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Impacts of Climate Change on Hydrologic Resilience to Shifting Water-Energy Balance Based on Budyko Framework Across Western Arid Regions of India

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Abstract:-Changing climate has been methodically shifting the equilibrium between energy and water-based parameters of all earthly systems as variations in warming and precipitation lead to a shift in evaporative demand. The trend has been expected to increase warming along with fluctuations in precipitation in the future. In this study, we demonstrate that as climate changes the equilibrium between water supply and demand, buffer to plant water stress has been provided by the groundwater, mainly in regions where the groundwater is at shallow depth. Persistent warming and changing monsoon patterns in India lead to the development of stress on groundwater storage, especially in areas within the vicinity of arid and semi-arid regions, which results in affecting groundwater connections. The aridity index map demonstrates the equilibrium between water demand (described as potential evapotranspiration, PET) and water supply (as precipitation, P). The Aridity index (AI, described as ratio of PET/P) was used to denote the water and energy drivers of the terrestrial and hydrologic systems across India. Two global datasets were used for this study, namely, Climate Hazards Ground Infra-Red Precipitation (CHIRPS), MOD16A2 data product for PET based on the widely used Penman-Monteith equation, which takes inputs of the meteorological reanalysis data. Analysis was carried out on the cloud-computing-based Google Earth Engine (GEE). To demonstrate the variations in annual PET, three warming cases of 1.5 °C, 2 °C, and 4 °C were chosen, with a focus on the semi-arid regions of Western Rajasthan, India. The Budyko framework-based observations clearly highlight the transition zones of water to energy-limited systems in northwest and peninsular India for the year 2020. Results demonstrate that continuous warming has a direct impact on the rise in evapotranspiration rates leading to higher stress on available groundwater resources.

Keywords*: Climate change, Groundwater, Remote sensing, Evapotranspiration, Aridity index, Google earth engine.*

1. Introduction

Increasing temperature comprehensively creates a shift in the equilibrium linking water and energy-based drivers of earthly systems. The fragile and highly dynamic ecosystems over the semi-arid regions are sensitive to the changes in climate induced by land use transition and anthropogenic activities. Recent studies suggest "an increase in groundwater droughts in the 21st century to be coincident with hot periods and reckoned that this shift has been likely due to evaporative shifts with warming" [1]. In contrast to increased evapotranspiration, elevated temperatures tend to increase evaporative demand, although how much of this increase will result in moisture shortage and the development of evaporative stress depends in part on the environment [2]. Annual groundwater recharge amounts to around 30% of the entire freshwater supply [3]. The slow-moving portion of the water cycle, groundwater, functions as a reserve for flora during dry spells and contributes to decadal oscillations in the availability of all terrestrial water [4]. A surge in evapotranspiration (ET) may alter the proportion of rainfall that runs off as surface water or penetrates into the sub-surface as recharge under a warming environment. Long-term fluctuations in recharge patterns can affect the availability and explored groundwater levels and, in turn, groundwater-surface water interactions along with the soil moisture of the region. Despite these well-established connections, it is still very difficult to assess the impact of groundwater in a continuously warming climate [5,6].

Here we apply a simplified surface water model over India, especially to arid to semi-arid regions of Western India, to investigate the vulnerable regions which shall be experiencing a shift in water energy balance in the near future due to various warming scenarios. We compare the recent climate scenario with trends of three flustered warming scenarios with consistent warming of 1.5, 2, and 4 degrees Celsius. The precipitation is held constant to insulate the impacts of elevated evaporative demand across various temperature conditions. The aim of the selected pseudo-warming scenarios used here is to assess the sensitivity of the existing hydrologic system across terrestrial extent. 1.5 °C is the expected increase in air temperatures by 2050 to 2060 if the current trend continues; 2 and 4°C give the possible outcomes regarding global warming by the turn of the next century.

