WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Using Ground Penetrating Radar and Tensiometry to Estimate Recharge from the Rillito Creek

Focus categories: WS, GW, SW

Keywords: Arid Climates, Evaporation, Evapotranspiration, Hydrology, Groundwater Recharge, Hydrogeology, Infiltration, Percolation, Rivers, Soil Physics, Subsurface Drainage, Unsaturated Flow.

Duration: March 2000 through March 2001.

Federal Funds Requested: $12,000

Nonfederal Matching Funds Pledged: $27,610

Principal Investigator: Paul Ferré, University of Arizona.

Congressional District of University: Arizona 5th Congressional District

Statement of critical regional or state water problems

The desert Southwest faces crucial decisions in the coming decades regarding the most prudent use of its water supplies. These decisions require detailed knowledge of the components of the water budget: recharge (both natural and artificial), evapotranspiration, and extraction. Of these elements, the contribution of infiltration at the ground surface to ground water reserves is most poorly understood. The major objective of this proposed research is to provide direct measurements of recharge from the Rillito Creek into the aquifer serving the city of Tucson.

Existing methods of recharge infiltration rely on indirect measurements of water flux through the subsurface. The proposed research will apply a geophysical mapping tool, ground penetrating radar, in a new way to determine changes in the water stored in the subsurface following an ephemeral flow event in the Rillito Creek. This will provide a more direct measure of the recharge flux, which can be used to verify the existing, less direct methods.

Statement of results or benefits

The proposed research project will produce direct measurements of water loss from the shallow subsurface following a stream flow event. We will use these results to constrain numerical analyses with to determine the rates of both recharge and evapotranspiration from the subsurface. Both of these measures are critical for the application of numerical models to long term water supply analyses. Finally, this work will demonstrate the ability of a new method of field water content measurement, which can be transferred to similar problems at other sites to improve in the design and monitoring of artificial recharge systems, landfill covers, and water-efficient irrigation schemes.

Nature, scope, and objectives of research.

The desert Southwest faces crucial decisions in the coming decades regarding the most prudent use of its water supplies. Water is central to the quality of life and economic viability of the Southwest. The need for water is evident to each individual user. However, the impacts of water extraction, including land subsidence, damage to protected riparian areas, and increased costs of water, can be determined and mitigated only by the larger community. Technically, these decisions require detailed knowledge of the components of the water budget: recharge (both natural and artificial), evapotranspiration, and extraction. One of the most poorly understood components of this water budget is the contribution of infiltration at the ground surface to ground water reserves. The major objective of this proposed research is to provide direct measurements of recharge from the Rillito Creek into the aquifer serving the city of Tucson.

In arid regions natural recharge can be highly complex. Sparse, heavy rain events often fall on very dry soils. Low antecedent moisture conditions retard the infiltration of water into the soil, leading to high degrees of runoff. Water flowing overland is collected in channels, often forming fast-moving, short-lived rivers. Very little is known about the processes of infiltration and recharge into the subsurface beneath these ephemeral water bodies. After the waters recede, much of the water that has infiltrated into the subsurface may be located very near the ground surface. To complete a water budget it is necessary to determine how much of this infiltrated water will be lost through evaporation before reaching the underlying aquifer as recharge.

The Tucson office of the United States Geological Survey (USGS) has undertaken an investigation to quantify recharge to the aquifer underlying the city of Tucson from ephemeral flows within the bed of the Rillito Creek. This project involves direct measurement of water table fluctuations and stream gauging, the application of surface gravity and seismic methods to estimate temporal changes in subsurface water storage, and estimations of percolation rates through the riverbed using heat as a tracer. However, no direct measurements of water storage within the vadose zone are planned as part of this investigation. The proposed research would add this key component to quantifying recharge from the Rillito Creek through a year-long program of direct field measurements in the creek bed. By quantifying water movement near the ground surface, these results will improve the reliability of our estimates of Tucson’s future water resources. In addition, the data collected during this study will provide necessary validation for unproven methods of water recharge measurement that would improve our ability to design and monitor artificial recharge systems, landfill covers, and water-efficient irrigation schemes.

