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Spatially Distributed Modeling of Runoff and Evapotranspiration Components to Estimate Groundwater Recharge under Ungauged Semi-Arid Environment

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Abstract: Spatial variation in recharge due to distributed land use, soil texture, topography, groundwater level and hydrometeorological parameters of 30 years data were used for developing runoff and recharge models. In semi-arid Kandi region, the occurrence of rainfall event was found to be related (r = 0. 9319) to difference of the mean minimum and maximum temperatures. The evaporation percentshare was 79.1, 82.1, 40.1 and 46.0 from urban, bare soil, cropped area and forest ecosystem, respectively, the rest being the transpiration. Highest average mean evaporation was 188 mm in June when mean sunshine duration was 11 hours and mean maximum temperature was 39 °C. The average annual runoff in the study catchments is 136 mm which is 16.4% of annual precipitation. Maximum mean runoff was observed to be 254 mm from urban area and minimum of 86 mm from forest and 136 mm from cropped land use. More actual evapotranspiration (AET) was found in cropped and forest land use compared to bare soil. The ground water recharge (GWR) varied from 2.5 to 14.3% with anincrease in annual rainfall from 400 to 1000 mm. Simple mathematical models were developed to estimate runoff, evapotranspiration and GWR from gauged/ungauged watersheds.

Key words: Modelling · Runoff · Evapotranspiration · Groundwater Recharge · Ungauged Watersheds · Semi-arid Environment

INTRODUCTION

Numerous methods have been developed to simulate the rainfall-runoff and groundwater recharge (GWR) processes. Selection of a suitable model for a given watershed is essential to ensure efficient planning and management of watersheds. It is quite difficult to cover vast areas with monitoring gauges. A simple mathematical model is thought to be appropriate for making quick decisions for planning and land use. Groundwater potential is directly dependent on recharge. Groundwater recharge can be defined as the entry into the saturated zone of water made available at the water-table surface [1]. It is the most important parameter for groundwater sustainability in arid and semiarid regions, because the abstraction from a groundwater reservoir should in the long term, not be larger than the long-term average recharge. Quantifying groundwater recharge is thus a prerequisite for efficient and sustainable groundwater resource management. As aquifers are depleted, recharge estimates have become more essential in determining appropriate levels of groundwater withdrawal [2]. Recharge can be estimated using a number of approaches depending on the availability of data and level of accuracy required [3-6]. However, models do not produce unique solutions, so should not be relied upon as a sole technique for estimating recharge. In arid and semiarid areas, recharge is relatively small and potentially more variable [3]. As such, the use of techniques that can handle spatial variability is necessary. A distributed water balance recharge estimation technique called WetSpass [7] has been to estimate long-term seasonal/ annual average recharge as a function of land-cover, soil type, topography and hydrometeorological factors. Evapotranspiration (ET) is the water lost to atmosphere, out of the remaining amount of rainwater, a substantial portion goes out of the catchment as runoff (RO), depending on the soil characteristics, vegetation, slope,

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geology, rainfall intensity and the infiltration rate. The rest of the water constitutes the groundwater recharge. The main objective of the study was to estimate the GWR, surface RO and ET amount in semi-arid Kandi region of Jammu, India, by simple mathematical models. Long term mean hydrometeorological data and physical characteristics of the watershed such as land use, soil type, topography, groundwater level and slope were used as an input to the models.

MATERIALS AND METHODS

Study Site: The site of study is the *Kandi* (drought prone) region of Jammu Province of Jammuand Kashmir state of India (Fig 1). The region is about 200 km in length with width varyingfrom 15 to 50 km and lying between 740 21' and 750 45' E longitude and 320 22' and 32055' N latitude. The elevation of the northern portion is about 1050m and the southern partmerge with plains with an elevation of about 300m above mean sea level. The area is mostlydenuded with sparse vegetation due to indiscriminate felling of forest vegetation. Because ofhilly terrain and undulating topography, the region is prone to heavy soil erosion. Extremewater stress is experienced during summers and winters and even water for drinking becomesscarce. Due to low rainfall, high evapotranspiration and, surface and sub-surface flows, thegroundwater recharge in the region is poor. The human use of groundwater has takenprecedence over its environmental impacts. The consequences are economic losses,environmental degradation, desertification, soil impoverishment and social disorder. There isadverse effect on water supply schemes due to reduced flow in seasonal streams and reduced aquifer recharge.

