

THE POTENTIALLY AVAILABLE GLOBAL WATER RESOURCES DISTRIBUTION UNDER CLIMATE CHANGE

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The major underlying factor in the water scarcities throughout the world is the inequality in the spatial distributions of the resource. The inequalities of global spatial distributions of potentially available water resources over the time axis from 1970 until 2100 were evaluated using the Gini coefficient. Output river discharges from Total Runoff Integrating Pathways (TRIP) from input runoffs of two climatic models; the Community Climate System Model (CCSM3) of USA and the Model for Interdisciplinary Research on Climate (MIROC3.2) of Japan, under SRES scenario A1B of the IPCC were utilized for the analysis. The resulting spatial distributions are extremely unequal, with Ginis more than 0.95, and appear to have increasing tendencies with the time horizon, as well as with the total potentially available water resources, due to climate change. This research is expected to assist the decision makers in the field of water resources management to identify the regions require immediate attention.

Key words: River discharge, unequal spatial distribution, Gini, climate change, potentially available water

1. INTRODUCTION

It is anticipated that severe water scarcities will shake the world especially in the first half of this century, amidst the present water scarcities suffered by several regions over the world¹. Northern China, India, the Middle-East, western and middle USA and southern Canada are only some regions which are in severe water scarcity even at present²⁻³. While high latitudes and wet tropics are likely to be receiving increased runoff and discharge, areas in mid-latitudes and some regions in dry tropics will experience decreased runoff and discharges³ due to climate change. Areas expected to have decreased discharges will undoubtedly experience increased water scarcities, and the human lives and the environment will be affected negatively.

Innumerable researches exist of the water

scarcity analyses^{2), 4-5)} of the water available in all forms, in this century. All consider gridded representations of hydrological components of world^{2), 4-5)} and all these global assessments utilize gridded data of horizontal resolution 0.5 degree longitude/latitude. Almost all employ some kind of an index⁴⁻⁵⁾ to represent the water scarcity; but none of the indices target the inequality in the spatial distribution of water resources. With the growing water scarcities, analysis of the water resource distribution is a timely requirement.

In conventional water scarcity assessment, the difference of precipitation and the evapo-transpiration over land is considered the maximum available renewable fresh water resources (RFWR)⁶⁾. A major portion of this RFWR constitutes of surface water or mainly river discharge⁶⁾. If the available river discharge is wisely

managed, grave social and environmental issues as arsenic contamination of ground water in Bangladesh could be avoided. Moreover, river discharge is the most easily exploitable mode of water for human needs and if available adequately, further exploitation of water resources as ground water or advanced methods of water recycling, and desalinization of water are not required.

Although theoretically, the total water resource available is sufficient enough to meet the needs of the world today, severe water scarcities exist due to uneven distributions of the resource in reality⁶⁾, often giving rise to various social and economical issues. Climate change will further worsen the prevailing water scarcities, vitalizing the identification of the regions that require immediate attention in water management decision making.

This study focuses on assessing the inequality of distribution of potentially available water resources, over the world within the 21st century, using 0.5 degree longitude/latitude resolution gridded annual river discharge data of the globe. The Gini coefficient (Gini, C., 1912)⁷⁻⁹⁾ provides the analytic tool for the water resources distribution analysis, which was chosen in view of developing a methodology to relate inequality of water to the inequity and resulting social issues thereby.

2. METHOD OF ANALYSYS

The potentially available water resources distributions over land of the globe, from 1970 to 2100 were analyzed for its inequality, using the Gini coefficient. The annual average river discharges were assumed as the potentially available water resources. The annual river discharge data have been produced using the output runoffs of two General Circulation Models (GCMs) routed by a global river routing scheme - The Total Runoff Integrating Pathways (TRIP). The future projections from 2000 up to 2100 have been done under the IPCC SRES scenario A1B.