Aridity signifies the relative equilibrium between water demand (PET) and its supply (P). The Aridity Index (AI) is calculated as PET/P (where, PET calculated as the potential evapotranspiration and P as precipitation). AI can be used to demonstrate a relationship amongst water and energy drivers of hydrologic systems. Precipitation is significantly higher than evaporative demand in case AI is <1 and the system is considered to be energy limited. The Budyko hypothesis shows a single curve-linear relationship that relates the relative fraction of rainfall leaving the watershed in the form of evapotranspiration to aridity [2]. Findings suggest that the Budyko Curve between the aridity index and the evaporative fraction can account for ninety percent of the variation amongst some of the major watersheds [2]. In the present study, an Aridity map was obtained for entire India using cloud-computing based Google Earth Engine (GEE), and the trend based on the selected warming scenario was analyzed specifically for western India using the Penman-Monteith and Hargreaves method using the data obtained from IMD.

2. Objectives

Aridity signifies the relative equilibrium between water demand (PET) and its supply (P). The Aridity Index (AI) is calculated as PET/P (where, PET calculated as the potential evapotranspiration and P as precipitation). AI can be used to demonstrate a relationship amongst water and energy drivers of hydrologic systems. Precipitation is significantly higher than evaporative demand in case AI is <1 and the system is considered to be energy limited. The Budyko hypothesis shows a single curve-linear relationship that relates the relative fraction of rainfall leaving the watershed in the form of evapotranspiration to aridity [2]. Findings suggest that the Budyko Curve between the aridity index and the evaporative fraction can account for ninety percent of the variation amongst some of the major watersheds [2]. In the present study, an Aridity map was evaluated for entire India using cloud-computing based Google Earth Engine (GEE), and the trend based on the selected warming scenario was analyzed specifically for western India using the Penman-Monteith and Hargreaves method using the data obtained from IMD.

3. Methods

India has a "monsoon" climate, a type of climate that is more common in South Asia and South-East Asia broadly. The genesis of the term "monsoon" can be traced back to the Arabic word "mausim," which literally translates to "seasons." Most of the precipitation across the country occurs during the monsoon season, which is marked by the beginning of June to September end. The annual statistics reports obtained from the Central Ground Water Board (CGWB) demonstrate that during the monsoon periods, maximum groundwater recharge takes place, especially in the regions far from the vicinity of perennial rivers [7]. The aridity index map [Figure 1] was produced for the year 2020 using the daily data product obtained from Climate Hazards Group InfraRed Precipitation (CHIRPS) for precipitation gridded data with a resolution of 5,566m and MODIS MOD16A2 Terra Evapotranspiration dataset, which is used to obtain the potential evapotranspiration (PET) data at a resolution of 500m. The CHIRPS data is provided by Climate Hazard Center [8] and MOD16A2 product is provided by USGS, which is freely available within the GEE environment. In the present study, three warming scenarios have been considered with a special focus on semi-arid regions of western India, which mainly comprise the regions in the vicinity of the Thar Desert encompassing parts of Western Rajasthan. To evaluate the variations in PET due to the selected warming scenarios, daily PET values were calculated using the Penman-Monteith and Hargreaves method. The two methods were applied to the weather data obtained from India Meteorological Department (IMD) for the Jodhpur station. Jodhpur city is located at 26.24° N, and 73.02° E and experiences an erratic climate. The mean annual rainfall in the country is about 118 cms as per data available from the meteorological department, while the mean annual rainfall in western Rajasthan is barely 32.7 cms. Due to scarce availability of station weather data for the semi-arid regions of Western Rajasthan, it has been considered that the temporal variations of the weather parameters remain same for the entire semi-arid region.

