ABSTRACT

Study of climate variability and human-induced land use change in hydrology is important for proper understanding of groundwater resources. Spatial and temporal changes in hydraulic head in an aquifer and associated water balances are influenced by both anthropogenic and natural factors which include influences by climate, physical characteristics of the catchment and human activities, especially pumping. Groundwater resources in general are related to climate through hydrologic processes, such as precipitation and evapotranspiration, and through interaction with surface water. Variability in rainfall and groundwater pumping brings in additional complexity in the groundwater dynamics. Decreased rainfall in a time period coupled with anthropogenic processes such as groundwater pumping could worsen the situation in a groundwater system resulting in declining groundwater levels.

The impact of precipitation variability and anthropogenic changes on groundwater levels can be investigated by analyzing the relationship between historical precipitation records and groundwater level fluctuations. This investigation would benefit in understanding the potential future changes in groundwater availability in the backdrop of variability in precipitation and ever increasing anthropogenic thrust. However, it is not clear whether this inter-annual variability in rainfall is carried to groundwater levels observed in semi-arid regions, and the regions being under appreciable groundwater pumping.

In this context, the main objective of this work is to define and apply a framework to study the spatiotemporal variability in groundwater system and the precipitation over long periods of time and large areas, and to estimate the groundwater balance components in semi arid hard rock aquifers. The framework adopts statistical methods to characterize spatiotemporal variability in the groundwater levels and rainfall, and understand the extent of influence of rainfall on groundwater levels under the effect of pumping. Further, the framework includes development and application of a groundwater model applicable over spatially varying scales to estimate the groundwater balance components over long spans of time.

Abstract

To study the main characteristics of spatial and temporal variability in groundwater levels and rainfall, Empirical Orthogonal Function (EOF) analysis has been used. The EOF analysis is a method to determine the main spatial and temporal patterns of variables along with a measure of the significance of each pattern. Further this can also be used to delineate homogeneous groups of stations based on the controlling parameters.

The EOF analysis is applied to monthly rainfall and monthly groundwater levels in the period 1976-2006 in the Kabini river basin. The data pertains to 31 IMD grid points, 46 rain gauge stations and 65 groundwater observation wells. The monthly rainfall series as well as a cumulative rainfall departure (CRD) series are analyzed. Similarly, monthly groundwater storage change as well as monthly groundwater levels are used.

It is observed from the analysis carried out in this work, that the humid and the sub-humid regions follow different rainfall patterns. In the Kabini river basin the rainfall shows mono-modal to weak bimodal and strong bimodal seasonal cycles. The rain gauge stations with these patterns are delineated using EOF analysis. Long term trends in groundwater levels are found to follow the long term trends of CRD, especially in the early years when the pumping was insignificant. While, in the later years, the correlation between them reduces due to the effects of pumping.

EOF analysis is able to delineate groups of stations groundwater levels based on intensity of pumping in the period post 1990. Two main groups are observed due to the effects of groundwater pumping in the basin. The first group is stations located close to streams and canal network where the groundwater levels are found to monotonically rise in the recent years. The second group comprises of wells away from the stream and canal system, which are located in groundwater pumping regions. Further, the EOF analysis with storage changes provides the spatial variations in the intra year groundwater dynamics and helps to classify the wells into two groups where one group is influenced by the mono-modal pattern of rainfall and the other by the bimodal pattern of rainfall.

Abstract

Joint EOF analysis of groundwater levels and CRD series is performed to characterize groups of stations with groundwater levels trends similar to that of the rainfall. The groups of wells and rain gauge stations with the similar long term trends in rainfall and groundwater level are separated. Another group of stations is also identified where the long term trends in groundwater levels are dissimilar to that in rainfall. This group corresponds mainly to the locations affected by pumping.

Presence or absence of long term trend and periodicities across the variables, say groundwater levels and rainfall, further shows the influence of one system over the other and the extent to which a signal in one is carried to the other. Identification of long term trends is facilitated by Singular Spectrum Analysis (SSA) which decomposes an original time series into the sum of a small number of independent and interpretable components such as a slowly varying trend, oscillatory components and a structure less noise. The periodicities are estimated using Lomb-Scargle method. To analyze periodicities in groundwater or rainfall time series in a region with large number of observation stations, an unique approach is adopted. The SSA along with Lomb-Scargle method is applied to the dominant temporal modes arising out of the EOF analysis to estimate the periodicities.

