown as follow Eq. (10).

$$ESM_p = 1 - \sum_{j=1}^k \omega_j x_{pj} \tag{10}$$

Equation (10) guarantees that the increasing value of the factors leads to the decreasing value of ESM, i.e. a better water situation.

3.4 Construction of TSM

To combine PSM and ESM, a parameter α is used to incorporate the relative importance of physical water scarcity (PWS) on total scarcity compared to economic water scarcity (EWS). Fo $\alpha > 1$ implies PWS is considered more crucial, while $\alpha < 1$ means that EWS may be more important, and $\alpha = 1$ gives PWS and EWS the same weight. With the help of α , the equation of TSM of a country p is given below:

$$TSM_p = \frac{ESM_p + \alpha PSM_p / 5}{1 + \alpha} \tag{11}$$

if ACR is used as PSM^5 , or

$$TSM_p = \frac{ESM_p + \alpha PSM_p / 4}{1 + \alpha} \tag{12}$$

if CI is used as PSM^6 .

α reflects the perspective of each country on the trade-off between PWS and EWS. Its value varies by countries so it's not so meaningful to determine a "global" α value. Nevertheless, we suggest that $\alpha = 1.1$ will be a good estimation value after verification. Besides, several sensitivity analyses on α will be showed in the following sections.

3.5 Verification and Sensitivity Analysis

3.5.1 Verification

The data sources for the verification include World Bank(World Bank Database 2015), WRI(World Resources Institute Database 2015), FAO(Food and Agriculture

Organization Database 2015) and UNESCO(Uneso Database 2015). (e.g. 2015c) After the preprocessing of data, a data set of 83 countries is obtained and the model can be verified by all factors mentioned previously. Therefore, we use the observations in the latest year, rather than in a single specific year, because an astonishing data missing exists in all sources. We consider this data set sufficient for our verification, but more complete data is required if we want to determine the TSM for all countries more accurately.

The weights of the 5 factors in ESM model, and 3 components in the climate factor(CF) are first provided. Then, both of them are calculated by the Grey Relational Analysis in Table 5 as below.

Therefore, the PSM and ESM values for 83 countries are calculated by the established model. Figure 2 shows the results, where a point represents a country. Note that PSM have only 4 values, so all points are on 4 horizontal lines. According to our analysis, lower PSM and ESM mean slight water scarcity while higher PSM and ESM means severe water scarcity. After that, the weight of PSM and ESM are computed by using GRA, and we get $\alpha > 1.1$, which implies that a little more emphasis on PSM (e.g. we consider Saudi Arabia face more scarcity than Mozambique) should be laid.

In this paper, UN Water Scarcity Map shown on Fig. 3 (UNEP Database) is used as the benchmark to verify the results. The comparison of the results in Figs. 2 and 3 indicates that the established model performs quite well. Nearly half of the countries in Fig. 2 having low PSM (=1, 2) and low ESM (less than 0.4), which is similar to that of countries printed blue and yellow respectively in Fig. 3. Sudan, Pakistan and Saudi Arabia is regarded water-scarce in the model, and these countries are basically printed the deepest color in Fig. 3, showing water there is heavily or overexploited. Japan and Belgium has small values in PSM and ESM, which is consistent with their light color in UN's map. But for some countries like Tunisia and Kenya, the result is not the same as UN's result. It may because these two models have different angles.

3.5.2 The Sensitivity Analysis of α

Eight countries (the points marked by the country names) were picked in Fig. 2 to make sensitivity analysis. These countries represent the variable degree of the combination of PWS and EWS in the world. We change α from 0.5 to 1.5 and present the results in Fig. 4. Taking Figs. 2 and 4 into account, (a) with α increases, countries with larger PSM tends to increase while those with larger ESM tends to decrease; (b) countries whose normalized PSM and ESM have insignificant difference are not sensitive to α , while those with large difference between them change significantly with respect to the value of α . These findings remind us to choose those robust to α to analyze.

