EOF and SSA analyses of hydrological time series to assess climatic variability and land-use effects: a case study in the Kabini River basin of South India

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Abstract In the last two decades, significant changes have taken place in the semi-arid areas of the Kabini River basin (an area of 10 000 km² and a sub-basin of Cauvery River basin) in the south of India on the use of groundwater for irrigation. Depletion of water tables due to over-extraction of groundwater has become a critical issue in some parts of these areas. However, the impacts are found to be non-uniform across the region due to the heterogeneity in terms of aquifer characteristics of the hard-rock system, spatio-temporal pumping patterns of micro-scale land parcels, variations in the soil types and in addition the spatial variability of the recharge. Empirical orthogonal functions (EOF) have been applied to analyse the spatial and temporal signatures of the behaviour of the rainfall and the groundwater in 66 piezometers monitored during the last three decades in the semi-arid zone of the Kabini River basin. The approach helped in delineating the non-uniform spatial clusters in the groundwater system resulting due to the various factors discussed above. Singular spectrum analysis was applied to study the rainfall, streamflows and groundwater levels in the system to comprehensively analyse the climatic and anthropogenic effects on the regional system. The respective roles of climatic and land use changes on the groundwater recharge and discharge components are simulated using the CRD model, which illustrates its utility for the sustainable development of the groundwater system under a changing hydro-climatic scenario.

Key words time series; EOF; SSA; groundwater; CRD model; climatic variability; land use changes

INTRODUCTION
The spatio-temporal trends of groundwater dynamics in a catchment are often controlled by complex processes influenced by climate, physical characteristics of the catchment, and human activities (Winter, 2001). Study of climate variability and human-induced land use change on hydrology and water resources has become an important area of research in hydrology (Scanlon et al., 2007). The groundwater reservoir dynamics can be influenced both by long and short time scales associated with decadal variations in rainfall/climatic changes and droughts, as well as extreme events. In addition, they are influenced on a large scale associated with the size and the shape of the catchments and at short scale due to the erratic distribution of rainfall. On a large scale, groundwater reservoir storage will depend on the inter-annual and seasonal precipitation, evaporation, vegetation cover and possibly on the pumping. At smaller scale, geomorphological controls and interactions between aquifers may also play a role. Several analytical techniques have been reported to investigate the sensitivity of aquifer water levels to climate variability. Using the crossing theory approach, Eltahir & Yeh (1999) assessed the asymmetric response of aquifer water level to floods and droughts. They reported that the drought left a significantly more persistent signature in the aquifer water level than the corresponding signature of the flood. To examine the relative importance of climate on groundwater level variation, Chen et al. (2004) used cross-correlation analysis between historical climate records and groundwater levels. Their results showed that the annual precipitation significantly explained the variations in groundwater levels. In another study, water levels with multiple periodic components that are correlated to El Ninô-Southern Oscillation, variations in monsoonal precipitation, and Pacific Decadal Oscillation (Venencio & Garcia, 1999) have been identified in unconfined aquifers using spectral methods. The reconstructed cyclical components estimated by spectral frequency analysis have been used to infer time-varying climate controls on groundwater recharge. Regional impacts of climate variations on groundwater dynamics vary from place to place. Further, the human-induced land-
use changes may induce specific spatial patterns in the catchment, which are reflected in the
recorded groundwater dynamics. By using principal component analysis as a tool, Winter et al. (2000) were able to relate typical hydrograph features either to groundwater recharge characteristics or to the effect of difference in geological properties. Recently, Luque-Espinar et al. (2008) performed spectral analysis on hydraulic heads across a Spanish aquifer and studied the influence of climatological cycles and their spatial variations across the aquifer. The impact of land use/land cover (LU/LC) changes in certain settings is found to be much stronger than the climate variability and hence there is a need to characterize dominant patterns of climate and land use controls on the groundwater system for developing sustainable groundwater resource programs (Scanlon, 2006). Recently Ma et al. (2008) evaluated the impacts of climate variability and human activities on changes in mean annual streamflow based on precipitation and potential evapotranspiration in catchments in the Shiyang River basin in the arid region of northwest China.

