Ground Water Monitoring&Remediation

Surveying Ground Water Level Using Remote Sensing: An Example over the Seco and Hondo Creek Watershed in Texas

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Abstract

The Normalized Difference Vegetation Index (NDVI) derived from satellite data has been applied to various vegetation studies. The objective of this study was to assess the feasibility of using the NDVI response to plant water content to predict ground water level over a watershed located in the Edwards Aquifer of Texas, USA. Results showed that the precipitation data collected inside the watershed were not highly correlated to ground water depth within 10 d of the event, though a 60-foot sinkhole in the study site was expected to collect rainfall and recharge ground water in a short time. Alternatively, the NDVI derived from SPOT-VEGETATION satellite data and potential evapotranspiration (PET) based on the Hargreaves PET model were significantly correlated to ground water depth. Moreover, the stream flow measurements were correlated to ground water level as well. Two simple models were developed for estimating ground water levels in the artesian and recharge zones. Independent validations were performed to verify both models. All three variables (NDVI, PET, and stream flow) were directly or indirectly related to the precipitation. The PET was mainly controlled by air temperature, and the temperature was negatively related to precipitation. The NDVI values were affected by both temperature and precipitation, and the amount of rainfall was strongly correlated to the stream flow. This study initiated a unique approach to surveying ground water level based on satellite information and meteorological data.

Introduction

Several places on the earth have experienced severe drought in the past decade (e.g., McCabe et al. 2004; Munne-Bosch and Penuelas 2004; Delissio and Primack 2003), while demand for water has increased. Drought conditions have caused losses in agricultural productivity and damaged the environment through vegetation loss and soil erosion. Several studies have introduced satellite data to real-time drought monitoring programs to detect potential droughts across North America, India, and China (e.g., Wan et al. 2004; Singh et al. 2003; Su et al. 2003). Protecting limited water resources has become the first priority for water management.

The Edwards Aquifer, on which the city of San Antonio is located and relies for its water supply, is one of the largest ground water sources in south central Texas. The aquifer has provided the water supply for agricultural, industrial, recreational, and domestic needs. In recent years, the aquifer's capacity to provide fresh water could barely meet the demand (e.g., Chen et al. 2001). The Edwards Aquifer is divided into three main zones: the contributing zone, the recharge zone, and the artesian zone (Figure 1). The contributing zone is rugged and covered with mature live oak-Ashe juniper woodlands. Highly fractured limestones outcrop at the land surface of the recharge zone, which allows large quantities of water to rapidly flow into the aquifer. According to the studies by Eckhardt (2004), a small percentage of recharge occurs when precipitation falls directly on the outcrop, but >75% of recharge occurs when streams and rivers cross the permeable limestone. A ground water recharge project for the aquifer has been conducted over the Seco Creek area, where water is purposely collected and diverted into a sinkhole (e.g., Eckhardt 2004). The artesian zone is covered by relatively impermeable limestone, and the water is trapped inside. This aquifer is one of the most productive artesian aquifers in the world.

Several studies concluded that precipitation infiltration or seepage was the major source for the ground water recharge (e.g., Liu and Zhang 1993; Gau and Liu 2000). The study by Gelt et al. (1999) mentioned that stream flows strongly contributed to ground water recharge. Moreover, Sato et al. (1999) found that the drainage from river basins plays an important role in ground water recharge. In