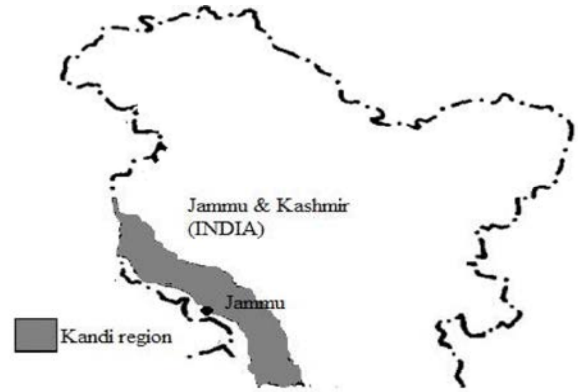

Fig. 1: Kandi region in the state of Jammu & Kashmir, India.

Model Development: A water balance model is a mathematical expression that describes the flow of water in and out of a hydrological system such as a drainage basin. Evapotranspiration is the water lost to atmosphere from the aerial surface of plants, ground and water. Out of the remaining amount of rainwater, a substantial portion goes out of the catchment as runoff, depending on the soil characteristics, vegetation, slope, geology, rainfall intensity and the infiltration rate. The rest of the water constitutes the groundwater recharge. The vegetation affects the recharge by increasing soil infiltration, reducing soil erosion, velocity of surface runoff and minimizing soil evaporation. Spatially distributed long-term averages and monthly groundwater recharge are needed as a boundary condition for non-steady groundwater models. One method of modeling groundwater recharge is by establishing a water balance of the active soil layer. Modeling of the processes of ET and vertical soil water movement can be done at different levels of complexity. The separation of runoff components is implemented in existing hydrological models. However, there is a gap between understanding of the process of RO generation and its conceptualization in hydrological models. Groundwater recharge from rainfall is determined by water balance equation;

$$GWR = (P - ET) \times (Q_b/Q_t) \quad (1)$$

where, P is the precipitation, ET is evapotranspiration. Losses by flow components are accounted for by multiplying total runoff with the proportion of base flow and total runoff (Q_b/Q_t), regionalized by a statistical model [8]. There was little variability in Q_b/Q_t ratio during the study period, indicating that it represented a stable, long-term catchment characteristic. Another method proposed is that of WetSpass methodology for estimating spatially distributed, long-term average recharge. It integrates GIS and a water balance method [7, 9, 10]. By using long-term average standard hydrometrological parameters as input, the model simulates the temporal average and spatial differences of surface runoff, actual evapotranspiration and groundwater recharge. The seasonal water balance for a vegetated fraction of a raster cell is:

$$P = I + S_V + T_V + R_V \quad (2)$$

where P is the precipitation, I the interception, Sv the surface runoff, Tv the actual transpiration and Rv the groundwater recharge in the vegetated fraction of the raster cell. The actual evapotranspiration, ETv, is the sum of Tv and the evaporation from the bare soil, Es. The total actual evapotranspiration, ETtot, is the sum of I, Tv and the evaporation from the bare soil, Es. The surface runoff, Sv, is simulated in two stages. An identical method of water balance was proposed by two researchers [11, 12]. It is based on the mass and energy conservation principle within an identified domain and specified time period. Water balance is the change in water quantity for a specific control volume over time.

