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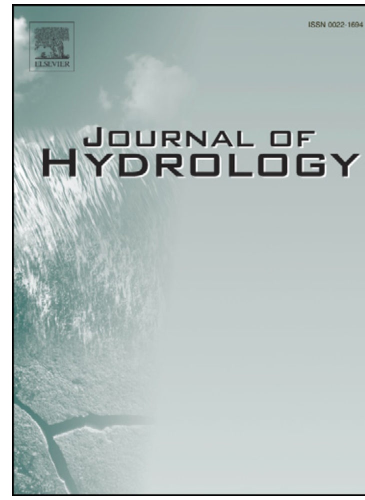

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Hwa-Lung Yu, Hone-Jay Chu

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Understanding Space-time Patterns of Groundwater System by Empirical Orthogonal Functions: a Case Study in the Choshui River Alluvial Fan, Taiwan

Hwa-Lung Yu[1], Hone-Jay Chu[1*]

Abstract

Natural or anthropogenic activities contribute to changes of groundwater levels in space and time. Understanding the major and significant driving forces to changes in space-time patterns of groundwater levels is essential to groundwater management. This study analyzes monthly observations of piezometric heads from sixty-six wells during 1997-2002 located in the Choshui River alluvial fan of Taiwan, where groundwater has been the important local water resource for myriads of agricultural or industrial demands. Following spatiotemporal estimations of piezometric heads by Bayesian Maximum Entropy method (BME), this work performs rotated empirical orthogonal function (REOF) analysis to decompose the obtained space-time heads into a set of spatially distributed empirical orthogonal functions (EOFs) and their associated uncorrelated time series. Results show that the leading EOFs represent the most significant driving forces to spatiotemporal changes of groundwater levels in the Choshui River aquifer. These include rainfall recharges from upstream Choshui and Pei-Kang River, pumping activities from aquaculture usages in the coastal areas, as well as water exchanges between surface and subsurface flow of Choshui River. In summary, this study shows the strength of the REOF analysis which can effectively provide integrative views of spatiotemporal changes of groundwater, gaining insights of interactions between the groundwater system and other natural and human activities.

Keywords: Empirical Orthogonal Function; Choshui River alluvial fan; Groundwater; Bayesian Maximum Entropy; Space-time data analysis.

[1] Dept of Bioenvironmental Systems Engineering, National Taiwan University, Taipei, 10617 Taiwan
* corresponding author (honejaychu@gmail.com)

Introduction

Groundwater has long been a reliable water source for a variety of uses such as domestic, agricultural, and industrial uses (Yang and Yu, 2006; Chu and Chang, 2009). In Taiwan, comparing to the surface water supply, several major aquifers provide the stable water resource, which accounts for over 30% of total amount of water supply annually. However, the changes of groundwater level are the responses of a complex interplay of a variety of natural and anthropogenic activities interacting with the groundwater system. In addition, the prevalence of the heterogeneity in subsurface environment and the lack of sufficient site characterization can significantly hamper the understanding of space-time groundwater flow and transport patterns, therefore, jeopardize the management of groundwater resources (Tartakovsky, 2007). Many studies about the changes of groundwater level often concentrate at the changes induced by a specific driving force, such as natural and artificial recharges from river or irrigation, pumping activities varying in space and time, and other driving forces like earthquakes(Liu et al., 2004). Addition to extensive studies on the impacts from specific activities by human or natural forces, it also requires the systematic and integrative studies to obtain the macroscopic view of spatiotemporal changes in hydraulic heads of the groundwater system of interest. For purposes of groundwater management, it is essential to be knowledgeable about the major ongoing underlying processes in space and time in the aquifer as well as the magnitude of these processes that contribute to varying piezometric heads at specific spatial and temporal locations.

In the groundwater monitoring investigations, the collected data may harbor significant complex or extremely complicated variations in the observed values of measurable characteristics of the groundwater level in time and space. Empirical

Orthogonal Function (EOF) analysis is an effective method to extract information from large datasets in time and space domains (North, 1984; Weare and Nasstrom, 1984; Kim and Wu, 1999; Hannachi et al., 2007; Munoz et al., 2008). EOF analysis conducts to the decomposition of the covariance kernel on the set of its eigen-functions. EOF analysis reduces the dimensions of a space-time random data fields into a smaller set of new spatial random fields which can be fairly accurate to reconstruct the space-time variances of the original random fields (Hannachi et al., 2007). Moreover, the purpose of the technique is to fit orthogonal functions to a set of observed data, resulting in a reduction in the amount of data with minimal loss of information while capturing the essential features (Munoz et al., 2008). Meteorology has applied EOF analysis for decades to extract the most significant spatial signals of atmospheric fields (Hannachi et al., 2007). Due to its advantage to obtain snapshots of essential pure spatial and/or temporal patterns of a space-time dataset, many other disciplines have recently applied EOF analysis in spatiotemporal analysis, such as ozone distribution (Fiore et al., 2003), and ecological processes (Bejaoui et al., 2008). For groundwater studies, EOF analysis was applied to extract significant temporal signals from the Rhine Valley aquifer located in France and Germany (Longuevergne et al., 2007), and was used to reduce the space-time variable to replace a large groundwater numerical model by a comparable reduced model (McPhee and Yeh, 2008; Vermeulen et al., 2004). For environmental monitoring, Munoz et al. (2008) considered Mid-Atlantic Stream Probabilistic Survey conducted from 1998 to 2002, incorporated the spatio-temporal information in sampling designs, and illustrated how to use the EOF model estimating at non-observed sites.