Methods, procedures, and facilities.

To develop a complete water balance, the recharge flux of water to an aquifer must be determined. Recharge represents the difference between the water that infiltrates across the ground surface and the water later lost to evapotranspiration. Alternatively, recharge can be defined as the flux of water past a depth at which evaporation and transpiration no longer act to remove water from the subsurface. The primary difficulty in measuring recharge is the lack of an easily applied, direct measure of water flux past a point deep in the subsurface. Rather, fluxes are commonly calculated from a measurement of the gradient of the energy potential of water at a point and an estimate of the hydraulic conductivity of the medium at the same location. Further complicating this approach, the hydraulic conductivity of an unsaturated medium changes nonlinearly in response to changes in the energy potential of the water at the point of measurement. In the proposed research, we will take a different approach, using detailed near-surface measurements to quantify evaporative loss coupled with measurements of total water stored in the uppermost 10 meters of the subsurface to estimate recharge.

Quantifying total water loss from the shallowest 10 m

In the proposed research, rather than attempting to determine the water flux at a point in the subsurface, we will measure directly changes in the total water stored in the near surface. Water content measurement in a dynamic flow system requires rapid, nondestructive measurement of the water content. Two indirect, nondestructive methods of water content measurement are applied widely in soils: neutron moderation and time domain reflectometry (TDR). Neutron measurements rely on the interaction of source neutrons with hydrogen atoms in the soil, relating hydrogen density to water content. In practice, a probe is lowered in a borehole and the water content is profiled with depth. In the TDR method, a metal probe is inserted into the soil and the velocity of propagation of an electromagnetic wave along the probe is measured to infer the water content. This method gives more accurate water content measurements over a more well-defined sample volume, but is practically limited to very short depths, typically less than one meter. We propose to use a third indirect method, ground penetrating radar (GPR), to measure the water content of the shallow subsurface beneath the creek bed.

Like TDR, GPR is based on the measurement of the rate of propagation of electromagnetic waves through the subsurface. However, unlike TDR, the waves are unguided, transmitted through the subsurface without the use of a metal probe. Two antennae are used. The first transmits a pulse of electromagnetic energy at a fixed frequency and the second records energy reflected from subsurface objects. In one typical application, measurements are made along a transect and plotted as the time delay between the transmitted and received energy as a function of the location along the path. Figure 1 shows the response from two buried underground storage tanks. Notice that the right axis has been converted to depth through the use of an assumed water content profile through the subsurface.

We propose a novel application of GPR, using the demonstrated capability of the method to locate buried objects to calculate the change in water stored above a buried object. The project will proceed in three steps: locating a suitable target, estimating the depth of the target, and monitoring changes in the travel time following a stream flow event.

Flow in the Rillito can be violent, with displacement of large objects, both natural and man made. Our first task will be to complete a GPR survey over a 10 m by 10 m grid to locate a clear subsurface anomaly. Ideally, we will locate a target that lies approximately 10 m below ground surface. At this depth, the target should be at least 1 m wide for clear identification. Likely targets include a boulder, a piece of construction material, or a section of a tree trunk. This survey will be conducted during the winter following an extended period with no precipitation or flow in the creek. Using a neutron probe, we will profile the water content in the vicinity of the target to ensure that the subsurface has drained completely. We can then assign a velocity appropriate for the dry material to determine the actual depth to the buried target.

Flow events in the Rillito are short-lived, typically lasting from 12 hours to 2 days. Numerical modeling of recharge into an initially dry creek bed shows that the wetting front will reach 10 meters depth after approximately 2 hours. Therefore, even for very short flow events, the subsurface should be saturated to a depth far greater than 10 m. The increased water content of the soil, compared to the background dry conditions, causes a decrease in the velocity of propagation of electromagnetic waves through the soil. As a result, a GPR survey over this initially saturated profile will show a similar reflection event from the buried target, but the measured travel time will be longer. The measured travel time under saturated conditions will serve as a second calibration point for the use of GPR for water content determination. As before, a neutron probe survey will be conducted to ensure that the water content is uniform through the subsurface at the time of the GPR survey.