$$PET_{PM} = \frac{0.408\,(R_n - G)\Delta + \gamma \frac{900}{T_a + 273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \quad (1)$$

$$PET_{Hargreaves} = 0.0023\,(T_{mean} + 17.8) \times (\sqrt{T_{max} - T_{min}})R_a \quad (2)$$

where, PET is the potential ET rate (mm per day), U_2 is the mean daily wind speed at height of 2m in m s^{-1} that is obtained from station data, value of G is determined as the density of soil heat flux (MJ $m^{-2}day^{-1}$) – here G is assumed to be zero as it is comparatively negligible at the daily time scale[9], T_a is mean daily air temperature (℃), e_s is the saturation vapour pressure (kPa), Δ is the slope of vapour pressure versus temperature curve (kPa $^\circ C^{-1}$), R_n is the net radiation flux density at the vegetation surface (MJ $m^{-2}day^{-1}$), e_a is the actual vapour pressure (kPa), $e_s - e_a$ is the saturation vapour pressure deficit (kPa) – these parameters are obtained using the methods described by FAO, γ is the psychrometric constant (kPa$℃^{-1}$), T_{mean} the mean temperature (℃) (provided by station data), R_a is the extra-terrestrial radiation (MJ $m^{-2}day^{-1}$).

4. Results

In the present study, the baseline trend from the daily weather data of 2020 for PET with three warming scenarios using equations (1) and (2) is assessed. An aridity map for monsoon season (June to end of September period of the year 2020) highlights the transition/vulnerable areas which are showing transition zones from energy to water-limited systems. Figure 1 clearly shows the western and southern regions, which exhibit an aridity index in the range of 0.8 to 1.2. Regions with AI <1 represent energy-limited conditions and where AI >1, regions are water-limited. As per the Budyko hypothesis, the systems are in a zestful equilibrium with no variations in available storage. Hence, an increase in the PET will develop shifts in the PET/P ratio. This shift will produce more stress on the already stressed groundwater resources as the temperatures increase over the coming years. In all three warming scenarios, the observed rainfall is kept constant in order to segregate the impacts of increasing temperature from changes in water supply, which might occur with fluctuations in the precipitation occurring during the monsoon season. Warming trends have been a major focus of this study as they provide more certainty when compared to precipitation forecasts which can be highly fluctuating [10].

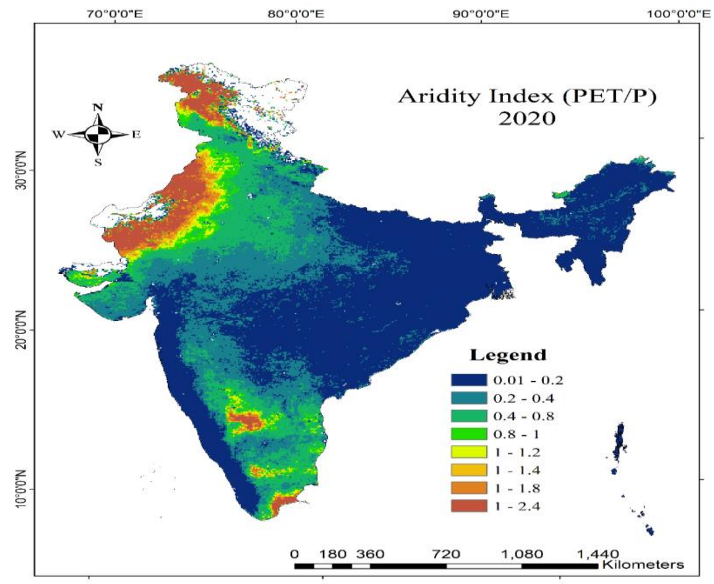

Figure 1 . Aridity Index Map of India for the year 2020 (monsoon season).

Aridity also acts as a predictor of watershed partitioning and elevated aridity results in a drying trend for the available groundwater. The magnitude to which expanded evaporative requirement causes an actual increment in evapotranspiration rate rather than increasing evaporative stress is predominantly determined by the amount of water available to meet the increased demand. Slight variations in aridity demonstrate greater fluctuations in the evapotranspiration rate in an energy-limited system when compared to water-limited regions.