The study applied the EOF analysis to the case study in the Choshui River Fan aquifer of Taiwan. The local farmers converted their crop lands into more profitable aquaculture ponds, owing to abundant and low cost groundwater resources. Due to the lack of an effective groundwater management policy in Taiwan, heavy groundwater usage by aquaculture activities has notoriously caused local land subsidence, sea-water intrusion, and aquifer salinization (Hsu, 1998; Liu et al., 2003; Liu et al., 2006). Since 1992, the Water Resources Agency of Taiwan initiated a groundwater monitoring network plan (GMNP) to systematically establish groundwater monitoring wells with a spatial density of about 20km^2/station throughout major aquifers in Taiwan (Hsu, 1998), to gather essential information including groundwater quality and level, as well as hydrogeologic characteristics of the aquifers. The evenly distributed space-time observations collected by the GMNP consist of a valuable database containing comprehensive information about spatiotemporal variation of groundwater quality and levels induced by a variety of physical and chemical processes. The database provides essential information for a myriad of hydrogeologic researches in areas covered by the GMNP, including the study area.

This study used EOF analysis to obtain the most significant spatially distributed processes (i.e. EOFs) and their associated temporal variation from space-time groundwater observations from the Choshui River alluvial fan. Before EOF analysis, the current work performed spatiotemporal interpolation by the Bayesian Maximum Entropy (BME) method to generate evenly distributed space-time estimations to minimize potential systematic biases from sampling. During the analysis, EOF rotation played an important role to extract the most informative signals from the observations. This study then identified and interpreted the leading driving forces in groundwater level variation.

Materials and Method

Study area

The Choshui River alluvial fan is located on the mid-western coast of Taiwan, and covers the fertile plain area of 1800 km^2 including counties of Yun-Lin, Chang-Hua, and northern Chia-Yi, as Figure 1 shows. Across the Choshui River, the largest river in Taiwan, the alluvial plain is surrounded by natural geographical boundaries of the Taiwan Strait to the west, the Central Mountain Ridge to the east, the Wu River to the north, and the Pei-Kang River as its southern border. Annual rainfall in this area is around 2460 mm and 78 percent of precipitation occurs from May to October, i.e. plum rain and typhoon seasons. The annual runoff in the Choshui River is about 6.08 billion tons (Chen and Lee, 2003). Because of insufficient surface water supply in the alluvial fan, residents extract groundwater to supplement their demands irrigation, aquaculture, and household, particularly in dry seasons. Among them, groundwater is the major clean water supply for aquaculture ponds and therefore residents illegally extract a great amount of water from aquifers into aquaculture ponds. The overdraft of groundwater in agriculture and fish cultivation is causing serious land subsidence in coastal areas (Yang and Yu, 2006).

The Choshui River alluvial fan is partitioned primarily into proximal-fan, mid-fan and distal-fan areas, according to their distinct hydrological formations. Figure 2 shows the conceptual hydro-geological profile in the Choshui River alluvial fan. The hydrogeological formation consists of three major aquifers, i.e. aquifer I, II, and III numbered from the ground surface level, and separated by the aquitards, which are low permeable with fine sediment, ranging from clay to fine sand. Considering hydrogeological formation, the proximal-fan is the major recharge area of the aquifer

(Jang et al., 2008; Jang and Liu, 2004). The aquitards located in the distal-fan and mid-fan areas gradually diminish in thickness toward the east. Moreover, Aquifer II is the major aquifer of the Choshui alluvial plain because of its large spatial extent and acceptable depth for groundwater retrieval (Liu et al., 2004). Data derived from pumping tests indicate that the observed hydraulic conductivity fields ranges from 10^{-3}–10^{-5} m/s, and decreases from the proximal fan to the distal fan (Hsu, 1998; Jang et al., 2008; Jang and Liu, 2004). Transmissivity ranges from 0.04–4.19 m^2/min. The storage coefficient is about 0.1 for the unconfined aquifer and ranges from 10^{-3}–10^{-4} for the confined aquifer (Hsu, 1998). In this study, the dataset includes pizeometric head observations of aquifer II obtained from sixty-six monitoring wells, evenly distributed over the entire Choshui River alluvial fan. The study recorded the observations monthly during the period from July 1997 to December 2001.

Method

The aim of EOF analysis is to decompose a continuous space-time random field $X(s,t)$ into the additive space-time multiplication form as follows

$$X(s,t) = \sum_{k=1}^{M} c_k(t) u_k(s) \quad (1)$$

where the vector (s,t) denotes the space-time location at time t and spatial position s. M is the number of modes in orthogonal space-time random fields, i.e. $c_k(t)u_k(s)$. The modes are formulated as an optimal set of orthogonal spatial functions ($u_k(s)$), i.e. EOFs, and their associated expansion functions of time ($c_k(t)$), i.e., the projection of $X(s,t)$ on $u_k(s)$, also called EOF expansion coefficients (ECs). The concept of EOF analysis is essentially conventional principal component analysis (PCA), which generates a smaller set of new random variables. The major leading EOFs can usually explain the fairly amount of the observed variances of the original space-time dataset, e.g. in this study, five EOFs can explain over 80% of the variances of space-time groundwater head data as shown below. To consider the geometrical relationship among the space-time dataset, not common in most PCA applications, this work first interpolates space-time observations into regularly spaced grids over the entire space-time domain. This mitigates data clustering effects, which can contribute to excess variances of clustering locations, therefore distorting EOF analysis results (Buell, 1971; Buell, 1978; Karl et al., 1982). This study uses the Bayesian maximum entropy method (BME) to estimate the spatiotemporal distribution of piezometric heads by accounting for spatiotemporal dependence, i.e. covariance, as well as for observations considered as hard data in this case. For a more detailed description of the BME method, the reader can refer to the literature (Christakos, 2000; Christakos et al., 2002).

In EOF analysis, the head covariance over spatial domain finds the uncorrelated spatial functions such that $Cu = \lambda^2 u$, where C is the covariance among the gridded data in space, $u = (u_1, ..., u_p)^T$ is the matrix that composes the eigenvectors u_k corresponding to eigenvalues (λ_k), and p is the number of space locations. Without generality loss, the spatial (temporal) covariance (C) can be expressed as $C = \frac{1}{n} XX^T$ where X is a $p \times n$ matrix containing space-time BME estimations of piezometric heads with the number of observed time (n). The amount of observed head variance explained by the eigenvector (u_k) is the value of its associated eigenvalue (λ_k).