(1) Potentially available water resources

The word “Potentially available water resources” could be debatable. The river discharge from a region, to the consecutive region, which is the combination of runoff from within the first region and the discharges from the regions upstream, could be considered the potentially available water to the first region⁴⁾. The total potentially available water was calculated as the summation of discharges from all grids. Nevertheless, when routed, the discharges from the upstream grids have a high influence on the discharges of the downstream grids. But, as mentioned earlier, the water flux leaving the grid is

considered to be the amount of water potentially available for the human use in that particular grid; this assumption validates the summation of all discharge values as the total water available.

(2) Gini Coefficient as a tool of measuring inequality

a) Gini coefficient in conventional inequality analysis

Among the various inequality measurement techniques^{7),9)}, the Gini coefficient is of a greater universality and popularity. The most prominent use is in the field of Economics, to measure inequality in distributions of income, wealth or other welfare indicators of society. It gives an idea of the inequality in the distribution, which is a quality of it, and also provides a means of unpretentious comparison of inequality conditions to the reader. A noticeable character of the Gini is its independence from the welfare scale being measured.

Although statistical methods using the un-ordered size data are also available^{7),9)}, the graphical method of calculating Gini coefficient is used in this research, for its excellent clarity.

The Gini coefficients are calculated using the plots of distributions of the size shares of ordered individuals, or the “Lorenz Curves”. Lorenz curves normally are plotted below the perfect equality curve, with the axes system shown. In a perfect society, all have the same income, the Lorenz curve would be a $y=x$ line (**Fig. 1**).

The curves 1 and 2 represent two distinct inequality situations of the same population. Curve 1 is more deviated from the perfect equality curve than the curve 2. So are the inequality situations; situation one corresponding to curve 1 is more unequal compared to situation two. Curve 2 represents a population of which the poorest 40 percent has only 20 percent of the total income, but the richest 20 percent enjoy almost 40 percent of the total income of the population. The total income of the population, or the income scale of these

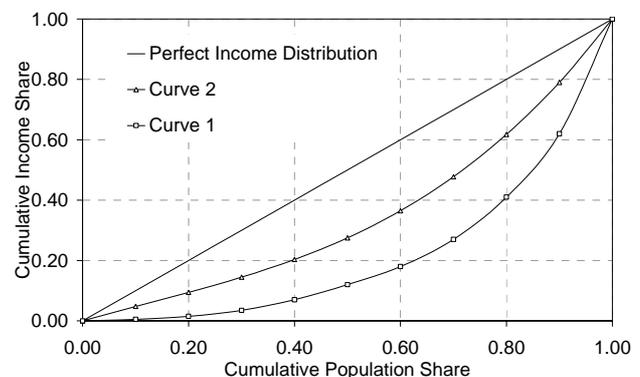


Fig. 1 Lorenz curves for perfect equality and actual income distributions.

situations need not to be the same, and it is not reflected by either the Lorenz curves, or the Gini coefficients.

The Gini coefficient is defined as, the mean difference between every possible pair of individuals, divided by the mean size of the population (Gini, C., 1912)⁸.

$$Gini = \frac{1}{2n^2 \bar{y}} \sum_{i=1}^n \sum_{j=1}^n |y_i - y_j| \quad (1a)$$

Here, n is the number of individuals in the sample, y_i and y_j are the incomes of individual i and j , while $i, j \in (1, 2, \dots, n)$ and $\bar{y} = (1/n) \sum y_i$ is the arithmetic mean income⁷.

In the graphical representation, Gini coefficient is equal to the area between the perfect equality line and the actual income distribution curve, divided by the area under the perfect equality line⁸.

The Gini varies from 0 to 1. The closer the Gini is to 1, the more is the inequality.

b) Inequality measurement in distributions of potentially available water

The Gini coefficient was applied to measure the inequality of the potentially available water resources distribution over land in the globe. The above described graphical method of calculating Gini was followed. In the case of water availability analysis across land, the X and Y axes of Fig.1 were modified as the cumulative share of land and the cumulative share of potentially available water, as shown in the Fig.2.