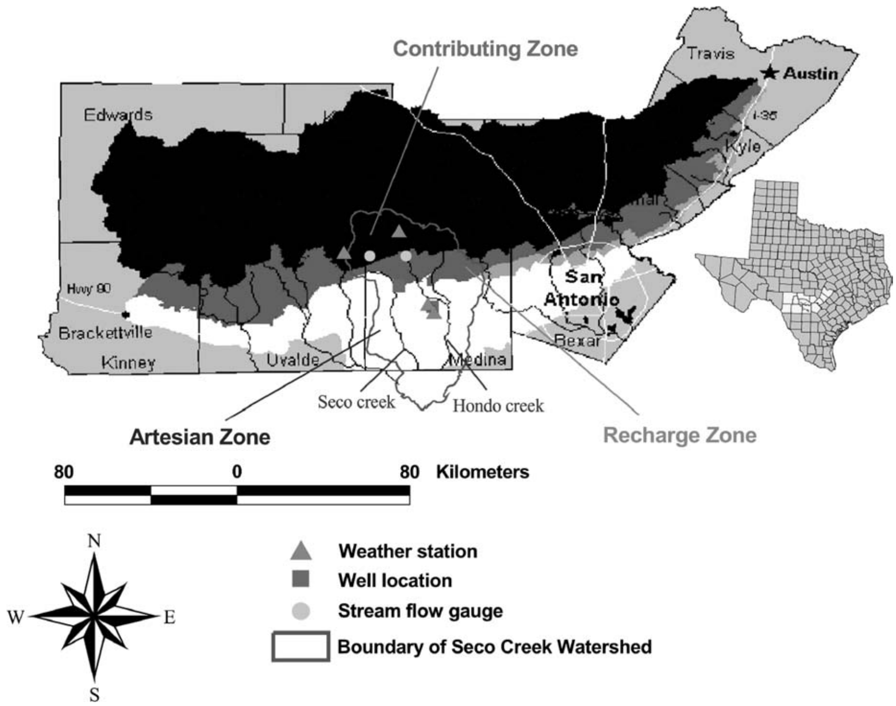

Figure 1. Geopolitical boundary of the Seco and Hondo creek watershed in the Edwards Aquifer, distributions of the contributing zone (shaded in black), the recharge zone (shaded in gray), and the artesian zone (shaded in white), and weather stations, wells, and stream gauges in the Seco and Hondo creek watershed.

general, recharge rate and amount were strongly related to local weather conditions (precipitation, temperature, solar radiation) and rock formation as well as slope, aspect, land use, plant water content, soil moisture, and evapotranspiration (ET) (e.g., Liang et al. 1994; Mitchell and DeWalle 1998; Wooldridge and Kalma 2001). The amount of precipitation affected not only the ground water recharge but also the plant water content (e.g., Lotsch et al. 2003; Martinez-Meza and Whitford 1996). Published studies showed that vegetation density responds to the plant water content, and the Normalized Difference Vegetation Index (NDVI) derived from digital satellite data corresponds to the density of green vegetation (e.g., Boone et al. 2000; Chen and Brutsaert 1998; Gao 1996).

The NDVI derived from the visible and near-infrared reflectance has been widely applied to a diversity of plant-related environmental studies (e.g., Baynes and Dunn 1997; Chen et al. 2003). The 10-d NDVI composites at a spatial resolution of 1000 m are available from the near-real time SPOT-VEGETATION (VGT) data (http://free.-vgt.vito.be). Two types of 10-d NDVI composites were produced from the VGT data. One is based on a revised maximum value compositing (MVC) method with improved removal of clouds and aerosol (e.g., Holben 1986), and the other one is bidirectional compositing (BDC) developed by Duchemin et al. (2002). Published results showed that the patchworks and orbital track patterns resulting from the association of adjacent pixels from orbits with significantly different satellite zenith angles were visible on the MVC images, but they were removed on the BDC images. The BDC approach took the average of the last 12 bidirectional reflectance distribution function (BRDF)-corrected and cloud-free single-date images to represent the 10-d composite, which typically removes visually noisy pixels (e.g., Duchemin et al. 2002).

Most hydrological studies using satellite data have focused on surface water flow modeling and soil moisture monitoring (e.g., Dettinger (2003) and the contributing and artesian zones was the recharge zone (Figure 1). The digital elevation model (DEM) and land use/Cayan 2003; Das et al. 2002; Moran et al. 2002). Little has been published on the use of a vegetation index to predict ground water level. The first objective of this study was to assess the statistical correlation between NDVI and ground water level. If the NDVI data proved to be a significant variable correlated to ground water level, then meteorological data, stream flows, and NDVI data could be combined to survey ground water level.