Following cessation of flow, the subsurface will drain. The response of the upper 10 m can then be represented as a one-dimensional system with free drainage at the base and loss through evaporation at the ground surface. The flux across the lower boundary represents eventual recharge to the aquifer. Figures 2a and 2b show modeled profiles of the water content during drainage. There is no evaporative loss at the surface for either case. The only difference between the cases is the saturated hydraulic conductivity: Ks = 360 cm/hr for case a and 1800 cm/hr for case b. Profiles are shown after 1, 4, 20, and 100 hours. The corresponding average water contents to 10 m depth for case a are: 0.29, 0.24, 0.19, 0.15. For case b, the water contents are 0.23, 0.19, 0.15, and 0.11. After calibration to the fully drained and fully saturated conditions, GPR will be able to resolve these water content differences. Then, the saturated hydraulic conductivity can be varied in a numerical model, constrained by the average water content in the upper 10 m of the profile, to determine an effective value for infiltration at the field scale. Further modeling will be conducted to assess the impacts of spatial heterogeneity of the hydraulic parameters on the applicability of this method.

Quantifying evaporative loss

The total water lost from a depth interval of the subsurface is the sum of the water lost through evaporation and the flux past the base of the measurement domain. We used the same numerical model to determine the potential impacts of evaporative loss on the drainage profiles. Two conditions were modeled: no evaporative loss from the ground surface and an evaporative loss of 0.034 cm/hr, equal to the maximum rate reported by AZMET for the summer months in Phoenix. The saturated hydraulic conductivity was 360 cm/hr for both cases. There was no measurable difference in the water content profiles with and without evaporation (not shown). However, there are significant differences in the near surface pressure head profiles that developed during drainage both with and without evapotranspiration (Figures 3a and 3b). Differences as large as 25 cm arise near the surface within one day. Differences of 10 cm are seen to a depth of 4.5 m after 4 days. Therefore, we propose to make detailed measurements of the pressure head profile to a depth of two meters and to use these values to constrain the numerical simulations, providing an in situ estimate of water loss through evapotranspiration.

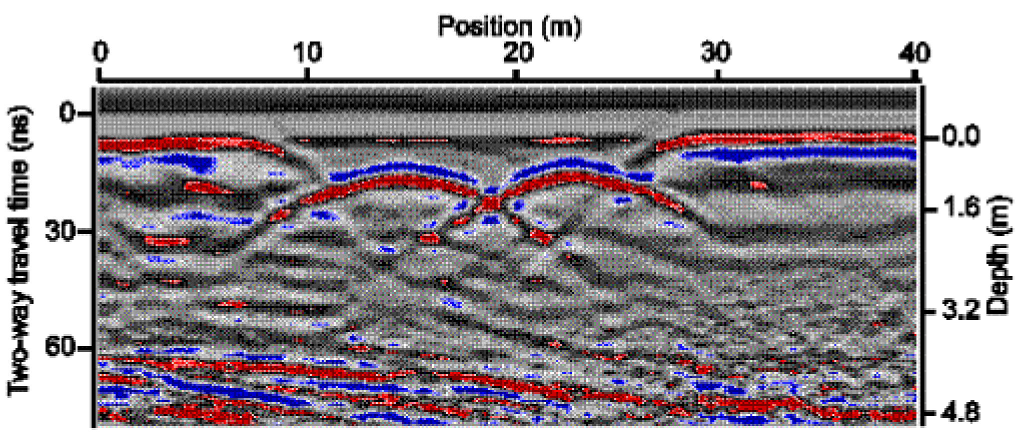

Figure 1. GPR survey conducted over two underground storage tanks. (Sensors and Software, Inc., http://www.sensoft.on.ca/envidata.htm)