Several regions in India are experiencing rapid development and population increase, and the demand on groundwater for water supply has grown considerably during the last decade, and will continue to grow further. Also during the past few years, India has experienced extreme weather events such as droughts, floods, and cyclones more frequently. To examine the spatial trends in groundwater level variation, Panda et al. (2007) used Mann-Kendall non-parametric trend analysis of groundwater levels over a 10-year period (1994–2003) in the state of Orissa to characterize regions undergoing groundwater declines, in spite of recharge occurring after the post-monsoon season, and attributed to anthropogenic pressures. However, their study does not determine whether drought, high temperatures or anthropogenic effects have had the largest influence on the groundwater levels decline. They suggest the need to establish relationships between the groundwater dynamics of the areas having a similar spatial pattern of significant trends and the weather variables. Hence, there is a need to examine the general trends of local climate variation and analyse the relationship between these trends and groundwater level fluctuations. In particular, a method is needed to identify distinct underlying patterns of spatial variations groundwater dynamics and their linkage to climatic variations in a way that accounts for these patterns and their temporal evolution. Further, groundwater models are often used with spatial and time varying/long-term average recharge rates in transient simulations to assess the limits of sustainability in developed aquifers. However, these groundwater flow models are very sensitive to recharge rates, which are difficult to quantify (Lerner et al., 1990). Therefore, understanding the temporal variability of inflows and outflows due to climatic variability plays an important role and improves the simulations for groundwater systems that are in overdraft conditions (Dickinson et al., 2004). Similarly, the transformation of droughts as a result of the propagation through groundwater systems is another important subject and was examined by comparing droughts in time series of groundwater recharge, levels and discharge by Peters et al. (2006).

In this paper, we propose Empirical Orthogonal Function (EOF) analysis as an effective way to characterize the groundwater dynamics of areas with similar spatial pattern and their relationship to annual and decadal variations in climate along with temporal evolution of land use controls. Further, Singular Spectrum Analysis (SSA) is applied to study the rainfall, streamflows and groundwater levels to analyse the long-term climatic dynamics of the system and to capture the relative impacts of anthropogenic effects. EOF and SSA analyses are commonly used in the meteorological field to characterize spatio-temporal variables (Preisendorfer, 1988; Ghil et al., 2002). In this study, we investigate the changes in the Kabini River basin in South India. The objective of the study is to: (1) determine spatio-temporal trends in monthly groundwater levels in this region, and (2) estimate the effects of climate variability and human activities on groundwater levels and to model the groundwater dynamics (e.g. recharge and discharge components).

STUDY AREA

The Kabini River basin comprises of the climatic and the geomorphological gradient forming on the edge of the rifted continental passive margin of the Karnataka Plateau in Peninsular India
EOF and SSA analyses of hydrological time series to assess climatic variability and land use effects