Study Site

The 3000-km^2 Seco and Hondo creek watershed was located mostly in the western part of Medina County, Texas. Most of the watershed was located in the artesian zone, while the upper 20% of the watershed belonged to the contributing zone. The strip between land cover and soil maps for the study site of the Seco and Hondo creek watershed were available on the Web site of the Environmental Protection Agency (http://www.epa.gov/waterscience/ftp/basins/gis_data/huc/). Elevation data were in raster format, and both land use/land cover and soil maps were in vector format. The DEM elevations decreased from north to south. The soil maps from the State Soil Geographic database were based on the detailed soil survey data, which were aggregated to a mapping scale of

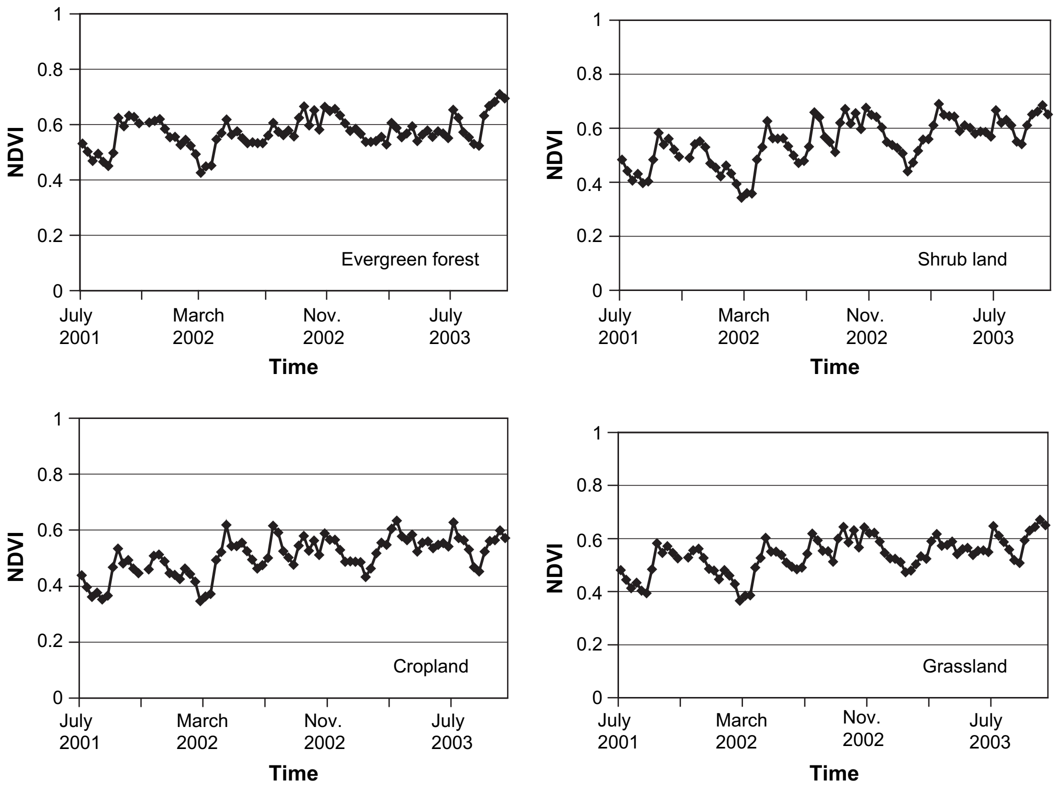

Figure 2. Temporal NDVI profiles of four major vegetation types (evergreen forest, shrub land, cropland, grassland) over the Seco and Hondo creek watershed.

1:250,000. The study area contained 14 soil types, most of which were poorly drained clayey soils with low permeability. A land-use map obtained from the LANDSAT multispectral images at 30-m resolution displayed that >99% of the watershed was dominated by evergreen forest (41%), shrub land (29%), cropland (21%), and grassland (9%).

Two weather stations operated by the National Climatic Data Center were located in the artesian zone, while the other two stations were in the contributing zone (http://www.ncdc.noaa.gov/oa/climate/stationlocator.html) (Figure 1). The stream flows in the watershed area were measured daily by the USGS stream gauges (http://tx.usgs.gov). One gauge was located in the contributing zone, and the other one was located in the recharge zone (Figure 1). Ground water levels in the study area were measured from two wells managed by the USGS. The well in the recharge zone had a depth of 538 feet (164 m) below ground level (BGL), and the other well in the artesian zone had a depth of 1600 feet (488 m) BGL (Figure 1).