Spectral analysis on the dominant temporal modes arising from the EOF analysis of the cumulative rainfall departure series is performed. It is observed that some periodicities are common among the first two dominant modes. The first mode representing rainfall of one group has 4.3 years, 6.6 years and 9.3 years as significant periodicities. The second mode representing the other dominant rainfall group has 5.1 years, 6.3 years and 8.6 years as the significant periodicities. Spectral analysis on the temporal modes obtained from the EOF analysis groundwater level series is performed and the significant periodicity of 5.2 years is common among the dominant modes and 6.5 year periodicity is observed in the first mode, which corresponds to stations near to the streams and canals. This periodicity is not clearly present in the other group where the pumping effects are dominant.

Abstract

The temporal modes arising on EOF analysis of the joint series of rainfall (CRD) and groundwater levels when subjected to spectral analysis show that 4.3 years and 6.3 years are the significant periodicities which is in agreement with the periodicities found in the individual rainfall and groundwater series. When dominant temporal modes obtained by EOF analysis of the monthly stream flow from four gauging stations is subjected to spectral analysis, it is observed that the first mode (90%EV) has significant periodicity of 6.5 years. Spectral analysis made directly on the stream flow of Kabini river also shows a similar spectrum as that of the first temporal mode from the EOF.

SSA also provides the information of time lag between rainfall and the groundwater levels. This is analyzed for stations located in semi-arid zone and having long term rainfall variability along with groundwater pumping effects. It is observed that there is time lag between rainfall and groundwater level rise of ~1.5 months, which is sensitive to the depth of groundwater level.

To study the groundwater variability caused by precipitation variability and other basin developments should consider long periods, preferably running into decades, in order to capture multi-decadal variability of climate and groundwater system. Lumped models are found to be better suited for assessing the groundwater balance components over decadal scales. However, when modeling such long periods, the depth to the groundwater table across years can change over tens of meters, which require considering the effects of specific yield variations with depth due to the presence of stratification. This is especially the case when dealing with hard rock aquifers. A CRD method based lumped groundwater balance model is developed to estimate the groundwater balance components (e.g. rainfall recharge, groundwater underflow) due to inter-annual variations in rainfall and groundwater pumping. This model in addition to the estimation of specific yield also considers its variation over depth.

The performance of the groundwater model is tested on nested catchments of Terakanambi watershed, Gundlupet catchment, Gundal river sub basin and Kabini river basin with spatial scale varying by two orders of magnitude and during 1976-2006. These areas are characterized with appreciable pumping affecting the systems from ~1990 onwards. A multi-objective parameter optimization which considers the groundwater levels and groundwater underflow is used for estimating the recharge parameter. For all the cases, the model is calibrated using the earlier years with negligible or no pumping in them and applied to simulate the groundwater levels for years in which pumping is appreciable (period post 1990). It is observed that in all the cases this calibrated model is unable to capture the observed groundwater levels in the pumping years which suggests that the pumping is significant in the pumping years and requires that its effects be included in the model for the pumping period. The model also assists in developing the relations for groundwater discharge and specific yield as functions of depth to groundwater table.

The model is further used in all the cases with due consideration now being given in the model to take care of the effect of pumping in the years post 1990 when pumping is appreciable. The model for each of the cases estimates recharge factor through which the recharge is calculated and moreover, the model simulates the series of groundwater discharge (underflow) and pumping values. Recharge factor is found to vary from 5.33 % to 9.4%. Similarly, groundwater underflow discharge is observed to be as much as ~80 mm/year at very shallow depth to groundwater table to ~20mm/year at larger depths (40-50m) to groundwater table. It is observed that with this approach, not only are the observed levels captured by the model but also the annual pumping values are estimated which are in reasonable agreement with the field observed pumping values.

As a result of the modeling, relationships of recharge with rainfall and groundwater underflow with depth to groundwater table remain estimated. These relationships are put to use at a microscale level in the smaller parcels (e.g. villages) of a watershed for computing groundwater balance components and groundwater storage change in a year. Further, an alternative model is also introduced and applied to the watershed to compare its performance with the other model.