$$dS/dt = \text{Inflow} - \text{Outflow} \quad (3)$$

$$\text{and } dS/dt = P - ET - Q \quad (4)$$

where d*S/dt* is the change in water recharge for a certain interval of time, *P* is precipitation, *Q* isrunoff and ET is evapotranspiration. In the present study the spatially distributed conceptual mathematical water balance model has been developed to simulate and quantify the main water budget parameters for semi-arid kandi region of Jammu. Lack of data is a major obstacle for the application of hydrological models for complex semi-arid catchments. Groundwater recharge by rainfall depends on the infiltration rate, which is either downward or lateral [13]. Under shallow groundwater levels, there is variation in natural groundwater recharge, however, under deeper groundwater levels the recharge is much greater due to the reduced ET [14]. Furthermore, because the gauged watersheds comprise only a minute fraction of the total ungauged area of the region, estimating GWR necessitates spatial extrapolation on a spatial and temporal basis. Real time series data was collected for 10 years while 30 years earlier recorded data were used for modeling. Spatially distributed long-term averages and monthly groundwater recharge are needed as a boundary condition for non-steady groundwater models. One method of modeling GWR is by establishing a water balance of the active soil layer. Modeling of the processes of ET and vertical soil water movement can be done at different levels of complexity. Since the amount of rainfall affects the RO generation process, a multiple regression equation was developed to quantify the runoff and groundwater recharge from ungauged basins. The model involves a partial regression equation of the form:

$$RO/GWR = a + b_1x_1 + b_2x_2 + b_3x_3 + b_4x_{4} + b_5x_5 \quad (5)$$

where RO is the runoff (percent of rainfall) and b_1, b_2, b_3, b_4 and b_5 are the partial regression coefficients for slope (x_1) in%, annual rainfall (x_2) in cm, vegetation cover (x_3) in 1 to 5 scale, soil moisture content (x_4) in% and soil clay content (x5) in%, respectively. The equation was developed using the Dolittle method as described by [15], which gave a reasonably high degree of accuracy in prediction or estimation of soil erosion [16] and runoff. The equation can be solved by a direct application of elementary methods involving successive elimination of the unknowns. The vegetation is the only independent variable for which the values (1–5) have to be based on visual estimates. 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%. Thirty years earlier recorded real time hydrometeorological data were used for modelling taking into account four land uses. To make it simple the equation can be written as:

$$GWR = a - b_1S + b_2P + b_3V - b_4Sm - b_5Sc \quad (6)$$

$$\text{and } RO = a + b_1S + b_2P - b_3V + b_4Sm + b_5Sc \quad (7)$$

For annual evapotranspiration the parameters needed are; precipitation, temperature, humidity, wind speed, vegetation and sunshine hours. During the study it was observed that statistically highly significant relationship of evapotranspiration was with maximum temperature and sunshine hours. It was further found that values of, sunshine hours x maximum temperature, gave highest significant relationship with the evapotranspiration of a place. These two parameters are easy to determine in ungauged places. The model is:

$$\text{Evapotranspiration (mm)} = - 415.0 + 9.820x - 0 .012x^2 \quad (8)$$

where x, is the multiplication value of average maximum temperature with sunshine hours.

RESULTS AND DISCUSSION

Hydrometeorological Parameters: The water balance of a watershed would depend on its shape, size, slope, rainfall intensity and duration, direction of wind during the storm event, vegetation cover and spatial distribution of rainfall. In semi-arid Kandi region, average annual rainfall varied from 480 to 720 mm in summer and 117 to 198 mm during winters, annual evapotranspiration varied from 1167 to 1354 mm and average temperature from 23.6

Table 1: Hydro-meteorological parameters of the study area

Season	Minimum	Maximum	Average
Rainfall (mm)			
Summer	480	720	659
Winter	117	198	156
Annual	597	918	815
ET			
Summer	669	823	798
Winter	498	614	556
Annual	1167	1437	1354
Temperature (°C)			
Summer	23.6	34.8	29.0
Winter	12.3	24.2	18.2
Annual	18.0	29.5	23.6

to 34.8 °C in summers and 12.3 to 24.2 °C during winters (Table 1). Mean monthly temperature and rainfall in the region has been represented in Fig. 2. The occurrence of rainfall event was found to be related (r = 0. 9319) to difference of the mean minimum and maximum temperatures on daily as well as monthly basis (Fig. 3). Minimum the difference in temperatures, maximum chances of rainfall to occur.