Methodology

The VGT-BDC 1000-m resolution NDVI data were selected for this study because they contained less data noise (e.g., Duchemin et al. 2002). Moreover, the average value used in VGT-BDC data was more appropriate for representing vegetation conditions in a period of 10 d compared to the maximum value used in VGT-MVC data, since cloudy pixels were detected and sun as well as satellite zenith were corrected for. Averaged NDVI values acquired from the VGT-BDC data sets were recorded for each vegetation type over the study watershed every 10 d from July 2001 to October 2003 (http://free.vgt.vito.be) (Figure 2). A representative NDVI value for the vegetation greenness over the entire study area was computed according to the

Table 1
Summary of Statistical Correlations between Temperature, PET in the Artesian (A) Zone, and Ground Water Level in the A Zone and Recharge (R) Zone (p value = 0.05)

Independent Variables	Dependent Variables: PET (A zone)	Ground Water Level (A zone)	Ground Water Level (R zone)
Temperature I (A zone)	$p = 0.00$[1], $r^2 = 0.42$	$p = 0.00$[1], $r^2 = 0.27$	$p = 0.48$, $r^2 = 0.01$
PET (A zone)	—	$p = 0.00$[1], $r^2 = 0.58$	$p = 0.00$[1], $r^2 = 0.45$

[1]Significant outcomes.

Table 2
Summary of Statistical Correlations between Stream Flow in the Contributing (C) and Recharge (R) Zones and Ground Water Level in the Artesian (A) Zone and R Zone (p value = 0.05)

Independent Variables	Dependent Variables: Ground Water Level (A zone)	Dependent Variables: Ground Water Level (R zone)
Stream flow (C zone)	$p = 0.12$, $r^2 = 0.04$	$p = 0.94$, $r^2 = 0.00$
Stream flow (R zone)	$p = 0.02$[1], $r^2 = 0.09$	$p = 0.80$, $r^2 = 0.00$

[1]Significant outcomes.

proportion of each vegetation type. The NDVI values were scaled between −1 and +1. A large NDVI value indicated a high density of green vegetation, and negative NDVI values denoted the presence of snow, ice, water, or clouds.

Most soils in the study watershed consisted of >34% clays and <35% sands (http://www.epa.gov/waterscience), and a small portion (<10%) of sandy soil was located in the artesian zone close to the watershed outlet. No weather stations, stream gauges, and wells for this study were located in well-drained sandy soils for areas with low elevation. Due to homogeneous soil properties in the study area, the soil data were not considered as a correlation variable for this study.

All four weather stations provided daily precipitation data, but only the two stations in the artesian zone provided daily temperature data. Since the NDVI values were available every 10 d, the sum of precipitation in millimeters and mean of temperatures in degrees Fahrenheit were computed every 10 d for this study. The precipitation and temperature data obtained from each weather station were treated as an independent data set. The averaged amount of potential evapotranspiration (PET) (mm/d) was calculated every 10 d using the Hargreaves PET method and was dependent on the minimal/maximum temperatures and latitudes of the watershed, as well as the day of year (e.g., Hargreaves 1994). The units of stream flow and ground water depth were converted to the metric system for this study. Stream flow (m^3/s) data were averaged every 10 d for each gauge location. Two sets of averaged depths of ground water in meters every 10 d were transformed from BGL to heights above well bottom. Two sets of ground water level data were treated as the dependent variables for the recharge and artesian zones, while one NDVI, four precipitation, two temperature, two PET, and two stream flow data were the independent variables. This study included correlation development and data validation. Two-thirds of the data set (the last 20 d per month) was used for statistical correlation analysis, and the remaining one-third (the first 10 d per month) was used for independent data validation.

The intercorrelations between independent variables were examined first, and then linear regression was applied to identify significant independent variables. The level of significance (p value) was set at 0.05 in this study. The predicted and measured values of ground water levels were compared using the Nash and Sutcliffe (1970) equation:

$$E = 1 - \left(\frac{\sum_{i=1}^{n} (Q_{mi} - Q_{ci})^2}{\sum_{i=1}^{n} (Q_{mi} - Q_{m})^2} \right) \quad (1)$$

where E is the estimation efficiency, n the number of data samples, Q_{mi} the measured value, Q_{ci} the estimated value, and Q_m the mean measured value. The value of E could range from negative infinity to 1.0, where $E = 1.0$ indicates a perfect model. The E is similar to a correlation coefficient obtained from linear regression; however, the E compares the measured values to the 1:1 line of measured equals predicted (perfect fit) rather than to the best-fit regression line (e.g., Saleh et al. 2000). This statistic has been widely used for evaluating the performance of hydrologic simulation models (e.g., Legates and McCabe 1999).

