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Simple Mathematical Models for Aridity, Rainfall and Runoff in Semi-Arid Environment

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Abstract: Since it is difficult to monitor physically the water related parameters in all the catchments, prediction models become important to generate data for planning and development. Precipitation and temperature are two major variants affecting aridity of a region. A simple method was developed for assessing drought event by determining aridity index (Ia). Ia value below 25 indicated aridity and its severity increased with decrease in the value. Values above 25 are indicative of optimum rainfall of the area. The method can also be used for determining seasonal aridity index. A mathematical model to monitor runoff from catchments was developed with five independent variables based on a partial regression equation using the Doolittle method and it gave a reasonably high degree of accuracy in prediction or estimation of runoff. The models work very well and accurate predictions can be made under wide range of climatic situations. Reliable large data is required to evolve models for accurate predictions.

Key words: Aridity · Rainfall · Runoff · Semi-arid Environment and Simple Mathematical Models

INTRODUCTION

Water resources shortages are a serious environmental problem worldwide and a major threat to the sustainable development [1]. Modelling hydro-chemical catchment dynamics in basins deals with the detection and quantification of spatially distributed and time variable impacts. Droughts are extreme events characterized by persistency in time and large scale effects. It is a creeping hydrological phenomenon due to below average rainfall and can have devastating environmental and social implications [2, 3]. It is a regionally persistent and slowly developing phenomenon posing a significant threat to water resources and optimum crop growth. Countries, with agriculture based economies, are the most affected during the long-spell droughts, leading to famine or famine-like situations [4]. Drought occurrence and severity is not strictly due to climatic fluctuations alone but may include a sudden increase in demand for water because of socio-economic growth and development over space and time, which is beyond the water supply capacity. Droughts are usually hazardous and result in disruption of economic, social and institutional set-up depending on its duration, deficit and impacts on users. Quantitative indicators are needed to determine the timing, duration and severity of droughts. The indicators and methods should take into account hydrological characteristics of the region for which they are intended. The vegetation type and density is mainly influenced by the amount of rainfall and human interventions, besides other climatic factors such as temperature. It may be difficult to quantify the unsaturated infiltration processes of rain-water in field soil very accurately, though it is a major source of groundwater recharge and solute transport in the unsaturated zone [5]. The Kandi region of Jammu Province in India has semi-arid environment. Biophysical features, such as fragility, marginality, low accessibility and resource heterogeneity, are constraints in the region. Due to sudden increase in water requirement and unthoughtful planning to satisfy the demand, the practice has left the legacy of degraded aquifers, land subsidence and ecological damage [6, 7]. Until now, no systematic study has been undertaken on devising a methodology for assessing occurrence of droughts. Studies of the impact of rainfall variability on hydrological regimes are essential to plan the water management at a regional scale, particularly in countries whose development depends on

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agricultural resources. In most of the countries, these regions have had difficulties to maintain good measurement networks [8]. Simple mathematical models for aridity, runoff, rainfall and rainfall variability index were developed to make predictions in semi-arid environment, which could help in future planning and development.

MATERIALS AND METHODS

Study Site: The site of study area is the *Kandi* region of Jammu Province of Jammu and Kashmir state of India (Figure 1). The region is about 200 km in length with width varying from 15 to 50 km. The elevation of the northern portion is about 1050 m and the southern part merge with plains with an elevation of about 300 m above mean sea level. Major factors affecting runoff in the region include; type, amount and distribution of precipitation, land use, initial soil moisture, soil infiltration and slope. The area is mostly denuded with sparse vegetation due to indiscriminate felling of forest vegetation. Because of hilly terrain and undulating topography, the region is prone to heavy soil erosion. Meteorological factors such as amount and duration of rainfall, temperature, *in-situ* retention of rain water, rate of infiltration and amount of run-off as well as aquifer recharge capacity are important indicators of ground water sustainability in the region.

Model Description

Aridity Indices: For determining aridity index; rainfall, potential evaporation index and temperature were considered to get maximum accuracy in prediction as against rainfall and temperature considered by [9]. The aridity index was determined as,

$$Ia = (P - I_{PE}) / T \qquad (1)$$

where; Ia is the aridity index, P is the annual precipitation (mm), T is the mean annual maximum temperature (°C) and I_{PE} is potential evaporation index, calculated as,

