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Rapid estimation of recharge potential in ephemeral-stream channels using electromagnetic methods, and measurements of channel and vegetation characteristics ☆

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Summary To classify recharge potential (RCP) in ephemeral-stream channels, a method was developed that incorporates information about channel geometry, vegetation characteristics, and bed-sediment apparent electrical conductivity (σ_a). Recharge potential is not independently measurable, but is instead formulated as a site-specific, qualitative parameter. We used data from 259 transects across two ephemeral-stream channels near Sierra Vista, Arizona, a location with a semiarid climate. Seven data types were collected: σ_a averaged over two depth intervals (0–3 m, and 0–6 m), channel incision depth and width, diameter-at-breast-height of the largest tree, woody-plant and grass density. A two-tiered system was used to classify a transect's RCP. In the first tier, transects were categorized by estimates of near-surface-sediment hydraulic permeability as low, moderate, or high using measurements of 0–3 m-depth σ_a. Each of these categories was subdivided into low, medium, or high RCP classes using the remaining six data types, thus yielding a total of nine RCP designations. Six sites in the study area were used to compare RCP and σ_a with previously measured surrogates for hydraulic permeability. Borehole-averaged percent fines showed a moderate correlation with both shallow and deep σ_a measurements, however, correlation of point measurements of saturated hydraulic conductivity, percent fines, and cylinder infiltrometer measurements with σ_a and RCP was generally poor. The poor correlation was probably caused by the relatively large measurement volume and spatial averaging of σ_a compared with the spatially-limited point

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measurements. Because of the comparatively large spatial extent of measurement transects and variety of data types collected, RCP estimates can give a more complete picture of the major factors affecting recharge at a site than is possible through point or borehole-averaged estimates of hydraulic permeability alone.

Introduction

Mapping recharge and recharge potential have been proposed as national priorities for the purposes of assessing ground-water depletion and aquifer vulnerability to contamination (NRC, 2001). The goal of this study was to develop a rapid technique to assess recharge potential (RCP) in ephemeral-stream channels in regions with arid and semiarid climates. We focus specifically on RCP in ephemeral-stream channels, because, in areas with arid and semiarid climates, a significant proportion of regional recharge occurs in ephemeral-stream channels (Scanlon et al., 1999; Goodrich et al., 2004; Coes and Pool, 2005). Infiltration in inter-channel areas is less significant, because the majority of rainfall is either transpired by vegetation, evaporated directly, or flows into channels and depressions (Scanlon et al., 1999; Walvoord et al., 2002; Scanlon et al., 2003). The method developed here provides a spatial snapshot of the variability of recharge-controlling factors including sediment characteristics, channel geometry, and channel-associated vegetation. Without information on temporally varying factors, recharge cannot be quantified. However, by examining ephemeral-stream channel characteristics such as density and species of bankside plants, incision depth and width, and bed-sediment particle-size distribution, RCP can be estimated with one survey greatly improving knowledge along tens of kilometers of an ephemeral stream. One difficulty in assessing RCP that is not addressed by this method is that bed-sediment hydraulic permeability can change by orders of magnitude before, during, and after one flow event (Blasch et al., 2004). This variation depends on a number of factors including degree of saturation, water and sediment temperature, sediment source and load, flow duration and rate, channel gradient, and channel geometry. Flow-induced changes to hydraulic permeability are difficult to predict and measure, and so were not considered for this study. Though not typically the ultimate goal of most recharge studies, information on RCP can be used for a variety of purposes, from determining sites for retention and detention basins to identifying areas where ground-water may be vulnerable to contamination from the surface (Nolan, 1998; Maurer et al., 2004). Maps of RCP can be used in the initial phases of recharge studies to identify sites for long-term monitoring and for the extrapolation of study results to areas between monitoring sites.