Results

Intercorrelation of Independent Variables

The temperature data collected from the two stations in the artesian zone were very similar and highly correlated

Table 3
Summary of Statistical Correlations between Precipitation in the Contributing (C) and Artesian (A) Zones, Stream Flow in the Recharge (R) Zone, and Ground Water Level in the A and R Zones (p value = 0.05)

Independent Variables	Dependent Variables: Stream Flow (R zone)	Dependent Variables: Ground Water Level (A zone)	Dependent Variables: Ground Water Level (R zone)
Precipitation (C zone)	$p = 0.00$[1], $r^2 = 0.23$	$p = 0.28$, $r^2 = 0.03$	$p = 0.18$, $r^2 = 0.05$
Precipitation (A zone)	$p = 0.01$[1], $r^2 = 0.18$	$p = 0.19$, $r^2 = 0.05$	$p = 0.45$, $r^2 = 0.02$
Stream flow (R zone)	—	$p = 0.02$[1], $r^2 = 0.09$	$p = 0.8$, $r^2 = 0.00$

[1]Significant outcomes.

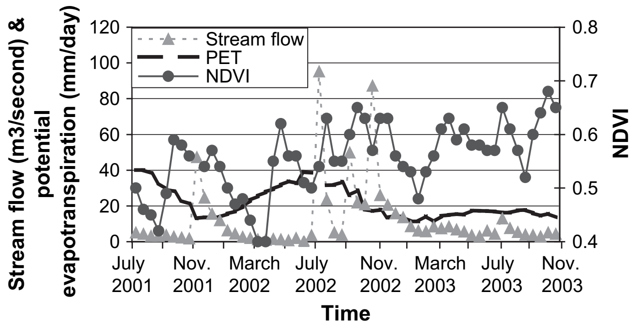

Figure 3. Ten-d averaged stream flow ×10 (m^3/s), PET (mm/d), and NDVI from July 2001 to October 2003.

(p = 0.00, r^2 = 0.98). The PET data for this study were derived based on the temperature data acquired from the station between the two wells, and certainly, it was strongly correlated to the temperature data (Table 1). The results (Table 1) showed that the temperature correlated less to the ground water level in both the recharge and artesian zones than the PET did. Hence, the temperature data were removed from this study.

Similar high correlations occurred with stream flow data in the contributing and recharge zones (p = 0.00, r^2 = 0.79). Both stream flows barely correlated to the ground water level in the recharge zone (Table 2). However, the stream flow from the recharge zone had a significant correlation to the ground water level in the artesian zone, unlike the stream flow from the contributing zone (Table 2). Thus, the stream flow from the recharge zone was selected as an independent variable for this study.

Two sets of precipitation data obtained in the contributing zone were significantly correlated (p = 0.00, r^2 = 0.74), and a similar correlation (p = 0.00, r^2 = 0.77) occurred for the precipitation data acquired in the artesian zone. Moreover, the precipitation data from different zones were significantly correlated with a lower r^2 value ~0.42. The results (Table 3) showed that significant correlations occurred between the precipitation and stream flow, and no significant correlations were observed between the simultaneous precipitation and ground water level in both recharge and artesian zones. Therefore, the precipitation data were eliminated from this study. A total of three independent variables, NDVI, PET, and stream flow, were applied to this study (Figure 3).