Table 5 The weights of factors

ESM	Weight	PSM	Weight
Access to improved water	0.2655	Flood occurrence	0.302834
Urbanization rate	0.184	Interannual variability	0.367241
Primary enrollment rate	0.2564	Seasonal variability	0.329925
Irrigation efficiency	0.1622		
GERD	0.1319		

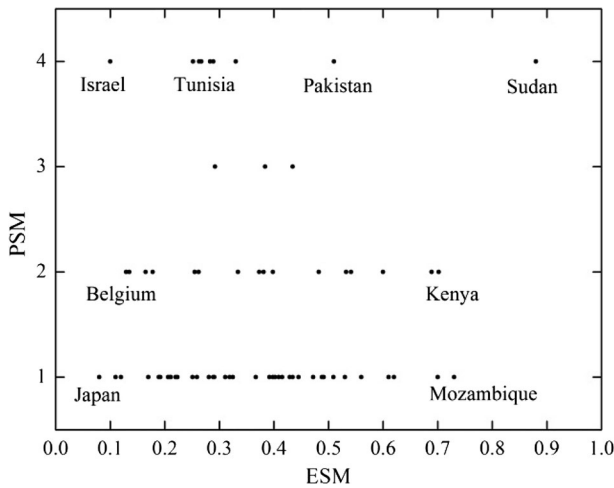


Fig. 2 PSM and ESM results for 83 countries

4 Water Situation in Pakistan

4.1 The Reasons for Current Scarcity

Pakistan, a country in the South Asia, is regarded as water heavily and over-exploited country in Fig. 3. In our model, its PSM = 4(ACR = 2.19) and ESM = 0.5071, also indicating that its heavy water scarcity. Its water scarcity is mainly manifested in: (a) Pakistan has a large population base and growth, which causes a small water resources per capita; (b) many river basins are polluted, resulting in a low proportion of population accessible to improved water and large occurrence of water pollution diseases (e.g. dysentery); (c) people’s awareness of

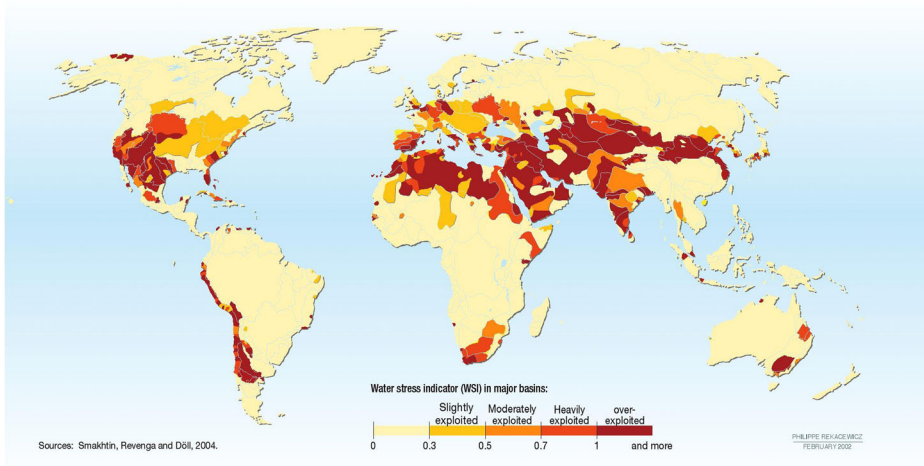


Fig. 3 UN water scarcity map. Source: UNEP Website

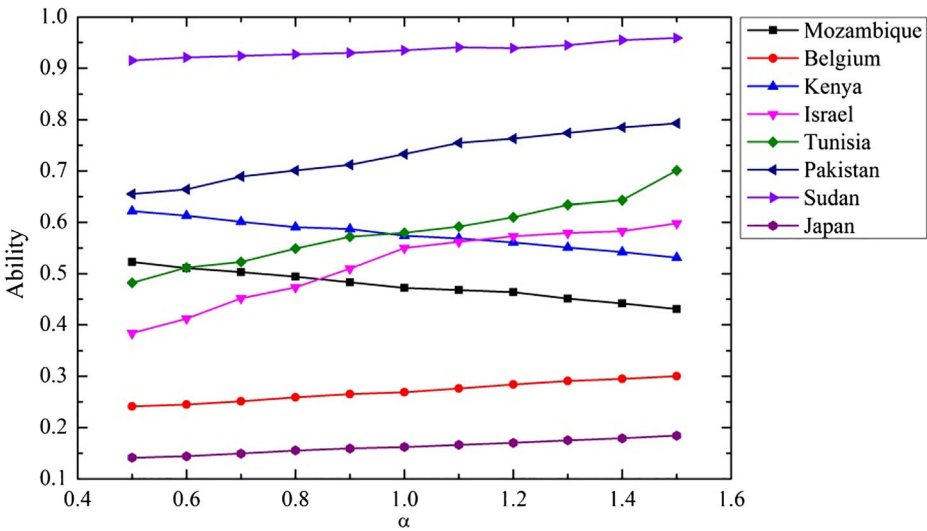


Fig. 4 Sensitivity analysis of α using data from 8 countries

water conservation is lacking; (d) it is hard to improve the current situation due to its economic development level.