Recharge is one of the more difficult components of any regional water budget to estimate (Goodrich et al., 2004). Many methods for assessing recharge and RCP at both local and regional scales have been developed (Osterkamp et al., 1994; Dowman et al., 2003; Hevesi et al., 2003; Murray et al., 2003; Goodrich et al., 2004; Maurer et al., 2004; Scanlon, 2004). Traditional methods for improving recharge estimates, by drilling and instrumenting boreholes, and by monitoring streamflow, are expensive owing to the physical scale of many watersheds and urbanized areas. These methods often require significant amounts of time to collect temporally representative data sets. Given the high spatial and temporal variability of precipitation in arid and semiarid climates and streamflow in ephemeral-stream channels, even studies of years to decades may not adequately capture long-term recharge variability.

The present study was motivated by a simple question: Can the understanding of spatial variability in recharge-controlling factors be significantly improved through application of existing geophysical tools, and field observations of channel and vegetation characteristics? The method that evolved offers several advantages over other existing methods. Specifically, the technique is areally extensive, noninvasive, rapid, and inexpensive. Important factors can be constrained that often are ignored or estimated, such as channel and vegetation characteristics. The method was designed to help maximize the efficiency and cost-effectiveness of traditional recharge-quantification methods. The high measurement density and wide areal coverage result in better constrained extrapolation of physical and hydraulic properties between boreholes than with traditional methods. Thus this approach, when combined with appropriate estimates of precipitation, evapotranspiration, runoff, etc., may be used to improve recharge estimates, when more involved, expensive methods are beyond the means of a project.

Objectives

There were two primary objectives in this study. The first was to develop a method to combine measurements of bed-sediment apparent electrical conductivity (σ_a), channel geometry, and vegetation type and density to estimate RCP along ephemeral-stream channels. The second objective was to compare RCP designations and measurements of σ_a to other measurements that can be used as surrogates for permeability at six unsaturated-zone research sites. These measurements include saturated hydraulic conductivity, cylinder-infiltrometer flux, and percentage of fines previously obtained by Coes and Pool (2005) and GeoSystems Analysis, Inc. (GSA) (2001, 2004).

Background

The climate in the study area, Sierra Vista, Arizona, is arid to semiarid with infrequent, sporadic, spatially-variable precipitation (Coes and Pool, 2005) (Fig. 1). The majority of stream channels are ephemeral. Meinzer (1923) defined ephemeral-stream channels as those that convey flow in direct response to precipitation events and which are permanently above the water table. When overland flow