Evapotranspiration: Evapotranspiration has two components: evaporation and transpiration. Soil evaporation was highest from bare lands and lowest from urban and built-up areas. Transpiration was highest from physiognomic vegetation and lowest from urban and built-up areas. Batelaan and De Smedt [7] have also found the highest simulated recharges on bare soils. Evapotranspiration (ET) is the most important of water balance computations in a semi-arid climate [17]. It is a crucial factor between land, water surface and the atmosphere. In semi-arid regions the evaporation from the bare soil assumes a greater importance relative to transpiration from plants. This is due to the larger area of bare soil and the frequency of small rainfall events [18, 19]. A broad analysis of the ET processes and determination of spatial and temporal ET and P estimates are required to obtain reliable estimates of water balance, as the difference between P and ET defines what is left for runoff generation. It was found that land use had a significant effect on the ratio of evaporation and transpiration, which has temporal and spatial variation. The evaporation percent share was 79.1, 82.1, 40.1 and 46.0 from urban, bare soil, cropped area and forest ecosystem, respectively, the rest being the transpiration (Fig. 4). The transpiration is the most important component in water balance in cropped land use. The evaporation is higher than rainfall during all the year except in July and August when rainfall surpassed the

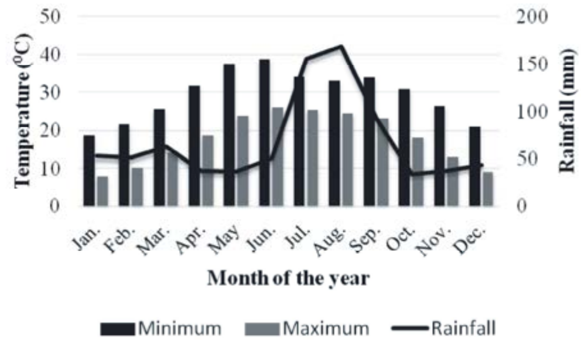

Fig. 2: Monthly minimum and maximum temperature and rainfall in Kandi region.

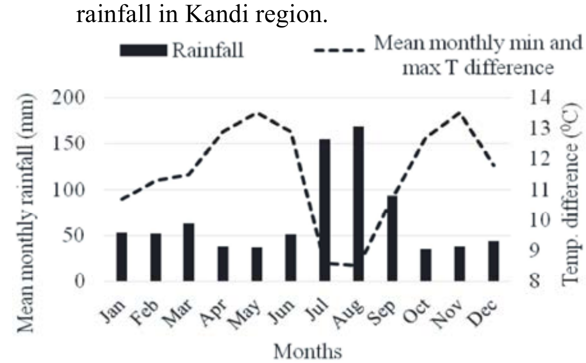

Fig. 3: Mean minimum and maximum temperature difference and the amount of rainfall.

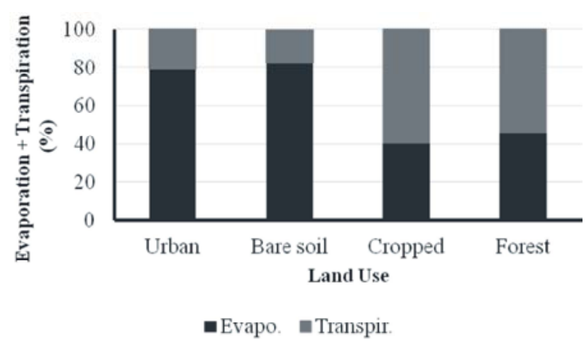

Fig. 4: Share of evaporation and transpiration under different land uses.