Depth of Ground Water in the Artesian Zone

The ground water level was independently correlated to each variable, PET, NDVI, and stream flow. Among them, PET carried the most information (r^2 = 0.58) for estimating the water level, and the stream flow provided the least information (r^2 = 0.09). The NDVI was the second most important variable (r^2 = 0.25). The estimation efficiency (E) was >0.71 when all three independent variables were applied for multiple regression (Figure 4a), and the fitted relationship was:

$$\text{ground water level} = 440.43 + (-0.40) \times \text{PET} + 15.21 \times \text{NDVI} + 0.89 \times \text{stream flow} \quad (2)$$

The time series between dependent and independent variables was considered in this study. Results showed that the present water level was significantly correlated to the current and future 10-d NDVI and PET. However, the estimation efficiency of close to 0.64 for the future 10-d data was lower than the 0.71 for the current 10-d data. Moreover, the objective of this work was to develop a method using remote sensing data to monitor the real-time ground water level. Thus, the multiple regression of future 10-d NDVI and PET data was not pursued further.

Depth of Ground Water in the Recharge Zone

The ground water level in the recharge zone was less predictable compared to the one in the artesian zone. Only two variables were significantly correlated to the water level in the recharge zone. One was PET and the other one was NDVI. The PET provided the most information and had an r^2 value of 0.45. The NDVI variable had an r^2 value of ~0.30. The PET and NDVI variables produced an

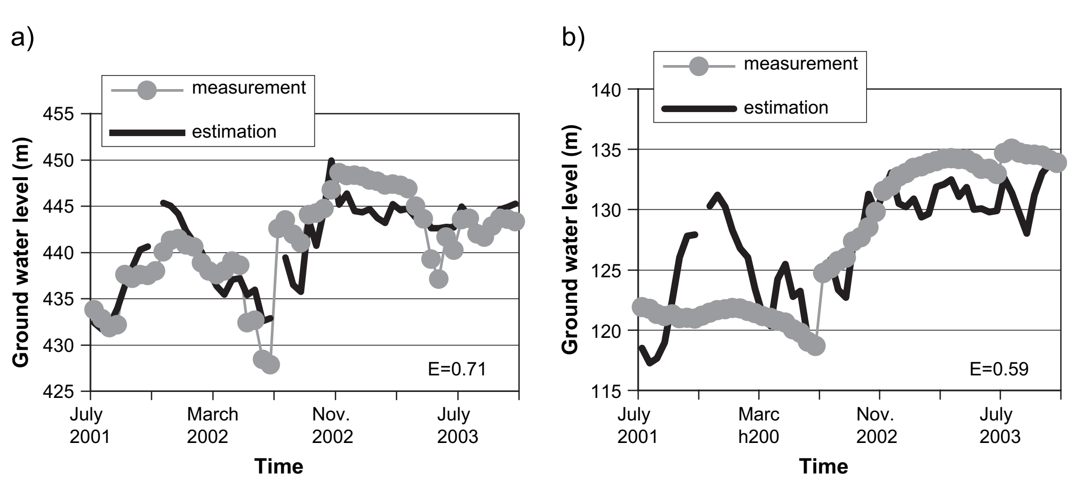

Figure 4. Ten-d profiles of measured and estimated ground water level (above well bottom) from July 2001 to October 2003 in (a) the artesian zone and (b) the recharge zone. The few missing estimations were caused by lack of NDVI or evapotranspiration data.

estimation efficiency of ~0.59 (Figure 4b), and the relationship fitted to the data was:

$$\text{ground water level} = 119.24 + (-0.4) \times \text{PET} + 30.57 \times \text{NDVI} \quad (3)$$

A similar time difference occurred between the variables of PET and water level, but it was not of concern because of a low estimation efficiency ($E < 0.50$).

Precipitation

The results revealed that the precipitation falling in the contributing and artesian zones did not recharge the ground water in the recharge and artesian zones within a short time (10 d). Additional work was pursued to determine the relationship between precipitation and ground water level in the study area. Monthly precipitation and ground water level data were collected for the past 10 years. No significant correlations were found when time lags from a minimum of zero months to a maximum of 12 months were considered. Moreover, the results showed that no significant correlation was found between the differences of 10-d precipitation and of 10-d ground water level. This finding conflicted with most published results where precipitation was significantly correlated to ground water recharge. One of the possible reasons is that the barrier faults control the movement of water in the Edwards Aquifer.