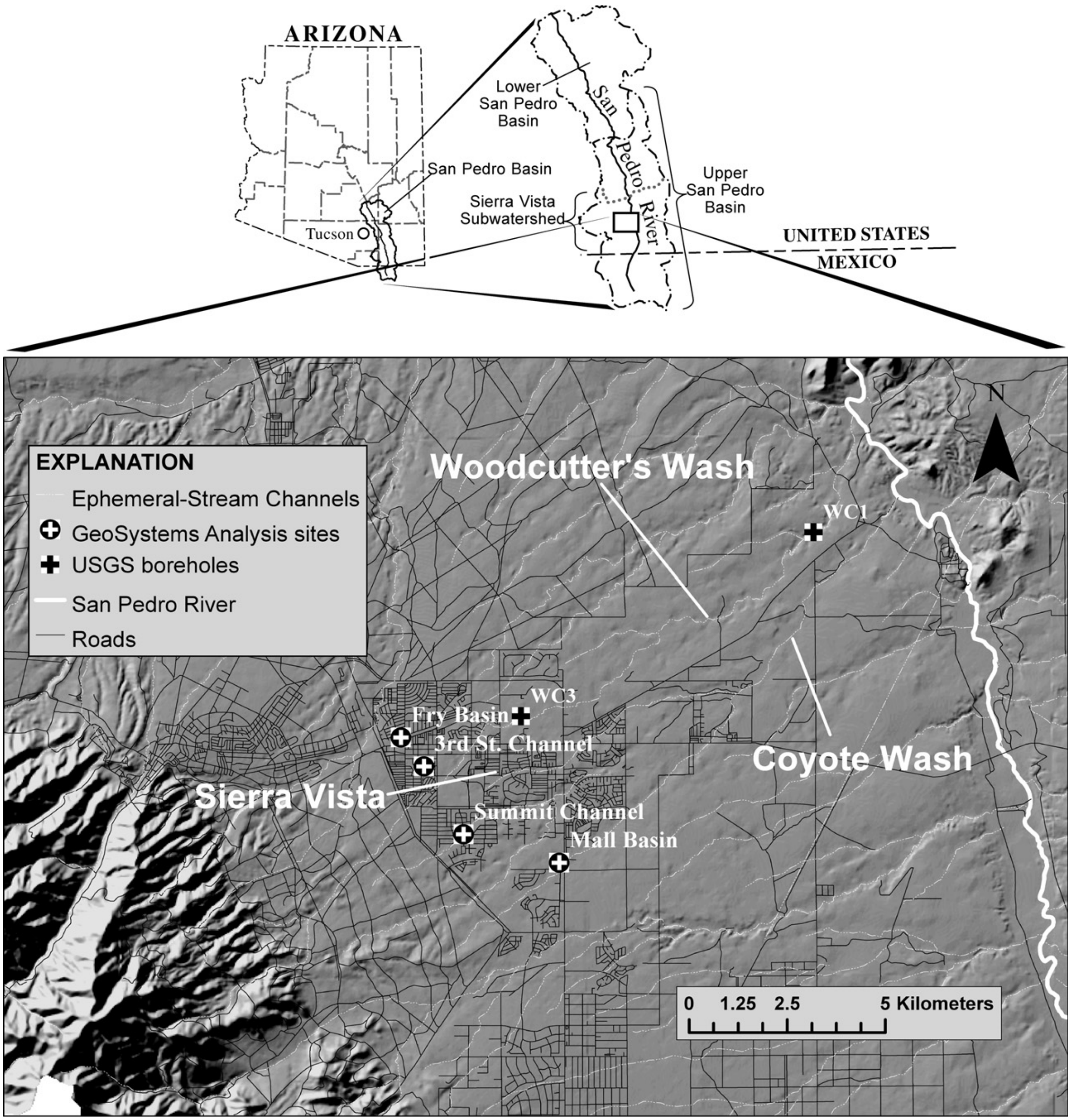


Figure 1 Index map of study area showing Coyote and Woodcutter's washes, the town of Sierra Vista, and the San Pedro River, as well as previously established unsaturated-zone monitoring sites.

events occur, much of the runoff enters ephemeral-stream channels. Even in arid regions with perennial rivers or streams such as the San Pedro River basin, a substantial portion of recharge may occur in tributary ephemeral-stream channels (Goodrich et al., 2004; Coes and Pool, 2005). Osterkamp et al. (1994) found that infiltration (transmission loss) into ephemeral-stream channels accounted for 90% of recharge in the Amargosa River Basin. Recharge is typically defined as water that moves from the unsaturated zone across the water table into the saturated zone (NRC, 2004). Water moving into perched systems is sometimes included in this definition. For the purposes of this study, recharge is defined as water that moves below the root zone.

A number of methods for determining RCP exist, but there is no clear agreement on approach or factors to be considered. Methods tend to be tailored to the type of investigation. For example, Murray et al. (2003) developed a GIS-based study to assess soil and geologic constraints on RCP at a scale of 1:24,000. Their interest was sustainable use of ground-water resources. They used soil-permeability rates, depth to bedrock, and presence of perched groundwater to develop maps of RCP. Though most of the recharge in the area studied occurred through areally extensive loess deposits, they acknowledged the significance of recharge in streams in which ground-water levels were below stream elevation. Munévar and Mariño (1999) used the concept of RCP to evaluate the possibility of artificial ground-water recharge on alluvial fans by considering available information on soil texture and hydraulic properties along with data from soil surveys, borehole logs, permeability tests, and monitoring of ground-water response to rainfall and runoff. Maurer et al. (2004) used five factors to assess RCP as a part of a project to develop a Nevada state map of aquifer contamination vulnerability. The factors were mean annual precipitation, soil permeability, land-surface slope, aspect, and hydrogeologic unit. A survey of modeling approaches to assess aquifer vulnerability to contamination was done by Nolan (1998). He compared both deterministic and stochastic solute-transport models with statistical, GIS-overlay, and index models. In contrast with the present study, most of these studies were broad-scale assessments of RCP (ranging from basin-scale to national-scale). They include the whole land surface – interdrainage as well as intradrainage areas. Because the scale and focus of the present study are quite different from these others (intradrainage areas only, scales of tens of kilometers), it was necessary to approach RCP differently.