In practice, the singular value decomposition (SVD) method is used for EOF analysis (Hannachi et al., 2007). A $p \times n$ matrix of space-time head estimations $X(s,t)$ can decompose as

$$X = U \Lambda A^T \tag{2}$$

where U and A respectively $p \times M$ and $n \times M$ are the unitary matrix, i.e. $U^T U = A^T A = I$, in which the columns $u_k(s)$ are essentially EOFs as the spatial orthonormal basis of the space-time data matrix. The diagonal matrix (Λ) with elements of $\lambda_1 \geq \lambda_2 \geq ... \geq \lambda_r$ are singular values of the matrix of $X(s,t)$. Therefore, the projections of EOFs (c_k) are expressed as $c_k(t) = \lambda_k a_k(t)$. The space-time decomposition of Eq. (1) by EOF analysis can be rewritten as

$$X(s,t) = \sum_{k=1}^{M} \lambda_k a_k(t) u_k(s) \tag{3}$$

One of the major challenges for EOF analysis is to interpret the estimated EOFs and their associated projections which are orthogonal to each other but may not be physically meaningful. The rotation of EOF patterns (REOF) can be one of the most common approaches to overcome the interpretation issue (Hannachi et al., 2007). The rotation concept systematically alters the original EOF structure based upon some criterion, such as maximizing the explained variances of leading EOFs. Studies of multivariate statistical analysis, e.g. factor analysis (Anderson, 2003) have proposed and widely applied a variety of rotation algorithms. Among them, the Varimax method is the most well-known and used rotation technique, by which an orthogonal matrix is applied to EOF rotation to simplify the EOF structure, pushing the loading coefficients of EOFs to either zeros or ± 1 (Kaiser, 1958). Determining the number of modes, M, for space-time decomposition is also a major issue in EOF analysis.

For reducing dimension, the value of M is always chosen to be much less than the numbers of space-time dimensions of observations, i.e. n and p. However, the general outcome of REOF analysis depends on the selection of M which can complicate understanding of the underlying leading physical patterns of the observations. To obtain the invariant leading REOFs, EOFs should be re-scaled according to their associated eigenvalues before rotation. Rotating rescaled EOFs generates invariant leading REOFs due to relatively little contributions from the scaled EOFs of smaller eigenvalues (Hannachi et al., 2007). The current study considers the varying piezometric head of the aquifer as the linear superposition of several contributions from independent natural or anthropogenic processes decomposed by REOF analysis.

Results

Spatiotemporal distribution of piezometric heads

This research predicted monthly spatial distributions of piezometric heads of aquifer II in the Choshui River alluvial fan by the BME method, accounting for the spatiotemporal trend and covariance among the heads. Figure 3 shows the piezometric heads results of two selected months and the triangles represent the monitoring wells. The highest piezometric head is at the proximal-fan of the Choshui River alluvial fan and the lowest is close to the southern coastal area i.e. Yi-Wu (Figure 3 (a) and (b)). The hydraulic gradient from east to west is caused by topography changes in the presented area significantly. The distribution of piezometric heads changes slightly from month to month, primarily from obvious seasonal precipitation over the study area, i.e. central Taiwan. The wet and dry seasons are from May to October and from

November to April, respectively. Piezometric heads over the Choshui River alluvial fan in March (Figure 3 (a)) and October (Figure 3 (b)) in 2001 represent the general spatial distribution of the groundwater level during the dry and wet seasons, respectively. The both figures show a slight difference in the piezometric heads between the two seasons, especially in the coastal areas.

The EOFs in spatial domain and Time series of the ECs

Figure 4 shows total variance among the observed head data primarily explained by the leading EOFs. Among them, the first five EOFs explain about 80 percent of the observed spatiotemporal changes of heads with their contributions of 47.9%, 10.8%, 9.8%, and 6.9% and 4.7%, respectively. Figure 5 shows spatial distributions of the first five EOFs. Each EOF has its distinct spatial pattern, which is generally localized. Figure 6 shows the associated ECs (shown as the black line) during the study period of the five EOFs. Equation (1) shows that jointly considering ECs and EOFs reveals positive or negative contributions from each of the EOFs to piezometric head changes in space and time. This study uses the bright areas (hotspot) of EOFs to represent positive contributions to piezometric head changes. In EOF1, the brightness hotspot is located upstream to the Choshui River, primarily in the Gu-Keng and Dou-Liu townships, shown in Figure 5 (a). The EOF3 also shows a similar spatial pattern where the brightness area is located upstream to the Pei-Kang River, shown in Figure 5 (c). As mentioned in previous studies (Jang et al., 2008; Jang and Liu, 2004), the proximal-fan is a major recharge region for aquifers, due to its hydro-geological formation being primarily composed of gravel and sand. Compared to rainfall observations at the Da-Pu station located upstream to the Choshui River, Figure 6 (a) shows that EC1 temporal variation highly associates with the hydrologic cycle in the area, yet with about two or three months delay, the approximate time required for rainfall to percolate in the aquifer. The temporal pattern of EC1 implies that upstream recharge from the Choshui River is the leading driving force causing spatiotemporal changes of the aquifer. This study also observes a similar rainfall recharging pattern in EC3 in which the trend varies closely to rainfall measurements at Dou-Nan, located upstream to the Pei-Kang River, i.e. the brightness area of EOF3.