First, the 0.5 degree longitude/ latitude horizontal resolution, gridded, annual average river discharge data of the year of concern were sorted into order. The basis for sorting was the water available (River discharge) per unit area, which was considered the individual water availability. The area unit was assumed to be one square kilometer for this purpose. For the calculation of grid areas, Eq. (1b) below was employed. Then the cumulative size shares of the ordered discharges and the grid areas were calculated and plotted. A suitable curve was fit to these plotted points, and was considered the Lorenz curve for that year. Finally, the Gini coefficients were calculated at 10 year intervals from 1970 to 2100, for both the TRIP-routed CCSM and MIROC data, utilizing the graphical method.

(3) Grid area calculation

The area of each 0.5 x 0.5 degree grid of the globe was calculated as follows, as the surface area between two latitudes Φ_1 and Φ_2 ($S_{(\Phi_1, \Phi_2)}$)¹⁰, per 0.5 degree of longitude.

$$S(\phi_1, \phi_2) = \left[\frac{\pi a(1-e^2)}{360e} \left(\frac{e \sin \phi}{2(1-e^2 \sin^2 \phi)} \right) + \frac{1}{4} \ln \left| \frac{1+e \sin \phi}{1-e \sin \phi} \right| \right]_{\phi_1}^{\phi_2} \quad (1b)$$

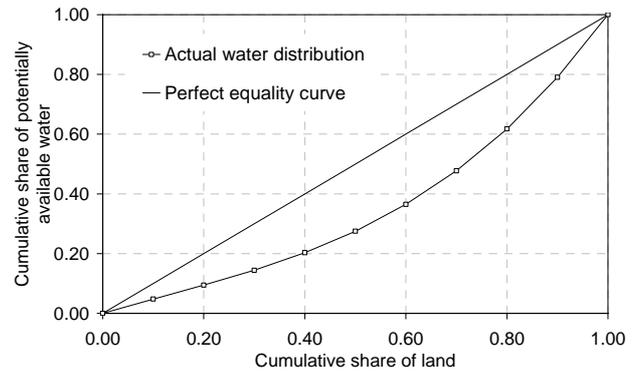


Fig. 2 The modified Lorenz curves for measurement of inequality in potentially available water distributions.

Here, the radius of earth, $a = 6378.136$ km, and the ellipticity of earth, $e^2 = 0.00669447$ ¹⁰. This furnishes grid areas variable along a longitude, and constant along a latitude. Along a longitude, grid areas maximize at the equator to 3077.229 km², and minimize near the north and south poles to 13.609 km².

(4) The data

The data set utilized is a 0.5 x 0.5 degree horizontal resolution gridded annual average river discharge data of the globe, produced by the Institute of Industrial Science, University of Tokyo. The annual discharges have been produced by runoff inputs from the following five climatic models, routed by Total Runoff Integrating Pathways (TRIP).

- (1) Community Climate System Model (CCSM3) of the National Centre for Atmospheric Research, Colorado.
- (2) Model for Interdisciplinary Research on Climate (MIROC3.2) of the Institute of Industrial Science, University of Tokyo, Japan.
- (3) Max-Planck-Institute for Meteorology, Germany (ECHAM5-OM)
- (4) Meteorological Research Institute, Japan (CGCM2.3.2)
- (5) UK Meteorological Office, United Kingdom (UKMO)

Total Runoff Integrating Pathways (TRIP) is a global river routing scheme developed in University of Tokyo. The role of TRIP in this data set is to convert runoffs from the above General Circulation Models (GCMs) into river discharges⁴.

The discharge data includes annual average river discharges of the globe from 1970 to until 2100, of which future projections are done under three SRES marker scenarios of A1B, A2 and B1, from the year 2000, up to 2100.