Fig. 1: Kandi region in the state of Jammu and Kashmir, India

$$I_{PE} = 1/100\ (TP) \qquad (2)$$

If a region has low mean annual temperature, a rainfall of relatively low magnitude may be sufficient for optimum flows and aquifer recharge compared to higher rainfall received in a region having high mean annual temperature. A value below 25 indicated aridity and its severity increased with decrease in the value. Values above 25 are indicative of optimum rainfall. The method can also be used for determining seasonal aridity index. If the aridity index is to be calculated for a particular month, the rainfall during a particular month is used in place of annual rainfall and the outcome is multiplied by 12 (12 months in a year), as:

$$Ia = \{(P - I_{PE}) / T\} \times 12 \qquad (3)$$

Considering 25 as the optimum or critical aridity index, the critical annual precipitation (CAP), required in the arid environment for optimum crop growth can be calculated as;

$$CAP\ (mm) = I_{PE} + 25T \qquad (4)$$

$$\text{or } CAP = 1 / 100\ (TP) + 25T \qquad (5)$$

By substituting the value of T, the value of critical annual precipitation of the area can be calculated.

Runoff: The proposed method for runoff makes use of the amount of rainfall, slope, crop land use or vegetation cover, soil moisture content and soil clay content of the study area. A runoff mathematical model was developed with five independent variables based on a partial regression equation of the form:

$$\text{Runoff (\% of rainfall)} = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5 \qquad (1)$$

where; b_1, b_2, b_3, b_4, b_5 are the partial regression coefficients for the slope (x_1) in %, annual rainfall (x_2) in mm, vegetation (x_3) on a 1-5 scale, soil moisture (x_4) in % and clay content (x_5) in %, respectively. The equation was developed using the Doolittle method as described by [10] and it gave a reasonably high degree of accuracy in prediction or estimation of runoff. The vegetation is the only independent variable for which the values (1 to 5) have to be based on visual estimates. The classification used for the vegetation values is: 1: bare ploughed soil surface; 2: scrub or effective covered area below 25%; 3: cropped soil surface or effective covered area 25 to 50%; 4: open forest vegetation or effective covered area 50 to 75%; 5: dense forest vegetation, including bushes and grasses or effective covered area more than 75% [11].

Following the same procedure as for simple regression, the problem is to find the values of b_1, b_2,….b_5, that will make the sum of squares of the error of estimation a minimum. Thus it is required to minimize;

$$\Sigma(\text{Runoff} - b_1x_1 - b_2x_2 - b_3x_3 - b_4x_4 - b_5x_5)^2 \quad (2)$$

and this leads by the methods of least squares to 5 simultaneous equations, which are given below for 5 independent variables and can be extended easily for the number of independent variables required.

$$\begin{aligned}
&b_1\Sigma x_1^2 + b_2\Sigma x_1x_2 + b_3\Sigma x_1x_3 + b_4\Sigma x_1x_4 + b_5\Sigma x_1x_5\\
&b_1\Sigma x_1x_2 + b_2\Sigma x_2^2 + b_3\Sigma x_2x_3 + b_4\Sigma x_2x_4 + b_5\Sigma x_2x_5\\
&b_1\Sigma x_1x_3 + b_2\Sigma x_2x_3 + b_3\Sigma x_3^2 + b_4\Sigma x_3x_4 + b_5\Sigma x_3x_5\\
&b_1\Sigma x_1x_4 + b_2\Sigma x_2x_4 + b_3\Sigma x_3x_4 + b_4\Sigma x_4^2 + b_5\Sigma x_4x_5\\
&b_1\Sigma x_1x_5 + b_2\Sigma x_2x_5 + b_3\Sigma x_3x_5 + b_4\Sigma x_4x_5 + b_5\Sigma x_5^2 \quad (3)
\end{aligned}$$

For abbreviate Doolittle solution for standard regression and partial correlation coefficients values, the equation (4) can be written as equation (4) below, (Goulden, 1960):

$$\begin{aligned}
&\mathbf{b_1\Sigma x_1^2 + b_2\Sigma x_1x_2 + b_3\Sigma x_1x_3 + b_4\Sigma x_1x_4 + b_5\Sigma x_1x_5 + \Sigma(x_1y)\ \ 10}\\
&\mathbf{0\ 0\ 0\ 0}\\
&\mathbf{b_2\Sigma x_2^2 + b_3\Sigma x_2x_3 + b_4\Sigma x_2x_4 + b_5\Sigma x_2x_5 + \Sigma(x_2y)\ 0\ 1\ 0\ 0\ 0\ 0}\\
&\mathbf{b_3\Sigma x_3^2 + b_4\Sigma x_3x_4 + b_5\Sigma x_3x_5 + \Sigma(x_3y)\ \ \ 0\ 0\ 1\ 0\ 0\ 0}\\
&\mathbf{b_4\Sigma x_4^2 + b_5\Sigma x_4x_5 + \Sigma(x_4y)}\\
&\mathbf{b_5\Sigma x_5^2 + \Sigma(x_5y)\ \ \ 0\ 0\ 0\ 1\ 0\ 0}\\
&\mathbf{0\ 0\ 0\ 0\ 1\ 0}\\
&\mathbf{1.0\ \ 0\ 0\ 0\ 0\ 0\ 1}
\end{aligned}$$