The EOF2 hotspot is near Yi-Wu and King-Hu, among the greatest land subsidence locations (TPWCB, 1996; TPWCB, 1997), shown in Figure 5 (b). Because of heavy aquaculture and irrigation demands over the entire township, illegal over-pumping resulted in groundwater level decline (Akudago et al., 2009), therefore consolidating soil layers (Liu et al., 2004). Cumulative land subsidence amounts from 1976 to 2000 obtained by a leveling survey at Yi-Wu and King-Hu (within the Ko-Hu township) were 195 and 188 cm, respectively. The temporal pattern of EC2 closely corresponds to the variation of measured piezometric heads at a monitoring well close to Yi-Wu, shown in Figure 6 (b). The piezometric head falls during spring and summer, and arises during the other seasons. During the high season of water usage, particularly from March to July, local farmers extract groundwater for irrigation, fish cultivation and household demands and result in the seasonal drawdown of groundwater levels. Figure 6(e) also shows the EC5 time series and piezometric heads in the Shi-Kong gauge. The EC5 increases with time. In fact, the groundwater level has begun to rebound and the subsidence rate in Shi-Kong has declined (Liu et al., 2004). The government has not allowed intensive groundwater use due to the industrial development in the area since 1998. Moreover, the EOF4 hotspot is in the Choshui River, shown in Figure 5(d). Figure 6 (d) shows the streamflow during the study periods in the Chang-Yun Bridge gauge and the EC4 varies with the streamflow. The EOF4 driving force is the exchange between the Choshui River and groundwater.

Moreover, groundwater and surface water are not isolated components of the hydrologic system, and interactions exist between ground water and surface water. During flooding, the river recharges the aquifer. During the dry season, groundwater flux drains into the stream, leading to increased stream flows (Sophocleous, 2002).

Discussion

Groundwater studies of the Choshui River alluvial fan have primarily focused on issues driven by anthropogenic activities, such as land subsidence and its associated impacts (Liu et al., 2004). An integrative study performed on the aquifers to identify the major underlying processes of the groundwater system would be more helpful for groundwater management. In this study, REOF analysis shows its effectiveness to reveal, not only the leading driving forces of groundwater level changes in space and time, but their interactions with the aquifer. The study by (Longuevergne et al., 2007), also shows that EOF analysis reveals the primary characteristics at the Rhine Valley aquifer (France and German). Both the study (Longuevergne et al., 2007) and our study require an extensive groundwater monitoring network for the aquifer, i.e. ninety-five and sixty-six monitoring wells for the Rhine Valley and Choshui aquifers, respectively. Contrasted to the Rhine Valley study, our study performs spatiotemporal interpolation of piezometric heads before EOF analysis to reduce the effects from uneven spatial distribution of monitoring wells (Karl et al., 1982; Wikle and Cressie, 1999). The current study also shows that rotating EOFs effectively increases EOF interpretability by generating more spatially localized and stable spatial patterns of leading EOFs.

As shown in previous studies (Chen and Lee, 2003; Jang and Liu, 2004), recharges play an important role in Choshui river aquifer sources, especially in the proximal-fan area, i.e. upstream to the Choshui and Pei-Kang rivers. In the proximal-fan area, the logarithm of hydraulic conductivities are generally higher, about 4-5 ln(m/day), than those in rest of the aquifer, about 1-3 ln(m/day) (Jang and Liu, 2004). One of the most valuable features of REOF analysis to groundwater analysis is its ability to clearly identify primary recharge areas for the aquifer. Identifying recharge areas is an important step towards protecting regional groundwater resources (Braun et al., 2003). The inappropriate use of these areas increases the risk of groundwater contamination. Moreover, identifying the recharge source could be useful for managing aquifers to meet increasing demand, and also help address environmental issues on effects of water level decline (Acheampong and Hess, 2000). In this study, time series EC1 and EC3 highly associate with rainfall measurements of local weather stations. The comparison between temporal variations of ECs and rainfalls, and percolation time for groundwater recharge depends on several hydrogeological factors, including hydraulic conductivity and depth of the groundwater table (Gau et al., 2006). The amount of recharges closely relates to the amounts of local rainfalls and stream flows. Quantifying groundwater recharge is typically difficult because direct recharge input to the water table is not easily measured, especially when the water table is several meters below the land surface in an aquifer (Gburek and Folmar, 1999), due to the absence of effective instrumentation. By different techniques, the estimations of annual groundwater recharge in the mountain region of Choshui aquifer range from 3.1 to 3.5 billion tons (Chen and Lee, 2003; Gau and Liu, 2000). In the proximal fan of the Choshui aquifer, percolation time for rainfall to reach the groundwater table is about two to three months, similar to results of the aquifer study in the central coastal plain (Israel) (Rimon et al., 2007).

The study also identifies exchanges between the Choshui River flow and ground water as the major contributing factor to changes in ground water level. The primary contribution of the Choshui river flow is along the Choshui River, as expected. Particularly, the most sensitive areas for river recharge are located upstream to the Choshui River and the Pei-Kang River. The results also reveal interactions between surface and subsurface water of the Choshui River. Changes in EC4 are much smoother compared to streamflow changes. Moreover, temporal variation of flow rate generally fluctuates significantly in response to rainfall. The changes in EC4 better reflect the base flow temporal pattern of the Choshui River, which reacts slower than the runoff to local rainfall changes. As a result, EC4 shares temporal characteristics similar to EC1; however, with different magnitudes, i.e. EC1 is directly associated with seasonal rainfall and EC4 is more connected to the flow pattern of Choshui River which is closely related to rainfall.

As expected, this study identified pumping at several places in the coastal area, as among the major contributing processes to piezometric head changes. In the area, the soil consists mostly of clay and fine sand; the strength and the permeability of this soil are relatively low (Liu et al., 2004). Furthermore, the Choshui River alluvial fan includes the major aquaculture towns in Taiwan, and therefore extensive groundwater demands are expected, because of insufficient surface water supply in these areas. Illegal overpumping of groundwater has been prevalent in almost the entire coastal area counties of Chang-Hua and Yun-Lin since 1950 due to a lack of ground water management. The accumulated land subsidence due to unmanaged pumping activities ranges from 50cm to 200cm along the coastline of the Choshui River alluvial fan (Liu et al., 2004). This study identified two hotspots where pumping activities were still active during the study period of 1997-2002, i.e. the piezometric heads still changed significantly. Among them, fortunately, the EC5 shows that unmanaged pumping seems to be under control and the groundwater level in Shi-Kang gauge has started to rebound consistently since mid-1998 at the hotspot area of EOF5. The Ko-Hu township identified by EOF2 shows that the regular seasonal pattern of hydraulic heads at its lowest time occurred in spring and summer every year during the study period. The seasonal pattern is closely associated to the water demands for local aquaculture ponds (Yang and Yu, 2006).