For this research, only data from the CCSM3 of

USA and MIROC3.2 of Japan under SRES scenario A1B were considered.

SRES scenario A1B assumes a future world with a very rapid economic growth, low population growth, rapid introduction of new, efficient technology and a balanced use of fossil-intensive and other energy sources¹¹⁾. The selection of the scenario A1B over the other scenarios does not have a base, as the authors¹¹⁾ themselves have recommended not considering any such scenario to be having more likelihood of occurrence than the other SRES scenarios¹¹⁾.

3. RESULTS AND DISCUSSION

(1) The inequalities in the global distributions of potentially available water resources

All the distributions of potentially available water resources from 1970 to 2100 show extremely unequal water availability situations, exhibiting Gini coefficients higher than 0.95.

The Gini coefficients have a general trend of increasing towards 2100 (Fig.3). TRIP routed MIROC data Ginis show local trends of increasing until 2000 and then decreasing until 2050 and again increasing; but the overall trend is increasing. The CCSM Ginis also exhibit a similar pattern, but peaks and valleys occur roughly 20 years before. The CCSM Ginis minimize in 2000 to 2030 and in 2070. The general increasing trend of CCSM well agrees with the MIROC Ginis.

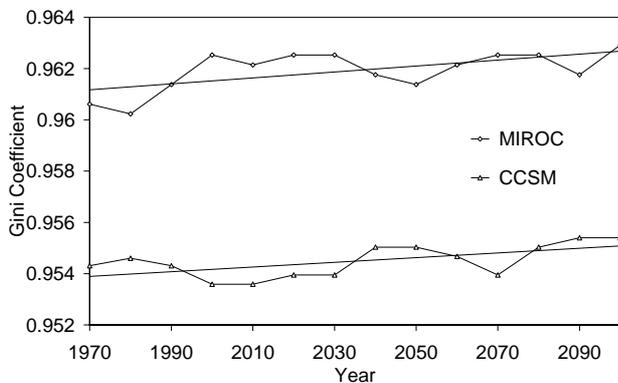


Fig. 3 The variations of global Gini coefficients in the time scale.

What is expressed by these variations of Gini coefficients is that, the potential water availability distributions will remain to be unequal, and the general global trend is to increasing of the inequality, en route for 2100. TRIP-routed MIROC data shows more eased surface water availability around 2050, while for the CCSM data, the unequal distributions are alleviated before; between 2000 and 2050. It is worthwhile noticing, although the surface water distributions are less unequal around the 2050s, the

inequalities are higher if not about the same as in the 1970s. The reduction of the water stressed area around the mid-century found by this analysis could be partially explained by the IPCC assessment, which exhibits increased discharge and runoff around the mid-century in higher latitudes³⁾. The observed increasing tendency of the inequality of the distributions of potentially available water, complement the predicted, pronounced occurrences of heavy and extreme events of precipitation and drought over the world¹²⁾.

Although the Ginis increase towards the end of the 21st century for both the TRIP- routed GCMs data (Fig.3), the total global potentially available water also increase (Fig.4), prompting us to deem the water distributions also to be more equal. However, Fig. 5 clearly explains the trend of Ginis is to increase with the increment of global potentially available water.