To arrive at a definition of RCP in ephemeral-stream channels and to decide which parameters to measure, the concept of a water budget was applied to an ephemeral-stream channel reach. Water flux in ephemeral-stream channels occurs below ground for much of the year. Therefore a reach is defined to include the region from the bottom of the root zone to the top of the vegetation on the stream bank. The water budget of such a reach is determined by precipitation, evapotranspiration, recharge, and horizontal inflow and outflow of surface and unsaturated-zone water. Internal processes include bed-infiltration and subsurface redistribution. Time and expense make it difficult to determine these fluxes with precision, but factors that are ''constant'' (i.e. vary slowly with respect to the processes in question) are relatively easier to study and can be used to infer the potential magnitude of some components of the water budget. Factors that vary slowly include particle-size distribution of channel-bed material, channel-incision width, density, and type of bankside and in-channel vegetation, climate, and gradient. All of these factors or their surrogates were measured for this study, with the exception of climate.

Conceptually, as used in this study, RCP is the relative potential for water entering a channel reach to infiltrate into the stream bed and to percolate below the root zone. The evaluation of RCP for a specific study area determines for a specified set of measurable, temporally constant parameters that control the main fluxes in and out of a channel reach, the relative potential for recharge to occur at a specific site in the study area. The measured ranges of specific parameter values measured in the study area are used to create the range of RCP values. Thus, if this method were applied to another site, a different range of RCP values would be produced. This makes it possible to compare sites only if the same data types and similar vegetation and climate are present. If it is desired to compare sites with different climate and vegetation, species-specific potential evapotranspiration rates also would need to be compared rather than just plant density and tree diameter as was done for this study.

Apparent electrical conductivity of the subsurface is related to, among other factors, the particle-size distribution of bed-sediment. Under certain conditions, σ_a is inversely proportional to particle-size and hydraulic conductivity of the subsurface (Curtis and Kelly, 1990; Slater and Lesmes, 2002). As clay content increases so does σ_a. The relation between particle-size distribution in soils and hydraulic conductivity also is well established (Zeleke and Si, 2005). Therefore, in unconsolidated sediment, particle-size distribution and thus σ_a may be used as a surrogate for estimating the potential for ephemeral-stream channel infiltration and percolation as well as for subsurface horizontal flow. Apparent electrical conductivity measured at two depths will give information on the vertical heterogeneity of the subsurface. For example, if the electrical conductivity of the near-surface material is low, and that of deeper material is high, it may be inferred that the near-surface-sediment is coarser grained than is the deeper material. Infiltration may occur through the coarser sediment, but percolation and ultimately recharge may be impeded at depth. Subsurface horizontal inflow and outflow are likely under such conditions.

Channel dimensions also play a significant role in ephemeral-stream channel recharge. During potential maximum flow, deep channels compared with shallow channels contain a greater depth of water leading to greater transmission losses: the deeper the flow, the greater the hydraulic gradient for flow into the bed (Mudd, 2006). Wide reaches have greater bed-surface area than narrow reaches and therefore greater potential for infiltration (Osterkamp et al., 1994). In some modeling studies, wetted channel width was found to have a greater influence on channel infiltration than evapotranspiration (Coes and Pool, 2005) or channel depth (Mudd, 2006).