Conclusion

This study presented a macroscopic and integrative approach to investigate the spatiotemporal changes of a groundwater system by REOF analysis. We analyzed the monthly records of groundwater levels from 1997 to 2002 for sixty-six monitoring wells operated by a water resources agency in Taiwan. This study shows that REOF analysis can effectively capture stable and localized features, and gain easy interpretation of EOFs. The current study identified five underlying processes as major contributors to changing groundwater levels in the aquifers of Choshui River alluvial fan, including recharges from rainfalls, stream flow and groundwater usage in the coastal areas. These five leading EOFs drive the system changes, amounting to about 80 percent of global variance for the entire groundwater system. More specifically, the sensitive recharge areas are located upstream to the Choshui River and the Pei-Kang River. This finding suggests a required groundwater management policy in these places to ensure avoiding any potential contamination. Though land subsidence is prevalent along the coastline of the Choshui River alluvial fan, the locations with the most significant groundwater level changes are near the coastal area, i.e. townships of Ko-Hu (Yun-Lin county), and Da-Cheng (Chang-Hua county) in our analysis.

This study shows the REOF analysis can effectively reveal the underlying space-time processes of groundwater system. The REOF analysis results provide the integrative view of interests in groundwater system and insights of major contributing factors to the groundwater level changes in space and time, which are the essential information for the effective management of a groundwater system.

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Figure Captions

Figure 1 Geographical location of the Choshui River alluvial fan in Taiwan

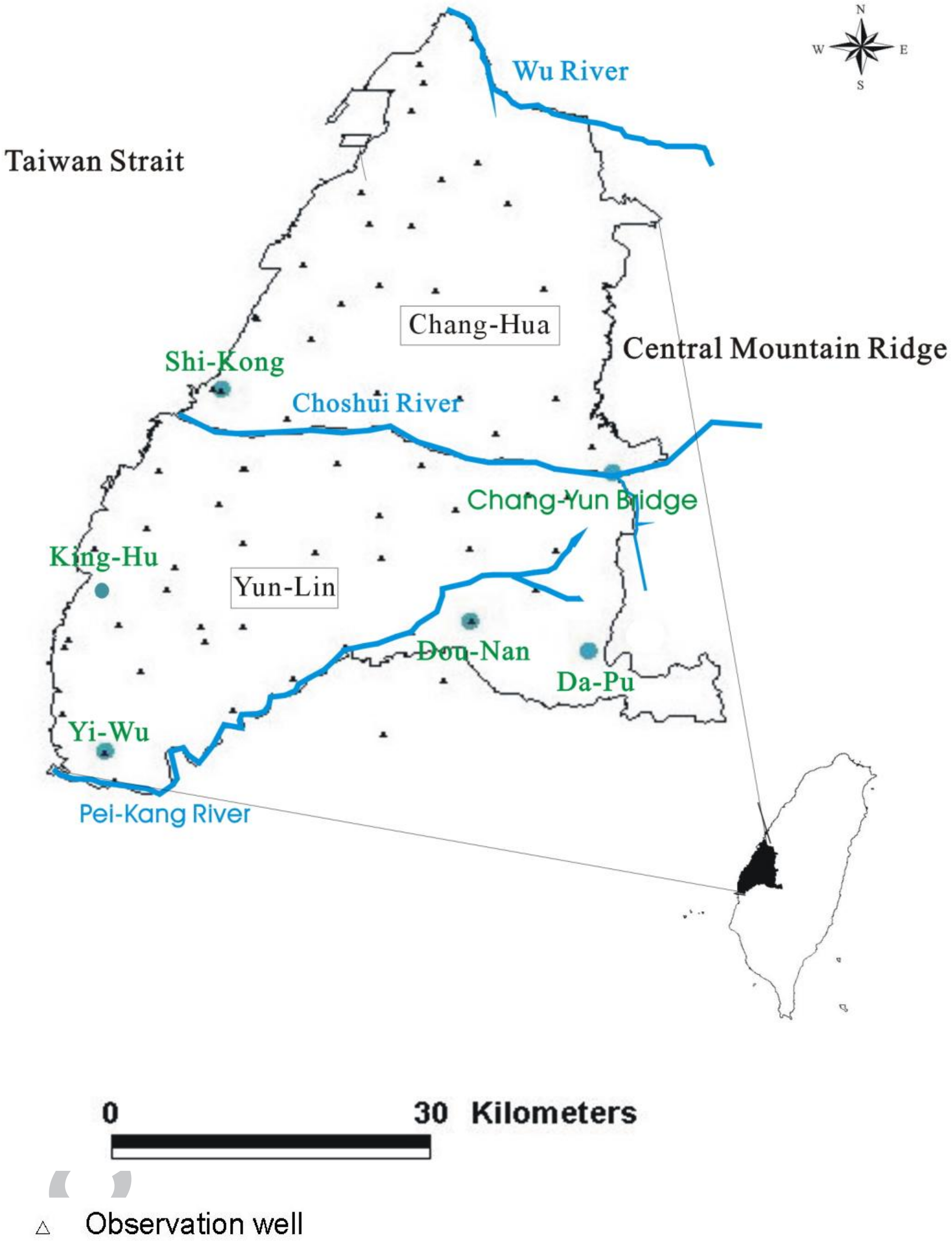
Figure 2 Conceptual hydro-geological profile of the Choshui River alluvial fan

Figure 3 The piezometric head (in meter) maps using BME on (a) March, 2001, and (b) October, 2001

Figure 4 Variance percentage of rank of EOFs

Figure 5 The first five EOF interpolations (Unit: m)