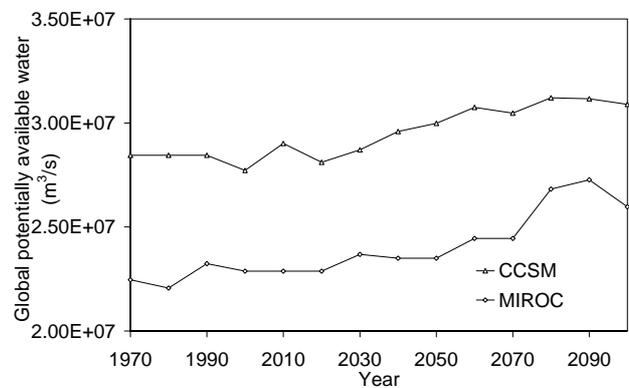


Fig. 4 Global potentially available water during 1970 to 2100

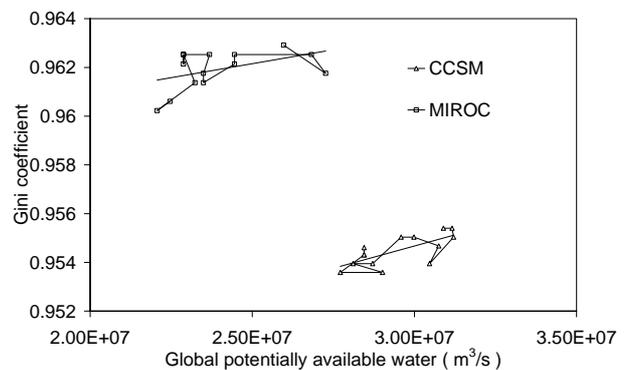


Fig. 5 The trends of global Gini coefficients with the global potentially available water.

The increasing trend of the cumulative annual average discharge (Global potentially available water) could be attributed to the increased precipitation intensities, especially in the West, due to climate change¹²⁾ and the increasing runoff and river discharges in northern latitudes due to increasing global temperature resulted by climate change³⁾.

(2) The observations from Lorenz curves on local potentially available water resources

The Lorenz curves for each year provides very valuable observations about the water availability of various regions.

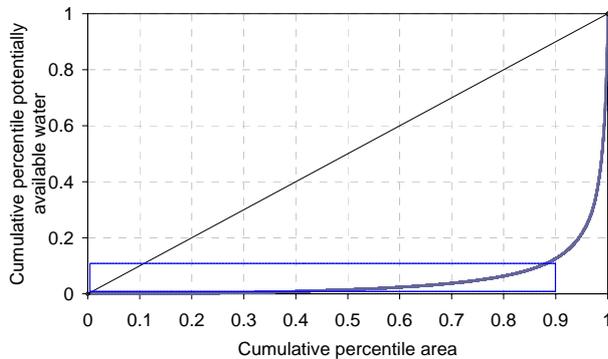


Fig. 6 The Lorenz curve for 1980 (CCSM data) potentially available water distribution.

In **Fig. 6**, 90 percent of the land of earth account for only 10 percent of the total potentially available water resources. The grids that fall onto 0-0.1 range of cumulative percentile water available (The marked range of the Y axis of **Fig.6**) possess very low surface water availability. This is exemplified by the following regional study. For example, in China, north-western, western and north provinces show very high inequality of water; they are in 0 – 0.1 potential water availability range (Marked area of the curve in **Fig.6**) of the Lorenz curve, all through 1970 to 2100. It is a known fact that, these areas are dominated by dessert. Twelve western provinces account for a 75 percent of China, only with a population of 28 percent of its total population, and contribute only 19.2 percent of total GDP of the country in 2002¹³). In order to examine the water availability in detail, Sichuan province, situated in the south-western China, was selected, the southern part of which is nourished by the Yangtze River. Sichuan had the third largest population in the country, of which an 80 percent were rural, in 2003¹³). It is an agricultural province, where most residents depend upon direct water sources as surface water, rain water and shallow wells¹³).

Almost 74 percent of the land area of Sichuan exhibited high water inequality, falling in the 0 -0.1 range in the cumulative percentile water availability scale in the Lorenz curves over the time scale considered, while other 26 percent were in the range 0.1-0.5 of the curves. **Fig. 7** illustrates how the water availability of Sichuan Province behaves over time. This Sichuan province analysis utilizes CCSM data.