The reasons for water scarcity were divided into water resource environment and social factors in the paper.

Pakistan has a dry climate. The annual precipitation is less than 250 mm in two thirds of its area. Besides, Pakistan has an asymmetric distribution with more water in the west and less in the east. As shown in geographic data, the water resources in Pakistan mainly come from the Indus, seasonal glacial melt water (from the Himalayas) and monsoon rainfall. Therefore, the main environmental factors causing damage to these sources include:

- (1) The climate warming effect will speed up glacier melting process. It seems good to Pakistan since it increases the amount of the water sources. However, the truth is this increase can be easily defeated by the dark side of the effect, including: (a) it will increase the frequency of the occurrence of extreme weather. Data from FAO (Food and Agriculture Organization Database 2015) monitor the increasing occurrence of natural disaster in the country. Besides, the Flood Occurance(FO) indicator of Pakistan (3.9) ranks among the highest, showing the frequent flood occurrence.(b) it will result in a faster depletion of water resources from glaciers in Pakistan. In general, it'll cause the descending water availability and a more volatile climate, exacerbating physical water scarcity.
- (2) Land degradation, desertification and salinization. It will reduce water-holding capacity of land, and thus decrease the available surface resources, making Pakistan more physically water-scarce.

More than 1 billion people are living in less than 800 thousand square metres of its land, over half of which are rural population. Some social factors play important roles in this country's water scarcity, which are shown as follow:

- (1) **Population.** The population growth of Pakistan is up to 2%, which means its populations will double 25 years later. Its high growth will rapidly decrease the usable water resources per capita, and worsen the water scarcity. World Bank data (World Bank Database 2015) also shows that countries with large water scarcity have higher population growth (e.g. Sudan), and more vice versa (e.g. USA).
- (2) **Pollution.** In the industrial sector, 99% of polluted water containing harmful and even poisonous industries is discharged into rivers without necessary treatments (Azizullah et al. 2011). Besides, over half of cities in the country lack sewerage collecting system. For the lack of that, the waste water is directly discharged to the land. But even with the system, only 10% of the sewage is treated effectively (Azizullah et al. 2011). The increasingly serious pollution will reduce people's access to clean water if related expenditure remains, which resulting in more serious water scarcity.
- (3) **Water conservancy construction.** The construction of water conservancy facilities such as dams and reservoir can reduce the seasonal variability of water resources and the possibility of flood occurrence, to alleviate the impact of climate conditions and physical water scarcity. But currently Pakistani authorities haven't laid enough emphasis on water conservancy construction.
- (4) **Economic development.** GDP per capita of Pakistan is about 1300 US dollars, lower than the global average. The low level of economic development limits its expenditure on education and R&D, thus gives little help to alleviate economic scarcity.
- (5) **Urbanization.** Although the urbanization rate of Pakistan keeps an annually growth of 1%, the construction of the cities still cannot meet the need of growing urban population. Particularly, water resources in cities are not improved much compared to rural areas. If the problem with urbanization process cannot be solved, Pakistan cannot afford the alleviation of economic water scarcity provided by urbanization.

4.2 Forecasting the Future Situation

In this subsection, the future Total Scarcity Metric (TSM) value of Pakistan in 2030 is forecasted on the basis of the methodology stated in section 3. The key of the forecast model is how to deal with the uncertainty of environmental and social factors. Due to the complexity of the uncertainty, we apply two models in this paper, the Regression Model and Grey Forecasting Model (GFM) to predict the future value of factors. Still, there are factors that we consider unsuitable to apply these two models. The setting of this kind of factors is discussed in our assumptions coming next.

4.2.1 Assumptions

Some assumptions below were made for the forecasting convenience.

- (1) The Climate Factor (CF) remains the same. Recall that CF is made up of Interannual Variability, Seasonal Variability and Flood Occurrence. As previously analyzed, the value of these 3 indicators, especially Flood Occurrence, may increase due to the climate change. Thus, under this assumption, our forecast will underestimate the PSM. Next, the TSM will also be underestimated. However, due to the lack of time series of these indicators and their complex determinant, this assumption was still be made.

