Using System Dynamic Model and Neural Network Model to Analyse Water Scarcity in Sudan

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Abstract. Many parts of the world are facing the problem of Water Scarcity. Analysing Water Scarcity quantitatively is an important step to solve the problem. Water scarcity in a region is gauged by WSI (water scarcity index), which incorporate water supply and water demand. To get the WSI, Neural Network Model and SDM (System Dynamic Model) that depict how environmental and social factors affect water supply and demand are developed to depict how environmental and social factors affect water supply and demand. The uneven distribution of water resource and water demand across a region leads to an uneven distribution of WSI within this region. To predict WSI for the future, logistic model, Grey Prediction, and statistics are applied in predicting variables.. Sudan suffers from severe water scarcity problem with WSI of 1 in 2014, water resource unevenly distributed. According to the result of modified model, after the intervention, Sudan's water situation will become better.

1. Introduction

The world is facing a growing pressure for water resources. It's shown on the United Nations Water Scarcity Map that one quarter of the world's people experience water scarcity. What is the criterion of determine whether a region is suffering from water scarcity? Will the region become increasingly vulnerable to water scarcity in the future? What if the government makes intervention to alter water supply and demand? Answering these questions is strategic to deal with the important issue of water scarcity in the world.

Due to huge variations of precipitation across the country, high fertility and population growth rates and many other factors, the present water scarcity situation in some regions of the world such as Sudan is extremely severe, leading citizens to suffer from insufficient drinking water, no irrigation for agriculture and poverty. Therefore there is an urgent need to understand the mechanism and dynamic nature of water scarcity quantitatively.

Water scarcity incorporates water demand and water supply, which are decided by factors such as population growth rate, river runoff and precipitation. Planning and reforming water strategies are essential to diminish water scarcity level and maximize benefits of citizens. The intervention is to be driven based on key environmental and social considerations.

Water is a key element to socio-economic development and quality of life. Environmental and social factors is a concern objective for organizations and government but is often vaguely defined and their cooperated contribution procedure to water scarcity is unclear.

2. Literature review

In 1961, Forrester [1] found a simulation model-System Dynamics methodology- to analyze industrial business cycles, and they applied the model on complex interactions of world economy, population in 1971. Sušnik et al [2] used SDM to simulate integrated water systems and assess the potential impacts of policy with respect to water scarcity in specific region.

Pfister et al [3] developed the method for assessing the environmental impacts of freshwater consumption, which considered damages to three areas of protection: human health, ecosystem quality, and resources. They adjusted the Water Stress Index to a logistic function. A global water assessment model called WaterGAP 2, which consists of two main components--a Global Water Use model and a Global Hydrology model, is described by Alcamo et al [4] to fill in many of the existing gaps in water resources data in many parts of the world and provide a coherent approach for generating scenarios of changes in water resources. Omer [5] proposed that water and sanitation in Sudan are severe, and water demand is increasing due to the rapid population growth.

3. Methodology

The extent to which water is scarce is estimated based on the calculation of Water Scarcity Index (WSI), concerning the relationship between demand, also called consumption, and supply in a specific area. Water Scarcity Index is calculated with formulas given by WaterGap2 global model [3]:

$$WTA_i = (WA_i)^{-1} \sum_j WU_{ij} \tag{1}$$

$$WSI = \left[1 + (0.01^{-1} - 1)\exp\left(-6.4 WTA^*\right) \right]^{-1} \tag{2}$$

where WA_i is the annual freshwater availability for each region i;

WU_{ij} is the withdrawals for different users j for each region i;

WTA_i is the ratio of total annual freshwater withdrawals to hydrological availability for each region i.

WU_{ij} in this model, is an indispensable and therefore, critical variable. In order to give an accurate estimation of WU_{ij}, models concerning water supply and demand are then developed. Water supply, as itself states literally, is thought of as renewable water resources available, determined by the process of hydrologic circle. With data availability and discernable relationships considered, only evaporation, precipitation and storage, that is, the gap between water flow in and water flow out in a given area, are involved in this model, which is proved to well explain the relationship among all factors mentioned above.

While certain data are released and accessible, model of relationship among water supply, precipitation, evaporation and water storage is needed, for the sake of prediction. Amount of researches are conducted concerning water resources, but so far few of them is able to describe a clear link between renewable water resources and other variables, which to a large extent implies an elusive and convoluted relationship remained unknown. As a result, a viable model that can clarify but keep

fuzzy a convoluted relationship, that is sometimes, network, is ideal in this case, and thus Neural Network is suitable and induced.