Figure 6 Time series of the ECs (black line) and the hydrologic components: (a) rainfall distribution in Da-Pu (b) piezometric head distribution in Yi-Wu (c) rainfall distribution in Dou-Nan (d) streamflow distribution in Chang-Yun Bridge (e) piezometric head distribution in Shi-Kang



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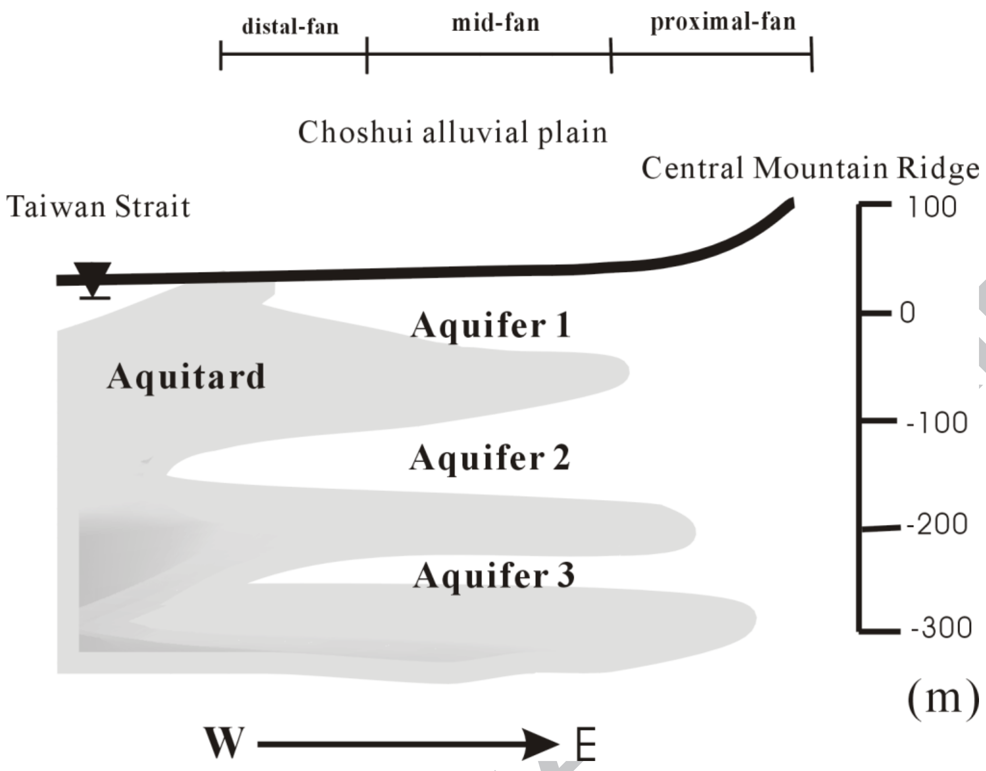
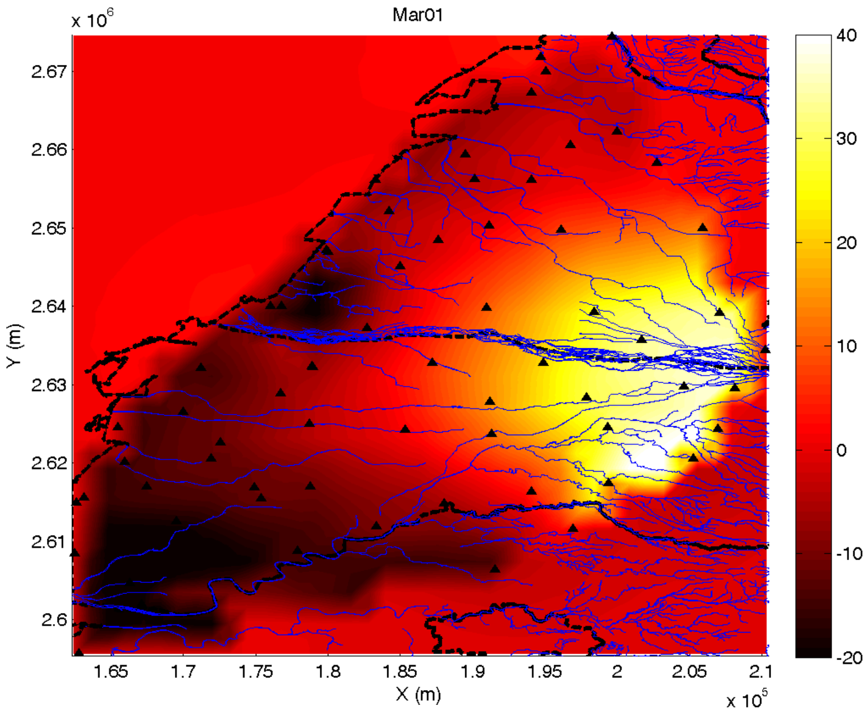
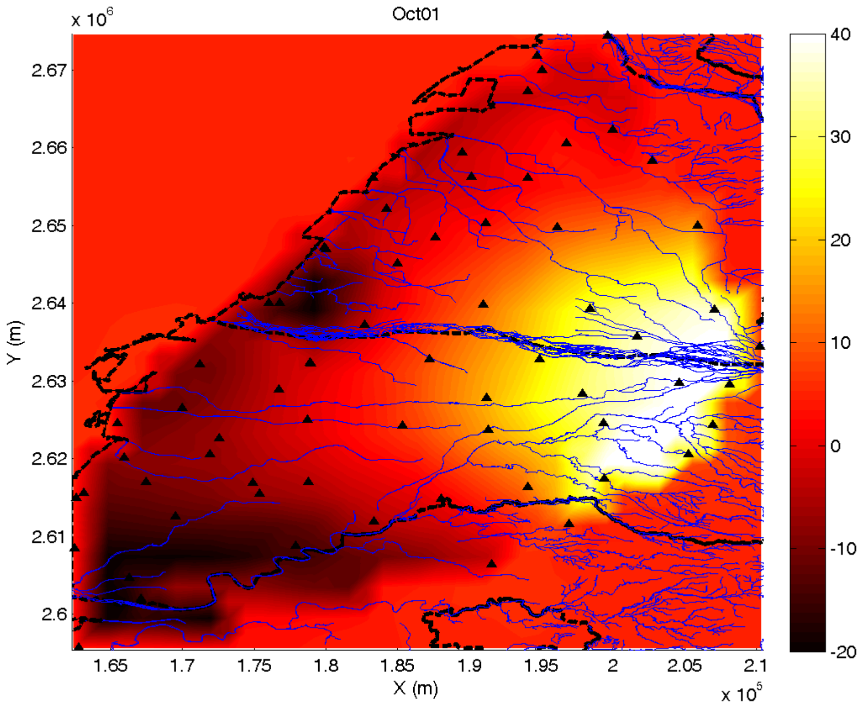