This plateau developed on the high-grade metamorphic silicate rocks of the West Dharwar craton. The west–east geomorphologic gradient is associated with a climatic gradient induced by the Western Ghâts, which form a barrier to the monsoon winds coming from the Indian Ocean and moving northeast. A steep decline of the mean annual rainfall is recorded along the inland region, from 5000 mm/year to 700 mm/year (Pascal, 1982). The dynamics of the southwestern monsoon exhibits a rapid change in the spatio-temporal pattern of the precipitation in the region (Fig. 1(a)). The Kabini basin is characterized by humid, sub-humid and semi-arid regions. The rainfall patterns also experience climatic trends as well as a strong inter-annual variability like the extreme 1990 (Parthasarathy et al., 1994) and 2002 droughts. A mono-modal rainfall distribution is associated with the humid zone in the southwest quadrant of the map, changing to a bi-modal distribution at the transition corridor, which persists to the eastern part of the basin. This gradient is steep, with yearly rainfall averages of 2500 mm and 700 mm recorded over the stations, separated by a distance of 100 km. The lithology, representative of the West Dharwar craton (Naqvi & Rogers, 1987), is dominated by complexly folded, heterogeneous Precambrian peninsular gneiss intermingled with mafic and ultramafic rocks of the volcano-sedimentary Sargur series. The humid zone is formed by thick laterites and in the semi-arid zone fractured granitic gneiss forms the geology of the region, with a system of 0.5–1.5 km long and 5–15 m width dykes dominantly oriented east–west (Sekhar et al., 2004). The soil distribution in the semi-arid areas are formed by gneissic saprolite, cohesive to loose sandy, which crops out both in the streambed and at the mid-slopes (Barbiéro et al., 2007). The lower part of the slope and the flat valley bottoms are covered by black soils (Vertisols and Vertic intergrades), which are 2 m deep on average. Shallow red soils (Ferralsols and Chromic Luvisols), which are 1–2 m deep, cover the upper slopes. Groundwater reservoirs are ubiquitous in the Kabini basin. The groundwater enters complex interactions with surface water flows that were studied and modelled (Sekhar et al., 2004, 2006). However, the observed groundwater level (hereafter GWL) fluctuations might not only reflect an influence of the rainfall space–time distribution patterns, but also interactions with surface waters and land use (Panda et al., 2007).

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**Fig. 1** The Kabini River basin. (a) Spatial variation of annual rainfall, (b) two administrative districts in the Karnataka state in the basin (dots show GW monitoring stations).

**Groundwater development in Mysore and Chamarajanagar districts of Karnataka state**

The sub-humid and semi-arid zones in the Kabini River basin form the two administrative districts (Mysore and Chamarajanagar) in Karnataka state (Fig. 1(b)) and the landscape in this region is composed of shallow regolith and outcropping tors/inselbergs. Two major dams exist on the Cauvery and Kabini rivers, which irrigate large areas, especially in the Mysore district (a total geographical area of 6577 km²) in the region between these two rivers. The south part of the Kabini River system in the Chamarajanagar district (a total geographical area of 5686 km²) is relatively lower irrigation from surface water systems and comprises of about 22 000 irrigation...
wells based on the census prepared by the Department of Minor Irrigation, Karnataka state in 2005. Conspicuous changes in the agriculture have occurred in the semi-arid zone of the Kabini basin, moving from an agriculturally low water consuming rainfed crops (sorghum and millet), to intensive agriculture (with double cropping), highly dependent on irrigation resulting in higher water demand and consumption. Large areas in the uplands in the districts of the lower Kabini River basin (located in Karnataka state) are under groundwater irrigation (Fig. 2(a)). Currently, groundwater is extensively used for perennial crops such as sugarcane and banana. The irrigation by canals, tanks, and groundwater (bore and dug wells) in the various taluks of Chamarajanagar and Mysore district, which are in the semi-arid region of the basin are shown (Fig. 2(b)). The canal network arising from the Kabini, Nugu and KRS dams provide irrigation in large areas in the taluks of Mysore district and crops, such as paddy and sugarcane, are grown in these commands. However, in the Chamarajanagar district groundwater forms the main source of irrigation. Perennial crops have a high percentage in taluks, having canal and tank irrigation in Mysore district. In the taluks of Chamarajanagar, Kharif crop (monsoon crop) is the main crop and also interestingly groundwater irrigation is mainly used for Kharif crops with certain areas having perennial crops and plantations. The growth of bore wells between 1992 and 2002 is approx. 3 times in Chamarajanagar district, while in the Mysore district is about 5–6 times. However, the density of bore wells in Chamarajanagar is higher. The growth of wells in the various taluks (e.g. in the Mysore district) during the last 15 years show a monotonic rise (Fig. 3(a)). The typical land-use land cover details pertaining to a sub-basin (e.g. Gundal sub-basin of approx. 1000 km²) located in the Mysore and Chamarajanagar districts is shown in Fig. 3(b). The land use map was obtained for the year 2002 using multi-season imagery of IRS 1C (LISS III sensor). The vegetation in Gundal sub-basin is characterized by agriculture activity. Traditionally, crops are grown during Kharif (southwest monsoon: June–October) and rabi (dry: November–February) seasons. Main traditional crops in Kharif season are finger millet and pulses, whereas paddy is grown in the command areas of tanks and canal command areas (northern part of the sub-basin). Kabini and Nugu canal commands provide irrigation requirements in the discharge area of the sub-basin. Since the last two decades, the major source of water for irrigation in the rest of the sub-basin is groundwater, allowing double crop cultivation. As a result of increased irrigation by bore wells, irrigated crops like sugarcane and cash crops replace traditional rainfed crops. It may be observed from Fig. 3(b) that substantial double crop areas (Kharif and Rabi) exist, not only in the discharge zone, but also in the recharge areas of the sub-basin. The double crop areas in the recharge zone are managed by groundwater pumping. It may be noted that sustained pumping for both Kharif and Rabi crops in these areas are possible due to the good yields in these areas, which are correlated to the presence of several lineaments and structural control of groundwater in these parts.