evaporation. This is the only period when recharge can occur in Kandi region, provided proper conditions are in place for maximum possible recharge. There was significant relationship between mean maximum temperature and evaporation (r = 0. 8115), sunshine hours and evaporation (r = 0.7406), sunshine hours x maximum temperature and evaporation (r = 0.8185). But no particular trend was observed between rainfall and evaporation because of the fact that this effect is modified by the temperature and sunshine duration in semi-arid and arid regions. During the rainy season, it is generally cloudy with reduced sunshine duration and, so, the evaporation and transpiration is relatively low, though the rain water

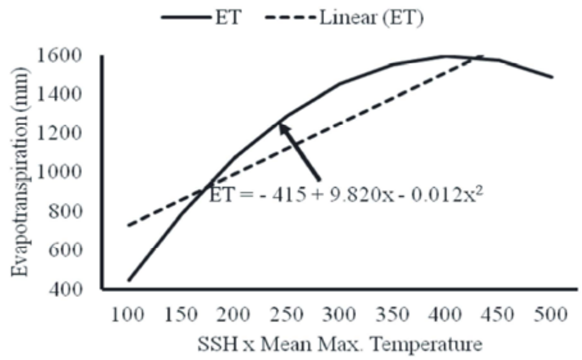

Fig. 5: Combined effect of Sunshine hours (SSH) and maximum temperature on evapotranspiration.

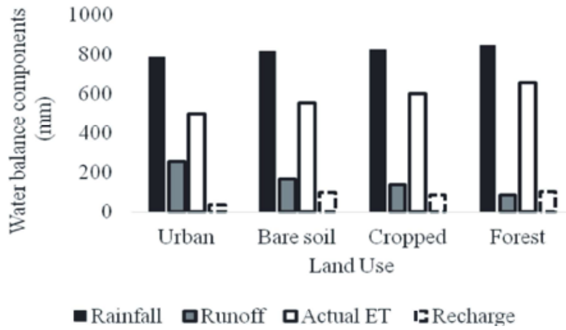

Fig. 6: Runoff, actual ET and recharge under different land uses in study area.

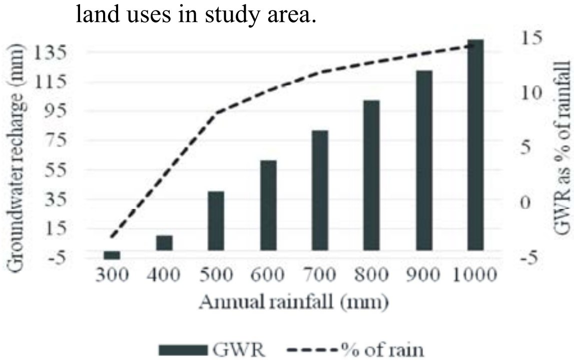

Fig. 7: Impact of annual rainfall on GWR as per cent of rainfall.

received is more. In semi-arid kandi region, the evaporation varied from 68 mm in November to 188 mm in June when the maximum temperature goes up to 45°C (Fig. 5). Highest average mean evaporation was 188 mm in June when mean sunshine duration was 11 hours and mean maximum temperature was 39°C. The model developed is; ET(mm) = - 415 + 9.820x -0.012x^2, where x is the multiplication value of monthly mean maximum temperature and sunshine duration in hours.

Estimation of evapotranspiration provides a better understanding of the relationships between water balance and climate. In semi-arid regions actual evapotranspiration (AET) is a key component in the hydrological cycle and may account for more than 90% of precipitation [17, 19]. Actual evapotranspiration is one components of water balance to determine groundwater recharge of Kandi region. In Kandi region, the evapotranspiration is higher than the rainfall during most part of the year. However, during the months of July and August, mean evapotranpiration is 62.6% of the rainfall. During these two months, recharge can be expected.

Runoff: Runoff is a unique hydrological variable and the last outcome of a large number of flow processes both vertical and horizontal within the entire catchment. To estimate the surface runoff trends in Kandi region, runoff coefficients were used, which varied its values depending on vegetation type, soil type and slope. The rainfall exceeds the infiltration capacity of the soil during the rainy season. This leads to high surface runoff. The runoff coefficient, defined as the portion of rainfall that becomes direct runoff during an event [20], is a key concept in engineering hydrology and is widely used for design and as a diagnostic variable to represent runoff generation.