Independent Validation

Accuracy assessment is essential to the validation of research methods using remotely sensed data (e.g., Congalton and Green 1999). A total of 27 data (average of the first 10 d of each month) from August 2001 to October 2003 were used to validate the remote sensing approaches for ground water level estimation. The estimated ground water levels acquired from Equations 2 and 3 were evaluated using corresponding real measurements. The results showed that the estimation efficiency (E) value of ground water level was 0.67 for the artesian zone (Figure 5a) and 0.47 for the recharge zone (Figure 5b). The validated E value of 0.67 was very close to the originally developed E value of 0.72, which indicated that the approach (Equation 2) for the artesian zone is reliable for estimating ground water level. However, the E value 0.47 was lower than the original (0.59) for the recharge zone, and moreover, Figure 5b showed a poor correlation between the measured and estimated ground water levels. Further investigation is required to reliably estimate the ground water level in the recharge zone.

Discussion

In general, it takes a long time, several weeks to years, for surface water to permeate through soil layers and rock formations and to replenish the aquifer. Studies related to ground water recharge normally used monthly to annual precipitation data (e.g., Hadzisehović et al. 1995; Ginting et al. 2000). The results of this study indicate that local precipitation did not notably affect ground water levels within 10 d in the study area. Several measurements in the recharge zone showed that rainfall events had little input on ground water levels, with several rainfall events coinciding with a decrease in ground water levels (Figure 6a). Conversely, the measurements of ground water level in the artesian zone correlated well to precipitation data (Figure 6b), though the increase of water level was not in proportion to the increase of precipitation. Moreover, the additional 10-year monthly data for the study area did not establish the relationship between the difference of precipitation and ground water recharge and discharge. All the results illustrated that the precipitation did not recharge the ground water in the short term in this study. Ground water level could be influenced more by decreased pumping after a rainfall event than by direct recharge. Ground water discharge was normally related to several circumstances, such as natural flow when water levels were very high, water pumped from the aquifer by industrial and residential consumers, and high ET (e.g., Laczniak et al. 1999; DeMeo et al. 2003). Certainly, a great number of barrier faults in the recharge and artesian zone play an important role in ground water recharge and discharge. More investigations are required to identify the source for ground water recharge and the cause of ground water discharge.

Although precipitation data were not correlated to the ground water level, this study showed that stream flows

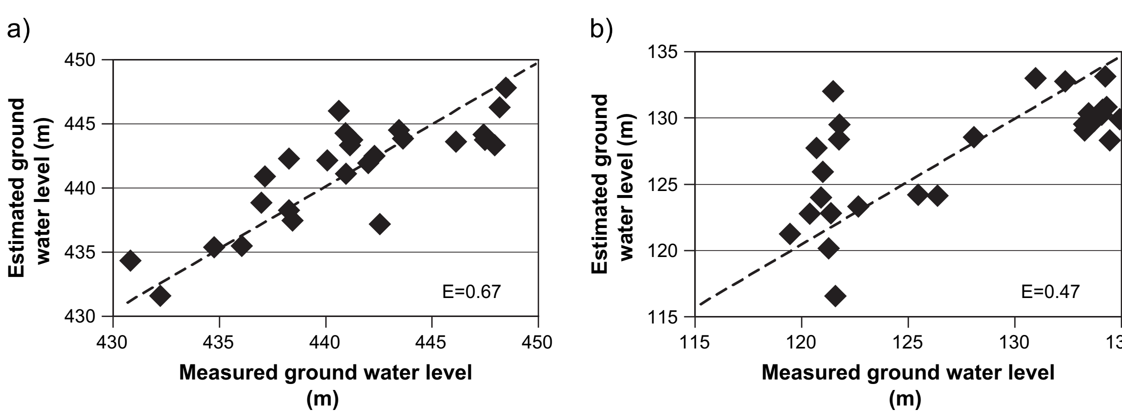

Figure 5. Estimation efficiency of ground water level (above well bottom) from July 2001 to October 2003 in (a) the artesian zone and (b) the recharge zone.