Fig. 2 The groundwater development in the two districts. (a) Mode of irrigation (numbers show total cropped area (in ha) and irrigated area respectively). (b) Type of crop irrigated (numbers show dug and bore wells in 2001 and also the increase between 1995 and 2001).
Groundwater level dynamics in Mysore and Chamarajanagar districts

Figure 4(a) shows the time series of spatial mean monthly groundwater levels in these two districts during 1977–2007. This is obtained using 66 selected groundwater stations monitored by the Department of Mines and Geology, Karnataka State. The spatial distribution of these stations is shown in Fig. 1. The series shows strong effects of all the India extreme droughts of 1990 and 2002 on the groundwater system. The groundwater levels decline monotonically during the drought period of 1984–1990 (droughts recorded at the all-India scale are 1982, 1985, 1986, 1987 based on Parthasarathy et al., 1994). However, the mean level reset back to normal due to higher rainfall in the period 1991–1994. Further, during the drought period of 2002–2004, the groundwater levels decline more sharply than that exhibited during the much longer drought period of 1984–1990, indicating a strong anthropogenic forcing on the groundwater system. The higher rainfall in the period 2006–2007 helps to reset back the groundwater levels, but they exhibit large intra-annual fluctuations. The mean groundwater level clearly shows that the intra-annual
fluctuations due to recharge from the Indian monsoon rainfall, and interestingly the amplitude of these fluctuations are found to be higher after 1994. The monthly rises and falls of the spatial mean groundwater levels (Fig. 4(b)) clearly shows the distinct recharge and discharge periods pertaining to the monsoon and non-monsoon period, respectively. The rise and fall in these recharge and discharge periods during the later years of 1994–2006 show trends of higher amplitudes. The higher falls may pertain to the effects of groundwater pumping, while the higher rises are hypothesized to be effects of induced recharge (Alley et al., 2002).

Fig. 4 Groundwater dynamics (a) spatial mean monthly levels, (b) monthly water level changes.

(a) 
(b) 

Fig. 5 EOF analysis of cumulative rainfall (monthly) departure: (a) first mode, (b) second mode.

RESULTS

EOF analysis of rainfall and groundwater level data

EOF is now a classical approach in geophysics that has already been used in several contexts such as Sahelian vegetation (Jarlan et al., 2005), soil moisture (Jawson & Niemann, 2006) or oceanography (Cazenave et al., 2001). Basically, EOF allows for rewriting a system of time series as a sum of modes. The rainfall and the GWL data sets used here are with a monthly sampling frequency. Before proceeding to the statistical analysis of the data set, we apply the following pre-processing to the raw data. Each time series is centred (removal of the time average). The centred rainfall data are then transformed into cumulative rainfall departures (hereafter CRD; Bredenkamp et al., 1995; Xu & van Tonder, 2001). The EOF analysis is performed with an algorithm developed by Toumazou & Créteaux (2001) that relies on a fast and robust decomposition with a Lanczos eigensolver. The accuracy of the decomposition into modes is ensured to the level of the computer accuracy.