Rainfall intensity, duration and distribution in a watershed werefound to be effective in runoff generation. The average annual runoff in the study catchment is 136 mm which is 16.4% of annual precipitation. The highest runoff rate occurs from urban and built-up areas because of impervious surfaces in this land-use class, followed by cultivated lands. Maximum mean runoff was observed to be 254 mm from urban area and minimum of 86 mm from forest and 136 mm from cropped land use (Fig. 6). More actual evapotranspiration (AET) was found in cropped and forest land use compared to bare soil. Equation 7 will serve as a simple mathematical model in determining runoff as per cent of rainfall in semi-arid regions. The coefficient values for b1 (slope%), b2 (rainfall in mm), b3 (vegetation in 1 to 5 scale), b4 (soil moisture%) and b5 (soil clay%) in calculating runoff in semi-arid regions based on 30 years of data were; 0.147, 0.048, 1.469. 0.054 and 0.125, respectively.

Groundwater Recharge: Regional groundwater models used for analyzing groundwater systems are often in quasi-steady state and, therefore, need long-term average recharge input [21]. Groundwater recharge was affected by the amount and intensity of rainfall (Fig 7). The GWR varied from 2.5% to 14.3% with increase in annual rainfall from 400 to 1000 mm. However, during a heavier single rainfall event in semi-arid Kandi region, the GWR recharge

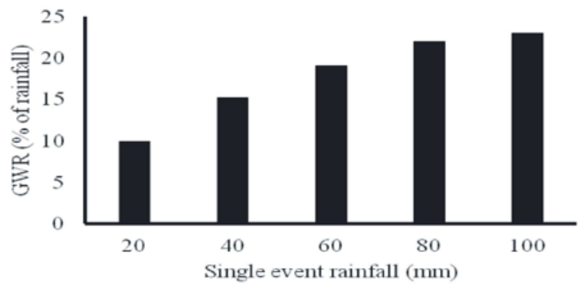

Fig. 8: GWR as per cent of single event of rainfall.

was 9.9% and 23.0% with the rainfall of 20 mm and 100 mm respectively (Fig. 8). In a semi-arid environment, groundwater is the only water resource that is available throughout the year and is crucial for catchments water balance estimation and sustainable management. The estimation of runoff is difficult in semi-arid regions where recharge may be as low as 1% of the precipitation [18, 22]. Here, ET captures most of the water entering the soil and recharge occurs only during extreme rainfall events [19]. Percolation out of the soil takes place before the actual soil water content reaches its maximum value, accounting for macropore flow and in the case of spatial application, for soil heterogeneity [23]. Equation 6 will serve as a simple mathematical model in determining GWR in semi-arid regions. The coefficient values for b1 (slope%), b2 (rainfall in mm), b3 (vegetation in 1 to 5 scale), b4 (soil moisture%) and b5 (soil clay%) in calculating GWR in semi-arid regions based on 30 years of data were; 2.234, 0.206, 4.332. 1.032 and 0.965, respectively.

CONCLUSIONS

A water balance of a semiarid region groundwater system in Kandi region of Jammu, Jammu and Kashmir state of India, was determined using hydrometeorological parameters of 30 years data. The objective was to develop simple mathematical models to estimate runoff, evapotranspiration and groundwater recharge in semi-arid regions. Use was made of the available field data and GIS technology to determine the seasonal and annual runoff, actual evapotranspiration and recharge. It was found that the mean annual rainfall could be apportioned as: 79% evapotranspiration, 14% runoff and 7% recharge. The uneven distributions of the hydrometerological parameters, associated with variations of land-use/land-cover, soil type, topography and slope are responsible for variations of the water balance element within the catchment.

It is very difficult to determine evaporation, runoff and GWR in ungauged watersheds in semi-arid and arid regions. The mathematical methods developed have been found quite accurate and useful in estimation of wide range of hydrometeorological situations. These models require minimum data to simulate the results from gauged watersheds.

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