Here 'y' is the dependent variable. The solution of these equations gives the values of b_1, b_2, b_3, b_4 and b_5 to be inserted in the prediction equation;

$$\text{Runoff (\% of rainfall)} = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_4 + b_5x_5$$

In the above multiple regression equation, the dependent variable is the runoff and independent variables are slope, rainfall, vegetation cover, soil moisture content and soil clay content. The greater the prediction power of this equation, the closer the agreement between the actual and the predicted values of runoff. More the data used for developing the model, the more will be the accuracy of predictions.

Rainfall: A statistically significant negative relationship was found between the difference of monthly mean maximum and minimum temperature and rainfall to happen, with gradient up to -54.52 mm per °C. The relationship is: rainfall (mm) = 724.2 – 54.52x, where x is the difference in monthly mean maximum and minimum temperature of the study area.

Rainfall Variability Index (RVI)
The RVI was calculated as:

RVI = (Rainfall in mm during the year - Average rainfall in mm over the years) / standard deviation.

RESULTS AND DISCUSSION

Meteorological Parameters: The area of study is mostly denuded with sparse vegetation due to indiscriminate felling of forest vegetation. Because of hilly terrain and undulating topography, the region is prone to heavy soil erosion. Extreme water stress is experienced during summers and winters and even water for drinking becomes scarce. Maximum temperature crosses 40°C in June-July on some days, causing huge evaporation from the water and soil surface. However, average highest average maximum and minimum temperatures were 38.9 and 26.0°C, respectively, recorded in June (Figure 2). The average evaporation loss was higher in May-June compared to July-August because of high temperature and more sunshine hours during this period, ranging from an average of 8.5 to 13.5 in a day. The evaporation losses were more than rainfall throughout the year, except in July and August (Figure 2, shaded portion). The climatic data helped in modelling aridity index and draw conclusions for better understanding.

Changes in climate occurring on decadal or multi-decadal time scales have been identified in a number of earlier studies [12-16]. Spatial distribution of droughts is a relevant characteristic for drought analysis and the regional approach demands comprehensive tools for drought studies. The methodology used for regional drought characterization in this study enables a clear identification of drought areas, simulation of the spatial distribution of droughts and the associated risk of their occurrence. The most important climatic characteristics that affect the hydrological regime are the air temperature and precipitation as well as their annual cycle [17]. The data analysis showed that the annual air temperature has a stable, increasing trend over the whole area.

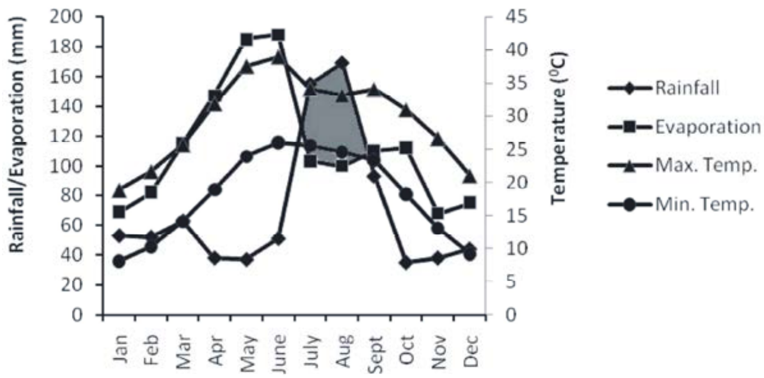

Fig. 2: Rainfall, mean maximum and minimum temperature and evaporation interrelationships

The physiographic and biophysical features of many regions change with time, due to natural and anthropogenic factors, thus increasing or lessening sensitivity to climatic impacts. Among the various causes, land cover and land use modifications and the environmental degradation such as overgrazing and deforestation, constitute a major focus of interest [9].