Water demand, or consumption, is regarded as the total amount of water consumed in various ways, from industrial to agricultural ones, all relevant to economic and demographical structure and stature of a country. Complicated wide-range as water consumption in a country is, another model, commonly known as System Dynamic Model, makes it possible to study the constitution of the domestic water consumption system, and also enables us to watch over the whole system in a dynamic way. As apparently population and Gross Domestic Product (GDP) best give a picture of the current stage an economy is in, and industrial structure shows how water consumption is distributed in different industries, we put all these variables into the System Dynamic Model, and keep other variables constant throughout the period we study. A simplified overview of the System Dynamic Model is displayed in figure 1.
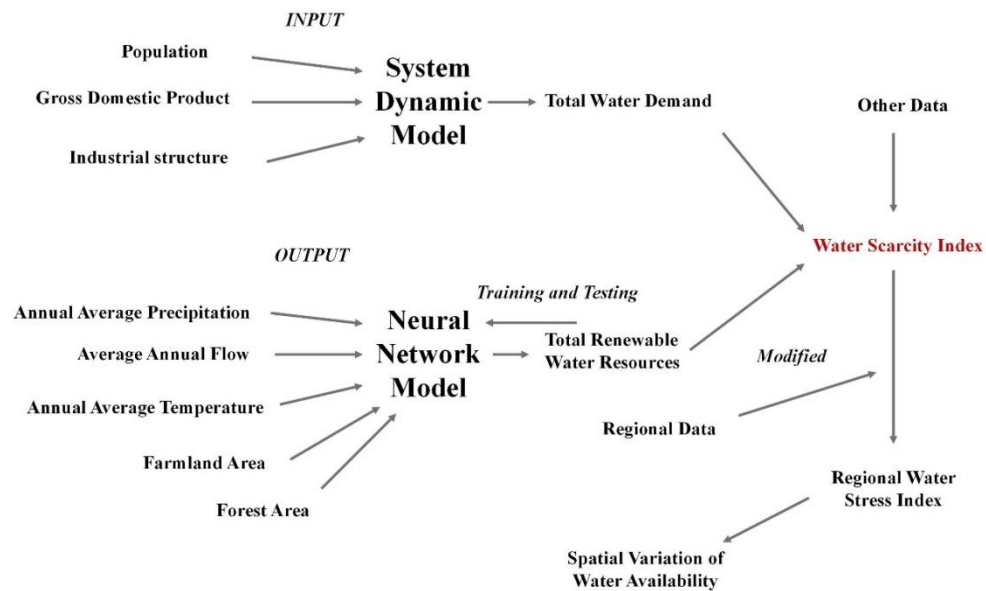
Figure 1. Overview of the water availability model.

When understanding water scarcity in a region, water distribution among areas is indispensable, for it exactly tells us how water is scarce in every corner of this country, instead in the whole country. This is important, for water is still scarce in a country, when some in this country are provided with so much water that they even squander it, while others are faced with terrible water scarcity, too terrible for them to survive, even if the country is seemingly water abundant on the surface. Therefore, Water Scarcity Indices in all regions in a country are also calculated. To keep simple, we assume that water consumption in every region only depends on population and GDP in that area, and only make effort to give an accurate estimation of water supply in an area, based on Neural Network mentioned above. While precipitation in specific region has been already observed and data are available, how citizens in different regions benefit from the main river in this country remains unknown, but critical. Thus, we establish formula below to speculate the extent to which citizens benefit from the main river:

$$benefit_i = \ln\left[ce^{-d_i} \right] \cdot runoff \tag{3}$$

where is c calculated by solving $\sum benefit_i = runoff$.

One-step-forward, prediction of water scarcity is also conducted. For relationships among variables keep stable and fast, only variables are predicted in this passage, and in various ways. Population is believed to fit a logistic progress, and increasing rate of which is described as below.

$$\frac{\mathrm{d}x}{\mathrm{d}t} = rx(1 - \frac{x}{x_m} - a), \qquad x(0) = x_0 \qquad (4)$$

where x is population at time t, x_m is environment population capacity, r is natural growth rate of population; a is net migration rate.

Besides, GDP is predicted with grey forecasting model, while precipitation and annual flow are predicted based on normal distribution, since they greatly fit a normal distribution according to what observed data in last decades show.