Figure 2 Conceptual hydro-geological profile of the Choshui River alluvial fan



(a)



(b)

Figure 3 The piezometric head (in meter) maps using BME on (a) March, 2001, and (b) October, 2001

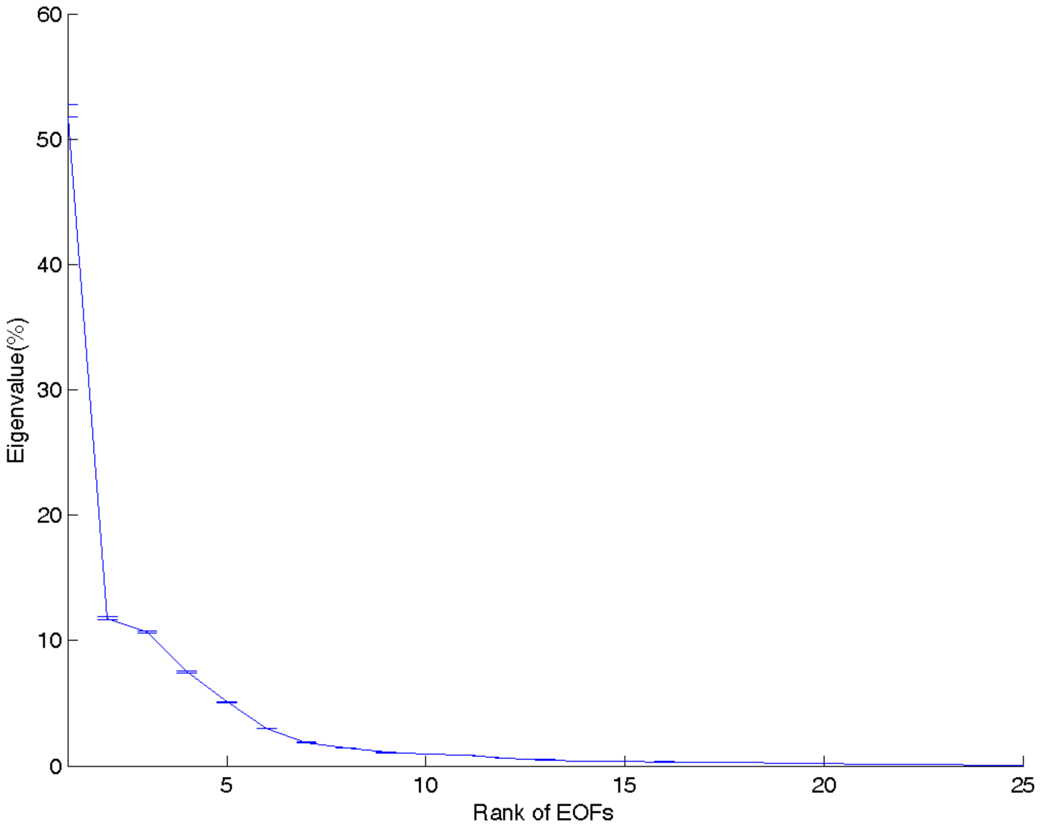