Evapotranspiration (ET), the sum of evaporation from soil and plant surfaces, and transpiration, is a significant component of water budgets in semiarid regions (Blasch et al., 2005). For instance, in sacaton grasses (*Sporobolus wrightii*) in a semiarid riparian ecosystem, Scott et al. (2000) found that total ET was nearly equal to precipitation. Thus, vegetation density and type can be used to estimate the magnitude of ET. Plants decrease the amount of recharge in a system by intercepting potential recharge. Some plant species in arid climates are able to use water at different depths within the soil (Snyder and Williams, 2000). This depends on vegetation type (e.g., grasses or woody plants) and the amount of water available from seasonal precipitation (Reynolds et al., 2000; Hultine et al., 2003). Grasses tend to draw moisture from the upper half-meter of the soil especially if ground-water is deep (Cox et al., 1986; Tiller et al., 2000). Woody plants, such as mesquite, grow deep tap-roots in addition to lateral roots, increasing access to water at depths unavailable to grasses. Velvet mesquite (*Prosopis velutina*) is a facultative phreatophyte and may have roots extending to a depth of more than 50 m; however, water is preferentially drawn from the top 1 to 3 m and outward to about 10 m beyond the root crown (Cable, 1977; Cuomo et al., 1992; Snyder and Williams, 2000). In the arid southwestern United States, areas dominated by woody plants will have greater ET rates than those dominated by grasses. For instance, rates of ET measured in a velvet mesquite bosque, were higher than rates measured in a nearby sacaton dominated grassland (Scott et al., 2000). Some mesquite species utilize both precipitation and ground-water (Cable, 1977; Scott et al., 2000; Snyder and Williams, 2000; Leenhouts et al., 2006). Velvet mesquites growing near ephemeral-stream channels may extract most of their water from deep sources, whereas those located near a perennial stream may derive most of their water from the shallow subsurface (Snyder and Williams, 2000). Riparian vegetation has an effect on potential recharge through interception and transpiration, and higher densities imply greater ET.

Methods

Apparent electrical conductivity

Measurements of σ_a were made at 25-m intervals of Woodcutter's and Coyote Washes, two ephemeral-stream channels in and near Sierra Vista, Arizona (Fig. 1). Measurements of σ_a also were made at six sites where either drill logs and/or measurements of *in situ* hydraulic properties were available from previous studies. The coordinates and elevations of the majority of σ_a measurement locations were surveyed using real-time kinematic global-positioning system (GPS) geodetic techniques. The rest, the 2.5 km of Woodcutter's Wash closest to the San Pedro River, were surveyed using a handheld GPS. June was chosen as the month in which to collect the σ_a data, because it is generally the hottest, driest time of year and is typically directly preceded by one or more dry months. The lack of precipitation helps to minimize temporal variations in water content and to accentuate the electrical conductivity contrast between sand or gravel, and clay, which retains water.

Variations in σ_a were measured using a low-induction-number frequency-domain electromagnetic-induction (LIN FEM) instrument (EM31-MK2, Geonics, Ltd.). The LIN FEM instrument, oriented parallel to the ephemeral-stream channel thalweg, was used to map the relative amount of fine-textured material in the subsurface to a potential maximum depth of about 10 m (McNeill, 1980; Callegary et al., 2007). The instrument gives a volume-averaged estimate of σ_a in milliSiemens per meter (mS m^{-1}) over two depth intervals depending on the orientation of its transmitter and receiver coils. At low values of σ_a ($\sim$10 mS m^{-1} or less), the shallower measurement, with the coils in a vertical-coplanar orientation (VCP), is focused primarily on material between the surface and the 3-m depth with an assumed maximum of about 6 m depth. The deeper measurement in this range of σ_a, with coils in a horizontal-coplanar orientation (HCP), focuses primarily on material between the surface and 6 m below ground surface with an assumed maximum of about 10 m depth. These depth intervals decrease significantly as σ_a increases, as much as 30–40% at a value of 100 mS m^{-1} (Callegary et al., 2007).