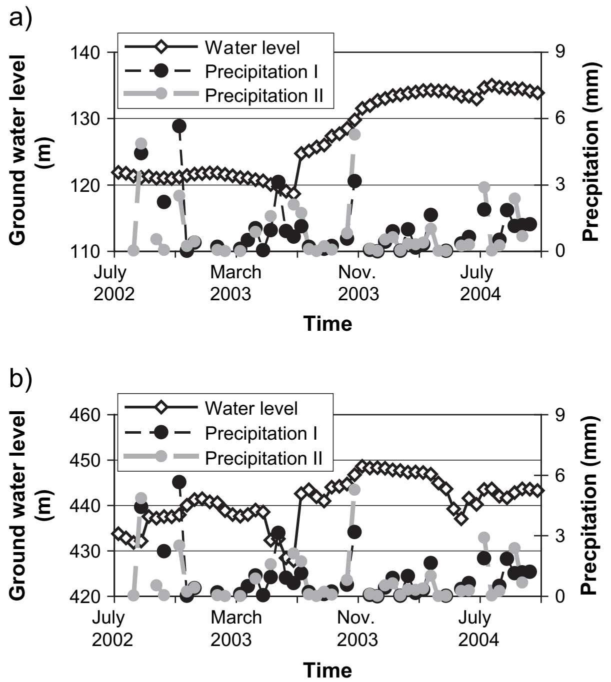

Figure 6. Ten-d profiles of precipitation and ground water level (above well bottom) in (a) the recharge zone and (b) the artesian zone.

significantly contributed to ground water recharge within 10 d in the artesian zone. According to the measured data, the stream flows responded to the rainfall, and the length of response time was dependent on the amount of precipitation. In addition to increasing stream flows, a portion of the precipitation was lost to ET and another portion to runoff. This study showed that stream flow contributed <10% ($r^2 = 0.09$) of information for ground water level estimation in the artesian zone, which could be related to the impermeable limestone in the artesian zone controlling water movement. No correlation was found between stream flows and the ground water level in the recharge zone. One possible reason was that complex faults in the recharge zone acted as barriers or partial barriers to ground water flow. Further studies are required regarding ground water levels in the recharge zone in response to stream flows.

This study showed that the NDVI was correlated to ground water levels in both the recharge and artesian zones. The vegetation index is a response of the green vegetation condition to environmental factors including soil moisture and water availability. Higher NDVI values implied sufficient surface water to stimulate vegetation growth and to support local water needs, and less demand for ground water was consequently expected. Hence, the NDVI value was positively correlated to ground water level. Studies done in Death Valley, California, and Nye County, Nevada, found that the ground water discharge was largely lost to ET (e.g., Laczniak et al. 1999; DeMeo et al. 2003). Higher values of ET indicated less ground water available for use in their studies. As a result, the PET was negatively correlated to ground water level in our study. However, the deep ground water had little potential to lose to ET directly. The negative correlation was in consequence that high PET corresponded to a high demand of ground water (pumping) due to less available surface water. This study showed that both variables of NDVI and PET carried more information for ground water level estimations in the artesian zone than in the recharge zone.

Results showed that the data in the artesian zone had a higher estimation efficiency compared to the data in the recharge zone. Moreover, the differences of estimation efficiency between original data and validated data were 0.04 for data in the artesian zone and 0.12 for data in the recharge zone. The Figure 6a showed that ground water levels in the recharge zone were barely affected by precipitation measured in the watershed. All results in this study showed that the ground water level in the recharge zone is difficult to estimate or model. Continued studies are needed to improve the approach for estimating ground water levels in the recharge zone.

Conclusions

Several research studies have applied digital satellite data to study surface water, such as flood mapping, seashore (or coastline) change, and sea surface temperature monitoring. Few studies have been conducted using remote sensing methods to survey ground water level. This study successfully linked satellite data to ground water levels in the artesian zone of the Seco and Hondo creek watershed, while more studies are required to develop a reliable approach for ground water level estimation in the recharge zone. Our study found that local precipitation did not recharge ground water. Numerous faults in the watershed may obstruct water movement or prevent uniform mixing of water throughout the aquifer. More research is required regarding tracking the fate of runoff and infiltration of surface water downward into the aquifer. The NDVI values from satellite data and PET from meteorological data provided an additional data source for monitoring ground water levels. Both NDVI and PET did not correlate to amount of ground water recharge but of ground water use. Since two-thirds of the world's fresh water is found underground, ground water studies are needed to efficiently protect the decreasing water resource.

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