Figure 4 Variance percentage of rank of EOFs

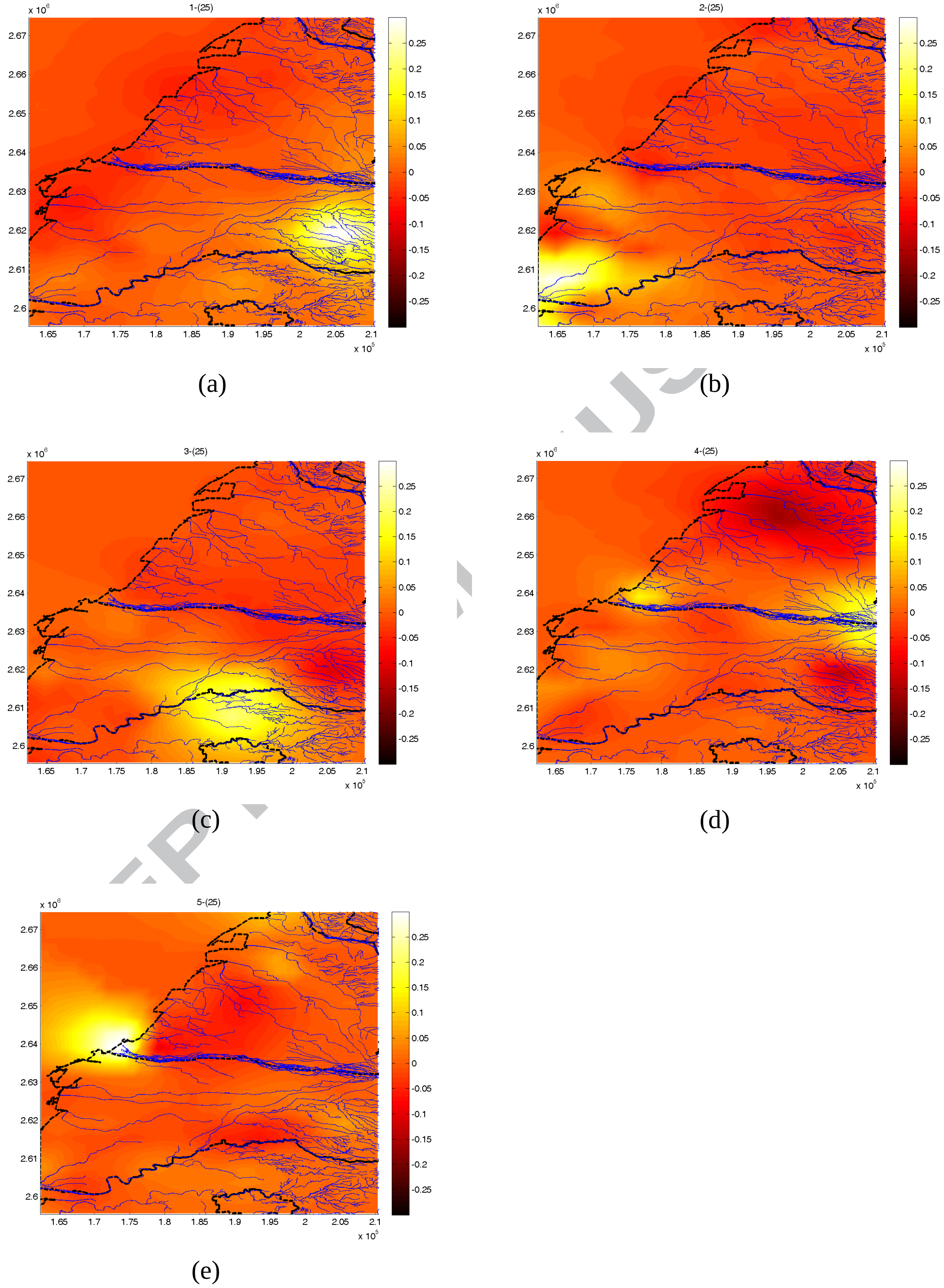
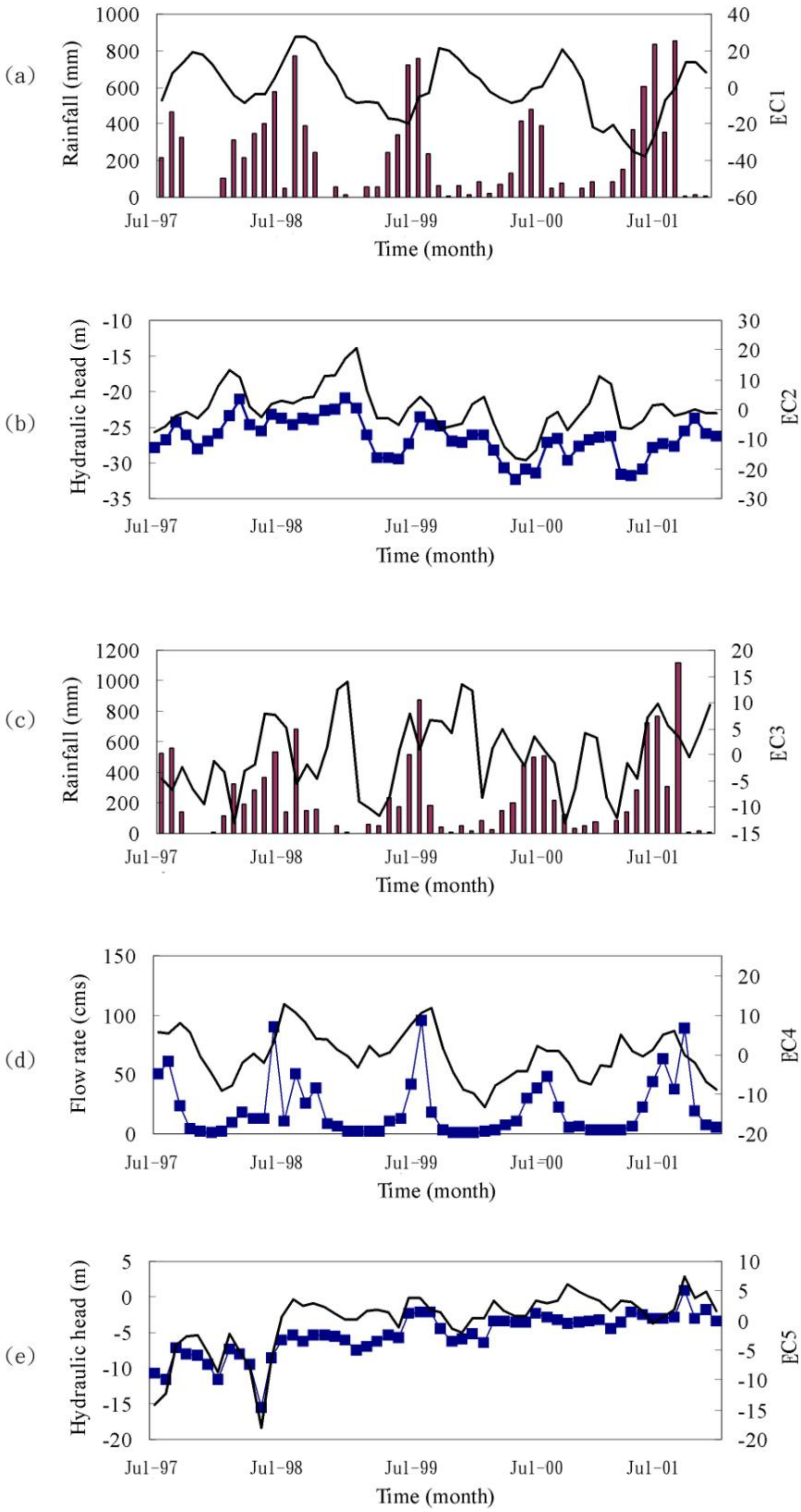


Figure 5 The first five EOF interpolations (Unit: m)



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