- (2) The Total Renewable Water Resources(TRWR) and Internal Renewable Water Resources.
- (3) (IRWR) remain the same, and desalinated water produced is still 0. Because the previous data show little variability as well as increasing and decreasing trend, we consider it reasonable that these values won't change in the future. Besides, the desalination technology requires huge initial investment so we consider Pakistan still unable to desalinate seawater.
- (4) The Irrigation Efficiency remains the same. In Seckler et al. (1998)'s paper, they created two scenarios in 2025, and place an upper limit of 70% on irrigation efficiency under both scenarios(Alcamo et al. 2000). So we consider Pakistan's current value of irrigation efficiency of 74%, which is too high to grow significantly. Under this assumption, the forecasting model in this paper might overestimate the ESM and then the TSM.
- (5) The 4 factors affecting ESM(other than irrigation efficiency) will keep the trend they already have. This assumption eliminates the possibility for occurring significant events on these factors(e.g. a breakthrough in water R&D on GERD rate). With its help, GM(1,1) model can be applied to these factors later.
- (6) The growth of agricultural water withdrawal remains the same as the latest growth rate. This assumption implies there is no significant change in agricultural technology and industrial structure. The assumption enables us to eliminate the directional and numerical uncertainty of this indicator to predict its future value, despite the decreasing power of our forecast.
- (7) The growth of industrial and municipal water withdrawal per capita only depend on GDP per capita. Actually, many factors may also determine each of them, such as industrial output and water price. But for the simplicity of regression, we have to sacrifice some accuracy.

4.2.2 Grey Forecasting Model

If a set of time series data has obvious trend, Grey Forecasting Model in the Grey System Theory can give a precise prediction even with few data(more than 4). Based on assumption 4, the GM(1,1) model was applied. After that, the most widely used Grey Forecasting Model can be used to forecast the value of 4 factors in ESM model, i.e. urbanization rate, primary enrollment rate, access to improved water and GERD rate. The research data is generated from World Bank(World Bank Database 2015). For each factor, the data from 2004 to 2014 (11 observations) is used, which is sufficient for GM(1,1) model.

The first 4 rows in Table 6 shows the predicted value in 2030 using GM(1,1) model, together with the respective value in 2014 and the forecast error. From the table, the forecast error is quite small, implying the good performance of the model. According to the results, in 2030, about half of people will live in cities, and nearly all people can get improved water. Furthermore, nearly all kids can receive primary education. However, GERD rate will drop in the future, if Pakistani government remains its policy on R&D. The last row in Table 6 is calculated under the third assumption.

4.2.3 Regression Analysis

The fifth assumption enables us to use regression analysis to predict the value of industrial and municipal water withdrawal in 2030. First, the industrial and municipal water withdrawal per

Table 6 Factor prediction results in ESM model

Factors	2030	Now	Error[%]
Access to improved water [m ³]	94.48277003	90.9	0.018912
Urbanization rate[%]	45	37.428	0.058607
Primary enrollment rate [%]	97.20673933	72.46411	1.85
GERD rate[%]	0.020755812	0.29	4.09
Irrigation Efficiency	0.74	0.74	/

capita(m³) on *GDP* per capita(2005US \$) were regressed by using data from 169 countries in the paper (World Bank Database 2015). The regression equations are as follows:

$$\ln(\text{Ind}) = 6.445 + 0.719 \times \ln(\text{GDP}), R^2 = 0.3167 \quad (13)$$

$$\ln(\text{Mun}) = 9.113 + 0.4829 \times \ln(\text{GDP}), R^2 = 0.4105 \quad (14)$$

Then a prediction was made on Pakistan's *GDP* per capita and population in 2030 by *GM*(1,1) model. Meanwhile, by substituting the predicted per capita *GDP* value, the industrial and municipal water withdrawal per capita (*Ind* and *Mun* in the above equation) were computed. Afterwards, this paper multiplied *Ind* and *Mun* by the predicted population and got the predicted water withdrawal respectively, as shown in the first two rows in Table 7. Under the forecast, industrial water withdrawal grows significantly. With the increasing *GDP* per capita, the value of industrial output is also increasing, requiring more water withdrawal for industrial sector. However, municipal water withdrawal drops, probably due to the change of people's water habits for living. Other rows in Table 7 show the projected values of indicators mentioned in assumption 1, 2 and 5.