The CRD data built using four series of the grid averaged (1° long. × 1° lat.) rainfall (1951–2004) provided by the Indian Meteorological Department for this region was used. Most of their signal variances are explained by the first two modes, which show decadal patterns (Fig. 5) and longer climatic cycle of 20 years (e.g. 1959–1979). Tiwari & Rao (2004) observed statistically significant signals indicating 22-year cycles (Solar cycles) when analysing the rainfall of all of India. The first two EOF modes explain 51.5% (n = 1) and 35.0% (n = 2) for CRD data set variance. The first mode (Fig. 5(a)) presents the cycles of rainfall patterns in the semi-arid region while the second mode (Fig. 5(b)) presents the humid region. The modes capture the intra-annual
behaviour of mono-modal rainfall in the humid zone (mode 2) and the bi-modal rainfall in the semi-arid zone (mode 1).

The GWL data built using 66 piezometers data (1976–2004) in the semi-arid region provided by the Department of Mines and Geology of Karnataka state was used. The first two time modes capturing the groundwater dynamics are shown in Fig. 6. The first time mode (Fig. 6(a)) explained by 24% EV (explained variance) shows that there is no trend during the low rainfall period of 1980–1990, while an increasing trend is shown during 1990–2004. The second time mode (Fig. 6(b)) on the other hand explained by 23% EV captures the dominant patterns of the CRD during this period. The first and second spatial modes are shown in Fig. 7. The first spatial mode (Fig. 7(a)) shows a coherent pattern of GWLs capturing the first time mode as indicated by the grey dots with the explained variance at each location by the size of the dot and using the classification in the legend. The piezometers located along the river and canal regions (Fig. 7(a)) show the prominent grey dots. The second spatial mode (Fig. 7(b)) shows the pattern of GWLs captured by the second time mode and indicated by the size of dots. The piezometers located away from the river and canal system and in the upland regions capture these patterns of the dominant climatic signals. The upland region between Cauvery and Kabini rivers and the upland region to the south of Kabini basin has these patterns.

**Fig. 6** EOF analysis of groundwater levels (a) first mode (b) second mode. The numbers inside indicate explained variance.

**Fig. 7** Contributions to the EOF modes of groundwater levels (a) first mode (b) second mode. The numbers adjacent to the dots indicate explained variance.

**SSA of rainfall, streamflow and groundwater level data**

The singular spectrum analysis is performed on the monthly data sets of rainfall, streamflow and groundwater levels in the Kabini River basin to capture the long term trends. Figure 8 shows the results of the analysis. The left panel shows the temporal trends and right panel shows the spatial location of the measurement stations on the classified remote sensing image (IRS-1C). The darker
colour region forms the humid zone while the grey region forms the semi-arid zone of the Kabini river basin. The decadal patterns of rainfall are shown in Fig. 8(b) (gridded data # 1) and Fig. 8(c) (station data in the humid zone #2) with two dominant cycles. The first cycle (1977–1990) has much stronger positive anomaly than the second cycle (1991–2003). The Fig. 8(d) and (e) shows the patterns in the streamflows at Kabini dam (#3) and at a station (#4) to the far-east after the confluence of Cauvery and Kabini rivers. The rainfall cycles are captured by the streamflows as well. However, the streamflows in the semi-arid zone (#4) show that the second rainfall cycle (1991–2003) hardly has a positive anomaly. This illustrates the effect of land-use changes and impact of groundwater abstraction in the later years on the stream system. The trends of the spatial mean groundwater levels of the Gundal sub-basin are shown in Fig. 8(f) while the station data (#6) are shown in Fig. 8(g). The Gundal sub-basin represents the semi-arid zone of the Kabini River basin also forms the southern part of the basin where the groundwater abstraction is dominant and also the region which captured climatic signals in the groundwater (based on the earlier EOF analyses). The regional groundwater dynamics follow the climatic trend during 1980–1990, while during 1991–2003 they show a weak correlation with the inter-year variations in the rainfall.