4. Application in Sudan

Sudan, located in South-Africa, is one of the countries that suffer from severest water scarcity, in accordance with water scarcity map released by UN. Water in Sudan is heavily overloaded as a result of both environmental and social constraints: for one thing, though the body of Nile river system is right located in Sudan, surface water in Sudan is subject to utter evaporation and discharge; for another thing, while water resources may be abundant, renewable and available water resources are still in dearth due to a lack of advanced water purification technology, and therefore citizens in Sudan find it difficult to obtain enough water without disease carried: as data shows, only 69% of rural dwellers and 86% of city dwellers in Sudan have an access to purified drinking water. To make things worse, population in Sudan keeps growing at a relatively high rate, generating an increasingly greater demand of clean water [5].
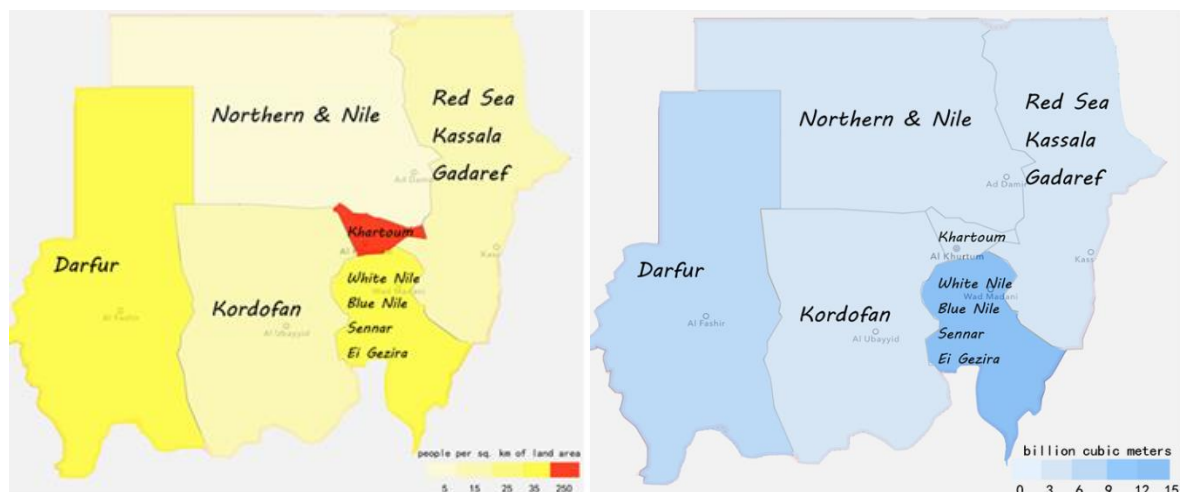
Figure 2. Uneven WSI distribution in Sudan.

Moreover, regarding water distribution and population distribution, the ordeal faced by Sudan seems tougher. Khartoum, for instance, is of highest population density and relatively low water resources in Sudan, which makes it the least water abundant city in Sudan. Figure shows a rough estimation of

population density and renewable water resources in every region in Sudan, from which we can draw a precise picture of a country with water utterly unevenly distributed, as in figure 2.

Table 1 presents overview of Sudan in 2014 regarding water supply and demand:

Table 1. Data of key variables of Sudan in 2014.

| Precipitation (km^3)	Annual Flow (billion km^3)	Population	GDP (dollar)
4.32×10^{11}	6.08×10^{10}	3.94×10^7	7.38×10^{11}

With System Dynamic Modeling and Neural Network Model, aggregate water supply and demand, as well as Water Scarcity Index, are stated in Table 2.

Table 2. Estimated water resource situation in 2014.

Water Supply (billion cubic meters)	Water Demand (billion cubic meters)	Water Scarcity Index
39.26	27.18	1

Water Scarcity Index is equal to 1, which means water resources are greatly overloaded in 2014. In contrast, Water Scarcity Index in Europe is generally below 0.5 in 2014, and estimation of Water Scarcity Index of Sudan in 2004 is 0.763, far below its current value, which shows that Sudan is not only faced with severe water scarcity, but also exhausting its water resources at a high speed.

Further estimation of the extent to which water is scarce in all regions is then conducted, and outputs are interpreted as left in figure 3, suggesting a more concerning water problem in Sudan. The result of water supply and demand prediction in 15 years is calculated by inputting date into the Demand-Supply Model as indicated in figure 3 at the right.
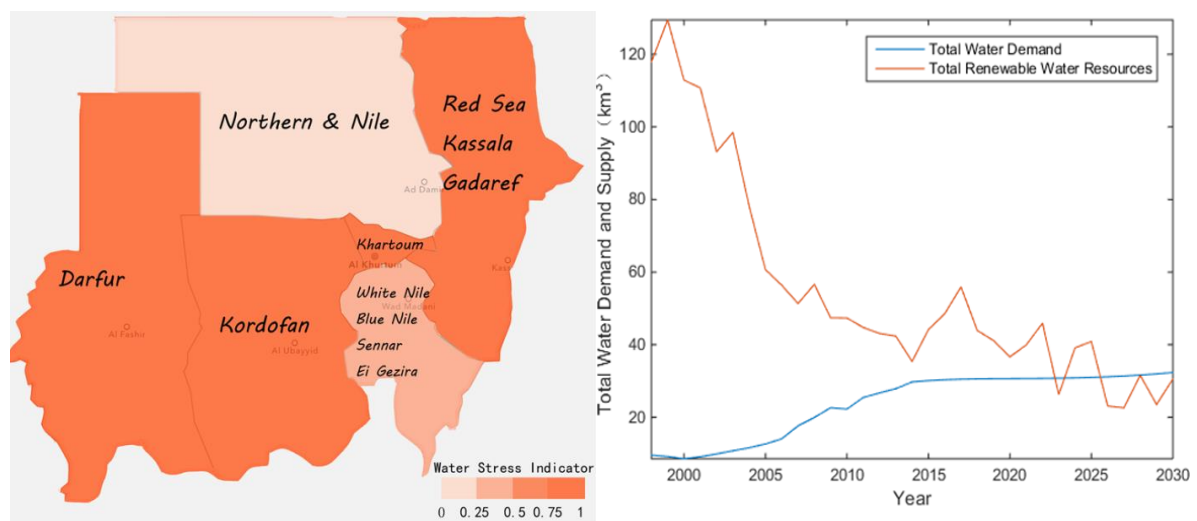