4.2.4 Forecasting Results

Using predicted or projected values in Tables 6 & 7, this study computed Pakistan's Economic Scarcity Metric(ESM) and Physical Scarcity Metric(PSM) in 2030 and get $CI = 4(ACR = 2.52)$ and $ESM = 3395$. By comparing it to current value: $CI = 4(ACR = 2.19)$ and $ESM = 0.5071$, it can be found that the economic scarcity is mitigated significantly because most factors increase largely from now to 2030. Moreover, if we take *ACR*, the physical scarcity is exacerbated for the increase of agricultural and industrial water withdrawal which makes total withdrawal largely increase. If we take *CI*, the increase will remain the same.

Table 7 Factor prediction results in PSM model

Factors	2030	Now
Total Renewable Water Resources [km ³]	246.8	246.8
Agricultural water withdrawal[km ³]	202.3	172.4
Industrial water withdrawal [km ³]	2.25	1.4
Municipal water withdrawal[km ³]	6.43	9.65
Desalinated water produced [km ³]	0	0
Climate Factor	2.953	2.95
Water Availability Per Capita [m ³]	212	297.1

To investigate the effect of α , a sensitivity analysis was made on basis of Eq. (11) (where we take ACR to measure PSM), shown in Fig. 5. It's easy to find that for all α , Pakistan's TSM in 2030 is lower than that now, implying a better water situation at that time. But with α value increases, the gap becomes smaller, that is, water situation in 2030 becomes more serious while that now becomes less serious. This shows a “object” trend of moving the emphasis from physical scarcity to economic scarcity.

5 Conclusions

In this paper, the ability was modeled to provide sufficient improved water for each country. Moreover, this study can assist Pakistan to management its water scarcity. First, we divided the established Total Scarcity Metric (TSM) into Physical Scarcity Metric and Economic Scarcity Metric. PSM was developed based on an indicator widely used in literatures, and a factor model was built with its weight calculated by Grey Relational Analysis. When incorporating them, a parameter α to reveal the relative emphasis between physical scarcity and economic scarcity of each country was introduced in this paper. In the model verification, we used data from 83 countries and found the similar result compared to UN's “World Scarcity Map”. Among our samples, Sudan, Pakistan and Saudi Arab face the most severe water situation.

Based on the established model and UN's map, Pakistan was chosen as a case country to make a deep investigation on its water scarcity. Its scarcity was attributed to two environmental factors and five social drivers in this paper. In addition, we pointed out what kind of scarcity does all the factors affect. To show its water situation 15 years later (in 2030), we used our model to predict PSM and ESM values at that time under assumptions. During our prediction, we determined the predicted value of influential factors by Grey Forecasting Model and Regression Analysis. We found it less vulnerable to economic scarcity but more to physical scarcity in 2030, with the total scarcity mitigated.

To help Pakistan improve its management on water scarcity, this model metric method was established. We analyzed the impact of many kinds of factors in a larger context. This model not only suit Pakistan, but also all kinds of countries with the similar conditions who face the

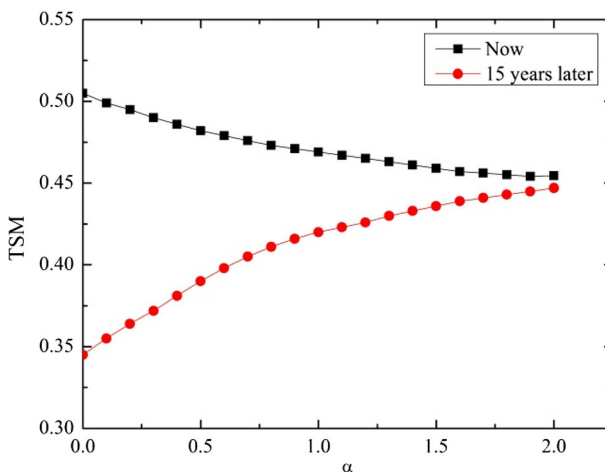


Fig. 5 Sensitivity analysis in TSM forecasting

challenge of water scarcity. It's found that although our model can give some suggestion in alleviating water scarcity, Pakistan will still face other uncertain difficulties. So it still has a long way to go.

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