**Groundwater modelling for assessing the climatic and land use effects**

The groundwater dynamics of the Gundal sub-basin are modelled using the CRD model (Xu & Beekman, 2003). As discussed earlier, Gundal sub-basin is illustrated here as it is located in the southern part of the Kabini River basin and in the semi-arid zone where groundwater abstractions
are higher and is also the upland region away from the main Kabini River and canal system. The spatial monthly mean of cumulative rainfall and groundwater levels are shown for this sub-basin in Fig. 9(a). The groundwater dynamics are very similar to the rainfall patterns capturing the long term cycles. The CRD model is calibrated during the period of 1979–1990 (Fig. 9(b)) for the groundwater recharge and discharge parameters. Using these parameters, the model is used in the simulation framework during 1991–2007 using the rainfall. The groundwater level simulations capture the measured patterns but fail to match the levels during 1997–2007. Clearly not considering the effect of pumping, shows a poor model response in the later period. In the next step, the model is simulated by choosing suitable pumping such that a good performance between simulations and measurements result during 1997–2007 (Fig. 9(c)). The pumping simulated using the model is compared with the field estimates obtained based on the crop statistics, number of wells operating, the yields and the number of hours of pumping (Fig. 9(d)). These estimates are made at each of the villages in the sub-basin and aggregated for comparison with the model simulations at the regional scale. The CRD model used here not only provides the recharge, but also the groundwater discharge. The temporal variations of annual groundwater balances simulated using the model are shown in Fig. 9(e). During the period 1979–1990, the imbalances of annual groundwater recharge and discharge result in the groundwater storage changes. In the later periods the groundwater discharge plus the pumping are balanced by recharge. The groundwater discharge during 1979–2007 at the scale of the Gundal River basin scale is analysed for the inter-year variations. These variations have peaks, which lag the precipitation peaks. Also the higher pumping in the later years result in reduced groundwater discharge. The groundwater discharge forms the underflow from the watersheds of the sub-basin and relates the baseflow to the stream system in this case to the Kabini River basin from this region.

![Fig. 9](image)

**Fig. 9** (a) groundwater levels and cumulative rainfall departure for Gundal sub-basin; (b) and (c), simulation of groundwater dynamics using CRD model; (d), comparison of pumping estimate and simulations; and (e), annual variation of recharge, groundwater discharge and pumping in mm.

**CONCLUSIONS**

In this article, the statistical approaches based on EOF decomposition and SSA are used in order to respond to the following questions: (i) at a regional scale, what are the spatio-temporal patterns of
precipitation, streamflow and groundwater in a river basin in south of India, and (ii) do they show any correlations and can we identify the signature of the precipitation or of other contributions in the groundwater level variability due to the changes in the land use and effects of groundwater abstraction? It was observed that the presence of strong decadal variations in rainfall such as droughts, along with recent trends of heterogeneous anthropogenic effects (land-use changes), provide distinct groundwater signatures in the system. Since the impacts are found to be non-uniform across the region in the piezometers located in various watersheds due to local controls, the EOF approach helps in delineating the non-uniform spatial clusters in the groundwater system resulting due to these factors. The results obtained using Singular Spectrum Analysis (SSA) in the Kabini River basin shows that the streamflows and groundwater levels in the system correlate well to the long-term decadal rainfall cycles and also illustrate the effects of land use changes and groundwater abstraction in the climatic cycle of 1991–2004. A CRD-based model is used to simulate the effects of groundwater dynamics in the Gundal sub-basin (higher groundwater abstraction zone in the Kabini basin) during the later years (1991–2006) when groundwater abstractions have a significant role. The model developed can also be used as a decision-support tool for simulating scenarios of groundwater evolution if the rainfall and pumping dynamics are given as inputs. The agriculture water use and groundwater storage changes observed suggest a need for groundwater management in this basin, similar to the concerns voiced in the semi-arid basins elsewhere in the world (Gleick, 2000).

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