The analysis of the annual rainfall with respect to multi-annual mean between 1979 and 2003 shows a significant variability of rainfall values from one year to another, an oscillating distribution of minimum and maximum rainfall values from one year to another and declining trend in the rainfall. Spatial and temporal distribution of droughts demands comprehensive tools for analysis and drought studies. Different methods have been used for identifying temporal variability of recharge as an indicator of droughts [18, 19]. The statistical model used in this study fulfils the objective of crop land use planning that is not satisfactorily dealt with some commonly-used methodologies. The calculated values of aridity indices agreed relatively well with the actual rainfall trends during different years e.g. 1979 to 2003. When the trend in frequency and severity is known for a specific area by using time-series data and resultant aridity indices, crop planning can be done in advance as well as relevant corrective measures can also be undertaken. The application of the model proposed requires time series data of rainfall and assumes frequency distribution according to the normal distribution.

Rainfall Variability Index: The rainfall variability index (RVI) was calculated to know about the extent of variability (Figure 3). The RVI gives the normalized annual departure in rainfall and is helpful in giving the status of rainfall variation during a particular year. The RVI varied from -1.64 to 2.45 in the area of study, indicating a wide

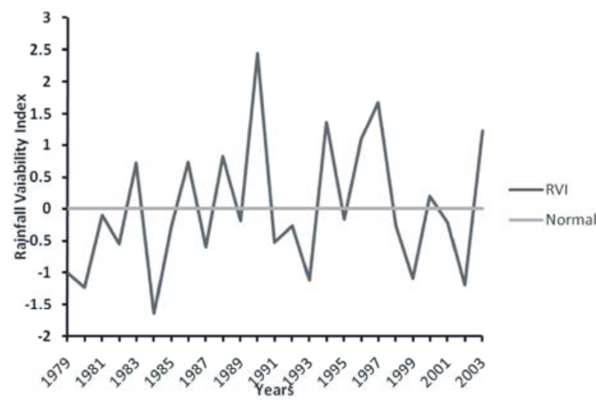

Fig. 3: Rainfall variability index in *kandi* region

departure in rainfall received over the average rainfall of the area. No particular trend in rainfall was observed with regard to deficit or surplus years. The deficit years were 1979 to 1982, 1984, 1985, 1987, 1989, 1991 to 1993, 1995, 1998, 1999, 2001 and 2002 while during all other years the rainfall was normal, that is, around average or above the average of the area. Above average rainfall was recorded for 9 years and below average for 16 years between 1979 and 2003.

The RVI is an indicator of the departure of rainfall received during a particular year from the average rainfall received over a period of time. Depending on the nature of the water deficit, drought can be classified as meteorological (precipitation scarcity) and hydrological (soil moisture, stream flow etc.). Spatial distribution of drought is a relevant characteristics for drought analysis and this demands comprehensive tools for drought studies. Meteorological drought is a creeping hydrological extreme phenomenon characterized by an appreciable below average precipitation, the magnitude of which can be assessed by its duration, deficit and impact on users.

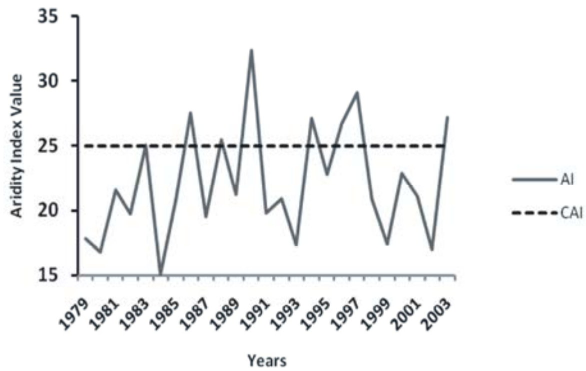

Fig. 4: Annual aridity index in the Kandi region between 1979 and 2003 (AI – Aridity Index, CAI – Critical Aridity Index)

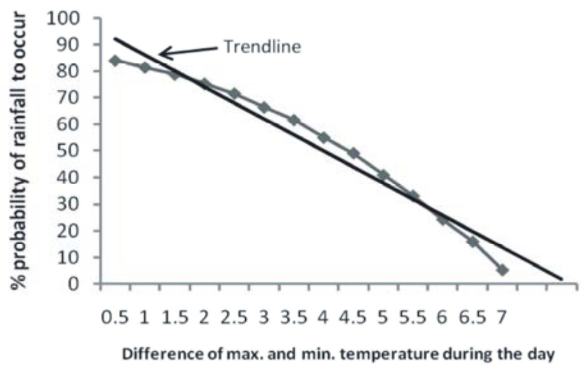

Fig. 5: Relationship between difference of max. and min. temp. during the day and probability of rainfall to occur