Figure 3. WSI in different states and water prediction in Sudan.

The results show that total renewable water resource has decreased sharply in the past decade while the water demand is increasing because of the accelerated increase of population. Without any intervention, Sudan's water supply will not be able to fulfil its demand after year 2025.

Rainwater should be collected in Sudan in order to get more water supplies. Besides, as the agriculture irrigation technology is applied and population control is enacted, the water demand would decreases accordingly. We put all parameters related to these interventions into our model and get a new prediction of demand of water resources for the following years. Figure show that our intervention plan will make Sudan less susceptible to water scarcity. However, the water shortage will reappear in the year 2027, although we put it off by 15 years compared to no intervention condition.

Water distribution can be optimized by redirect water courses in Sudan. We input modified data of water supply in various states in our model, and obtain a new WSI distribution figure. Figure 4 shows prediction of WSI distribution and water supply and demand after the intervention plan.
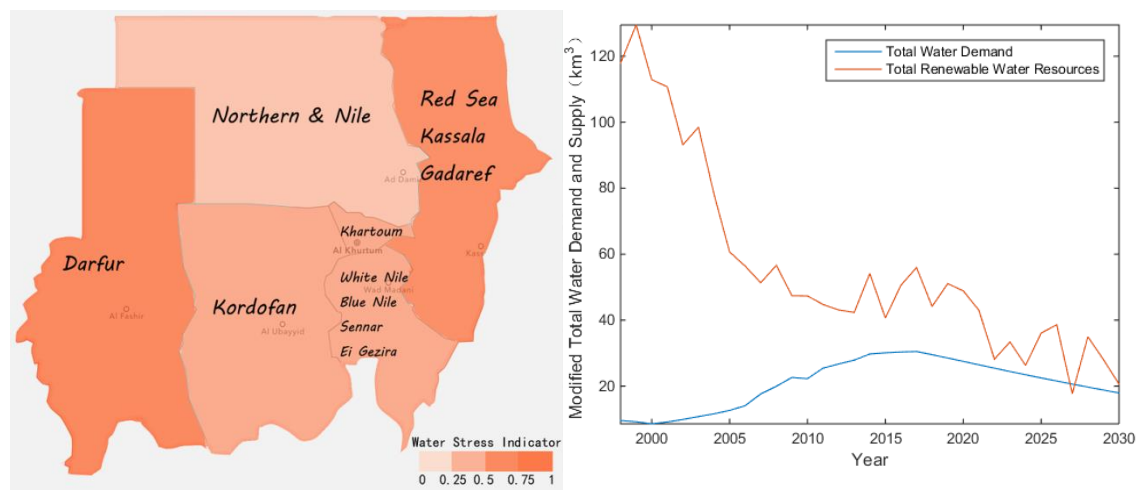
Figure 4. WSI distribution and water supply and demand after the intervention plan.

The results are quite important since we they give us a view of the effectiveness of possible intervention plans in a specific country and predict the reoccurring "bad time" so as to help policy makers greatly.

5. Conclusion

Estimation and Prediction of water scarcity in Sudan are conducted in this passage, and its outputs lead to some important conclusions.

Aggregate water demand and supply in Sudan were 27.18 and 39.26 million cubic meters in 2014, respectively, which shows that renewable water resource in Sudan was able to cover water consumption. However, as predicted in Demand-supply model developed in this passage, the country will exhaust its water resources in 2025, and as a result, leave citizens in an unprecedented water crisis.

Water Scarcity Index is calculated both domestically and endemically. While Water Scarcity Index of Sudan remains 1 from now on, that of regions in Sudan vary significantly, ranging from 0.541 to 1, implying that water distribution in Sudan is so uneven, that some dwellers have already suffered from a dearth of renewable water, while others may own more than necessity.

Therefore, intervention plans are needed. With some viable intervention plans induced in this case, depletion of water resources delayed to 2027 as predicted using our model. Though it takes time and effort, certain effective measures should be taken, for the sake of people's living.

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