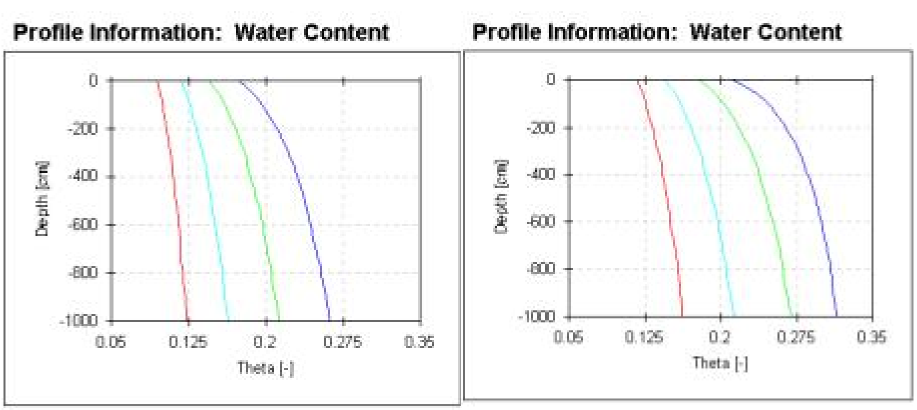

Figure 2. HYDRUS1D model with free drainage at the base of a 30 m domain, no evaporative loss at the ground surface, common van Genuchten parameters used for fine sand. a) Ks = 360 cm/day. b) Ks = 1800 cm/day.

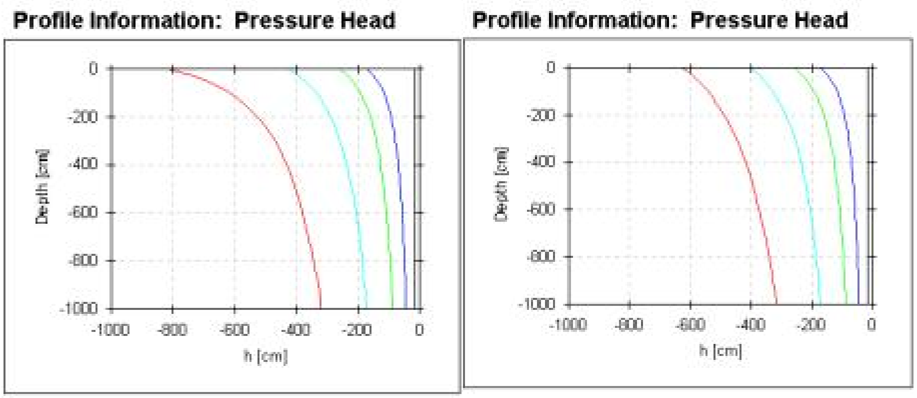

Figure 3. HYDRUS1D model with free drainage at the base of a 30 m domain, Ks = 360 cm/day, common van Genuchten parameters used for a fine sand. a) no evaporative loss at the ground surface. b) evaporative loss of 10 inches/month.

Facilities

The equipment necessary for the proposed project will be available through the USGS and the Department of Hydrology and Water Resources; funding for a graduate student to conduct the research is requested through this grant. A partial list of the equipment available for use in this project includes: geophysical instrumentation (ground penetrating radar, DC resistivity tomography, gravimetery, time domain reflectometry); support equipment (field trucks, computers, software for numerical analyses); and existing field monitoring equipment (monitoring wells, temperature probes, data loggers). In addition, the project will be integrated with an ongoing investigation and will benefit from the experience gained by the USGS personnel who have worked at the site.

Related research.

The proposed research will be closely coordinated with the USGS Rillito Creek project. Our survey will be conducted adjacent to the 1st Street sampling points used for their ongoing investigation. This site includes a monitoring well to measure the water table elevation and a string of temperature probes located within the well at depths both above and below the water table. Our estimates of both infiltration and recharge will offer a unique opportunity to compare stage gauging and temperature profiling methods of recharge estimation with more direct, near-surface measurements.

In addition to the ongoing USGS investigation of recharge into the Rillito Creek, the principle investigator and researchers at the USGS plan to conduct several geophysical surveys in the creek bed during redistribution following the cessation of flow events. Specifically, a DC electrical resistivity tomography survey and a gravity survey are planned. A detailed description of the near surface water content is necessary for a quantitative analysis of all of these methods. Therefore, the results of the proposed investigation will provide data that will be immediately useful both for assessing a hydrologic problem of interest to the state of Arizona and for advancing scientific methods for quantifying recharge.