Aridity Indices: The aridity indices are an indicator of arid environment of a place. The aridity indices in the study area varied between 15.1 and 32.4 from 1979 to 2003, minimum being 15.1 in the year 1984 and maximum being 32.4 in 1990 (Figure 4). The drought years were; 1979 to 1982, 1984, 1985, 1987, 1989, 1991 to 1993, 1995 and 1998 to 2002. Out of 25 years, 17 years showed drought of mild to severe intensity. The drought years had significant impact on the crop productivity in the region. The productivity of wheat (un-irrigated) in Jammu region was 0.750 tonnes ha^{-1} during 1984 (aridity index, 15.1) and 1.229 tonnes ha^{-1} during 1990 (aridity index, 32.4). Since the rains remain mainly confined to July and August, which is the season for growing maize, the yield of this crop did not show significant differences. Further. Well distributed of rainfall of even low magnitude, results in better crop growth than erratic rainfall events. The aridity indices showed highly significant relationship with crop productivity ($r = 0.8712$). However, this relationship is further influenced by spatial and temporal distribution of rains, more importantly temporal distribution if we consider a particular place. The impact of the amount and intensity of rainfall on the soil erosion from the catchments has been described through mathematical model earlier by [11, 20]. This aridity indices can be applied under variable situations and periods such as monthly, quarterly or six-monthly basis. The trend of signifying the aridity in both, RVI and aridity indices, agreed relatively well.

Runoff: Rainfall intensity, duration and distribution in a watershed with given geologic and surface cover conditions will be determined the surface runoff [21]. Once a surface runoff is given, erosion rates of a watershed can be computed. A summary of rainfall-runoff models has been published [22]. However none of the models are based on a uniform approach. Some rain water goes away as surface runoff and some infiltrates into the soil zone. The soils continue to store rainwater before the runoff occurs. At this point, soil begins to drain and recharge can occur. Type and amount of distribution of rainfall, infiltration characteristics, initial soil moisture content and topography has influence on the runoff. There can be heavy runoff when the rainfall is of high intensity even for a short duration compared to the rainfall of low intensity for a longer period, even though the total rainwater received may be same in both the cases. In the former case, the rainwater does not get enough time to infiltrate into the soil.

A partial regression equation model was developed for assessing the sediment transport from river basins by Doolittle method as; sediment transport ($t\ ha^{-2}$) = (runoff as % of rainfall)^2 x 0.0452; where 0.0452 is the coefficient and runoff (as % of rainfall) = 9.293 + 0.147 x slope (%) + 0.048 x rainfall (cm) – 1.469 x vegetation (1 to 5 scale; 1 being the bare soil surface and 5, being the dense forest cover with bushes and grasses) + 0.054 x soil moisture (%) – 0.125 x soil clay (%). The model holds well under wide range of agro-climatic conditions. Interestingly, a strong relationship was observed between difference in maximum and minimum temperatures during the day and the probability of rainfall to occur (Figure 5). It was observed that minimum the temperature difference, maximum are the chances of rainfall to happen in semi-arid environment. The relationship is:

Probability of rainfall to occur(%) = 85.24-2.387x-1.289 $x^{2,}$

where; x is the difference in maximum and minimum temperature during the day. The values obtained agreed well with the real time values in the semi-arid environment. However, there may be spatial differences as, for example, nearness to the sea. There is need for further studies to refine the approach.

CONCLUSIONS

The mathematical models for aridity index, runoff and rainfall to occur, proposed in the paper, can be successfully used in semi-arid and arid areas, during different years, with a high predictability. There is need to take cognizance of many other factors than those considered in this paper. Many anthropogenic and natural factors can impact these parameters overtly or covertly. The higher runoff takes away heavy sediment load to the seasonal and perennial streams. While the rainfall is a natural phenomenon and its amount and intensity cannot be controlled, judicious management and use of rainwater is what, can effectively be done. The methodology used for regional drought characterization in this study enables a clear identification of drought areas, simulation of the spatial distribution of droughts and the associated risk of their occurrence. The future strategies must entail rainwater harvesting as an important aspect of water management in semi-arid environment. The harvested water can be used for drinking after treatment and also as life-saving irrigation during off-season at the critical stages of crop growth. A well structured institutional framework and efficient capacity building is necessary in semi-arid and arid environment to cope with known and unforeseen situations. Estimation of drought frequencies is important for efficient water management, reservoir design and management and crop planning. There is a need for a policy from government side to regulate water system covering; planning, construction and operation of hydraulic infrastructure. A few constraints may limit the applicability of the models, the prominent among these are; unprecedented climatic events, very high slope of more than 100%, runoff variability which has spatial and temporal dimensions and, anthropogenic interferences.

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