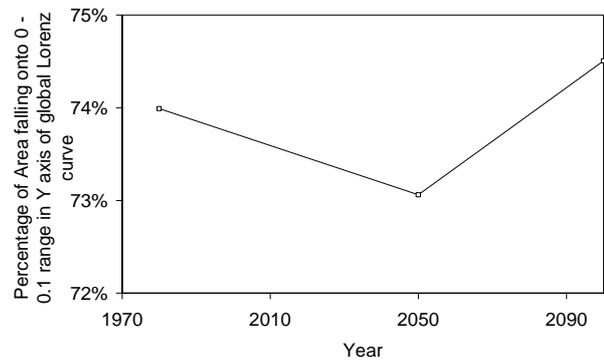


Fig. 7 The variation of area falling in between 0-0.1 global Lorenz curve, in Sichuan Province, China, in the time axis (For CCSM data).

(3) Sensitivity analysis

The sensitivity of the Gini coefficient to the changes in the discharges is very low and does not possess a clear relationship; but, roughly about 30 percent of change in all discharge values will result in only about 0.1 percent change in its Gini coefficient.

Consideration of all land area, inclusive of all the desert regions, and regions having year-through ice, which neither contribute in significant discharge, and nor are populated, might have resulted in the very high Gini coefficients. When those areas are neglected, it is expected that the Gini will significantly reduce, and the sensitivity of Gini to the changes in discharge values will increase.

(4) Uncertainties

a) Uncertainties of the data

Uncertainties of the data could be accounted to the future scenarios used for projections. However, considered two different climatic models, they have significant uncertainties in the modeling process, and they increase in the temporal scale¹¹) as agreed by **Fig. 3**, **Fig. 4** and **Fig. 5**. The global potentially available water in **Fig.4** and the Gini coefficients in **Fig. 3** lie in different ranges for the two GCMs, CCSM and MIROC. According to IPCC, the largest contributions of uncertainty in future river discharges are given by the variations between the climatic models used for the projections¹²). The future projections of runoff from GCMs, especially in the areas close to deserts, could be highly dependant upon the method utilized in correcting the model bias error⁴). Hence, this study should not be considered a prediction, but as an analysis of possible future conditions in a certain future path.

b) Uncertainties of the method of analysis

In this research, the potentially available water was defined as the annual average river discharges. Other water fluxes as ground water, rain water which are used for human activities were not

considered as potentially available water resources. Nevertheless, there are regions of the world where water resources are available as ground water and are largely dependant upon it such as Middle-East, Mexico and western USA. If ground water resources also were considered under the potentially available water resources, this study would be very comprehensive.

4. CONCLUSIONS

The inequalities in the potentially available distributions of water were evaluated using the Gini coefficient from 1970 to 2100. Annual average river discharge data, which had been produced using input runoffs from two GCMs (MIROC and CCSM) routed by TRIP river routing network, were utilized in this analysis. The future projections of runoff had been done under the IPCC SRES scenario A1B.

The distributions of potential water availability from 1970 until 2100 exhibit very high inequalities of Gini coefficients more than 0.95. Both the data sets used- MIROC and CCSM exhibit reduced inequalities of the potentially available water distributions around 2050. However, 2050 inequality situations are worse than that in 1970s. Nonetheless, the inequality conditions of the potential water available (Annual average river discharges) appear to have an increasing trend en route for 2100, although the total global potentially available water is increasing.

In the Lorenz curves over the time, regions in the lowest portion of curve are suffering from no or low water availability. In all the potentially available water resources distributions (Global Lorenz curves) from 1970 to 2100 in both the utilized data sets, only 10 percent of water was distributed over 90 percent of land on the earth. A regional analysis was done in Sichuan province, China to exemplify the key observations which could be made from the potential water availability distributions, which in turn are useful in water resource management in mitigation of effects of climate change. On average, 74 percent of all the land area of Sichuan was highly water-stressed from 1970 until 2100.

The method of analysis of this research is expected to help decision makers to identify the inequalities in water distributions, and the regions which would require immediate attention, in climate change mitigation and to be developed into a

methodology that facilitates water management decision making in terms of social equity.

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