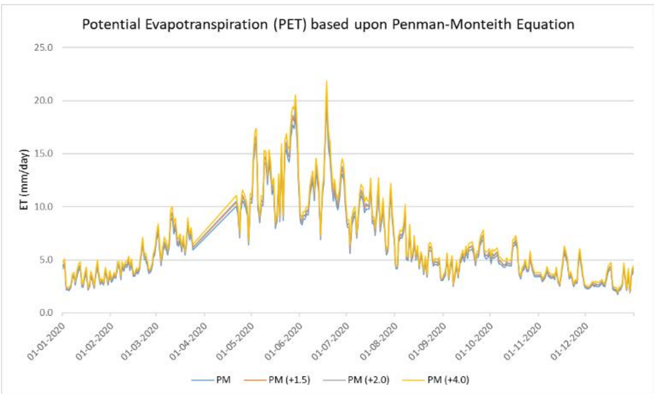

Figure 2. PET (mm/day) variation based upon the Penman-Monteith Equation for the year 2020 with existing and warming cases of 1.5 °C, 2 °C, and 4 °C.

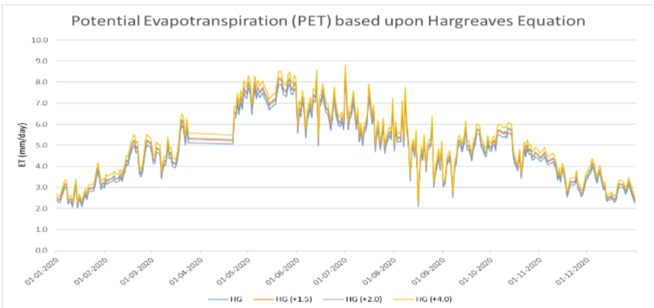

Figure 3. PET (mm/day) variation based upon the Hargreaves Equation for the year 2020 with existing and warming cases of 1.5 °C, 2 °C, and 4 °C.

The aridity map indicates the regions prone to shifting in terms of water and energy limitations. Regions shown in the range of 0.8 to 1.2 represent regions in the transient condition and are most vulnerable to changing climate. The increasing temperatures will exhibit an increase in ET as well, which will further increase the stress on the available groundwater. Figure 2 and Figure 3 show the annual variation of PET (mm/day) for the year 2020 based upon the Penman-Monteith equation and Hargreaves equation using the weather data obtained from IMD for the semi-arid region of Western Rajasthan. Based on the observations, it is demonstrated that continuous warming will result in increased ET and PET across the region. This increased ET and PET shall increase the demand for water, creating enhanced stress on the region's groundwater.

5. Discussion

Sustained warming can primarily affect the ET rates and thus reduce the subsurface storage. Even in the moderate case of 1.5 °C, considerable effects can be expected. We also illustrate the transient zones between water and energy-limited regions in this study. In the western arid regions, the groundwater available at greater depths is found to contain high salinity and is much more disconnected from the ground surface. In such scenarios, increased temperatures mainly reduce recharge rates. As the system warms, the western parts and parts of peninsular India become more arid, and with this, sensitivity to continued warming reduces. The simplified relationship outlined here does not represent the other complex non-linear interactions. Our approach is to isolate the effects of warming on ET and, in turn, its impact on groundwater storage and recharge rates. Warming-induced effects on dynamic groundwater interactions, lateral groundwater flow dynamics, solving variably saturated flow, and fluctuations to hydraulic conductivity demand enormous computational resources [10]. Instead, the present study outlines a simple relationship based upon the Budyko framework to exhibit the regions in a transient condition, showing an inevitable shift from energy limited to a water-limited case if current warming continues. The dynamic interactions of groundwater will most likely affect the productivity of the ecosystem and shall be adversely affected by the warming-induced variations in hydraulic conductivity [11]. CO_2 enrichment, subsurface flow, fluctuations in wind speed and relative humidity, and other complex interlinkages were not contemplated for the present work and might affect the assessment acuteness found here. Continuous efforts in efficient and optimized use of available renewable water are required to reduce stress on available groundwater in transient regions. Techniques like rainwater harvesting and the construction of reservoirs to retain the runoff from precipitation can help increase the groundwater recharge rate for stressed areas.

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