The LIN FEM instrument also recorded an inphase signal which was used to detect cultural interference. Unusual values of σ_a also sometimes indicate cultural interference. Cultural interference can include any object that generates electromagnetic fields such as generators and power lines, as well as metal or potentially metal-bearing construction waste such as concrete. Cultural interference can affect LIN FEM measurements to the point that they do not accurately represent the σ_a of the bed-sediment. Affected σ_a measurements were determined by noting the magnitude of the in-phase and σ_a measurements, as well as distance to interference. Transects having inphase values less than -10 or greater than +10 parts-per-thousand or measured σ_a values less than 0 or greater than 150 mS m^{-1} were excluded from the RCP evaluation. Transects also were excluded if power lines, heavy concentrations of metal (e.g. rebar-laced concrete), or large metallic objects were observed within 15 m of the measurement location.

Channel geometry

Channel-geometry transects were evaluated at 100-m intervals, coinciding with every fourth σ_a measurement. Incision depth and width were determined by assessing spatial changes in vegetation distribution and bank slope. In most cases, incision depth was defined as the vertical distance between the thalweg and the break in slope between the channel and the flood plain or first major terrace (Fig. 2a). Where no obvious channel boundary was visible, incision depth was defined by a contour on the bank that had relatively dense, permanent (woody) vegetation with no visible signs of flow above it (Fig. 2b). At any given transect, generally at least one of these criteria was present.

Vegetation characteristics

Bank vegetation was evaluated at 100-m intervals along all stream reaches. The bank-vegetation evaluation methods

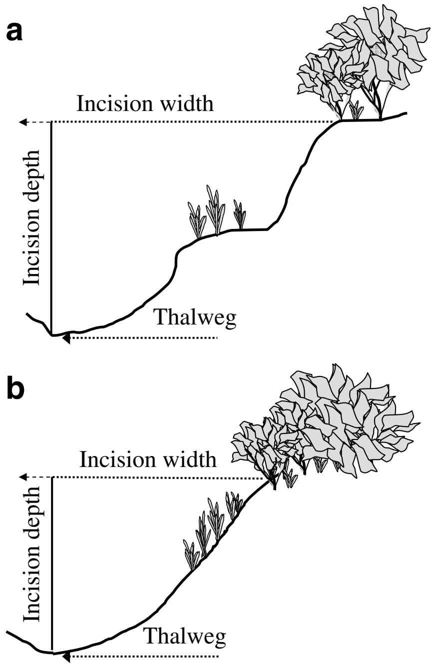


Figure 2 Cross-section of an ephemeral-stream channel showing incision margins. Incision width and depth were defined in reference to (a) the break in slope between the channel and the floodplain or first major terrace or (b) by the boundary on the channel slope formed by permanent (woody) vegetation.

used were modified from Kaufmann (2006). On each bank, a 10 × 10 m plot was visually estimated, and defined as an area 5 m upstream and downstream of each transect (Fig. 3). The plot extended laterally 10 m from the edge of the incision, and extended vertically to the height of the tallest plant. Vegetation density was estimated as the amount of shadow that would be cast by vegetation if the sun were directly over head. Vegetation density estimates were recorded as a percentage of woody plants and grasses, with 100% equaling complete coverage of the transect area. Both deep-rooted shrubs and trees were lumped into the woody-plant density category. Grasses included herbaceous perennial as well as annual grasses and were not differentiated. The four density classes were ''absent'' (0%), ''sparse'' (1—33%), ''moderate'' (34—66%), and ''heavy'' (67—100%). In addition to woody plant and grass density, diameter at breast height (DBH) of the largest tree was visually estimated at each transect. DBH was added to the RCP evaluation, because of the correlation between woody-plant size and the ability to extract water (Meinzer et al., 2004; Scott et al., 2006). DBH may seem unnecessary because woody plant density is included in the evaluation. However, some sites with large trees did not have high woody plant density, and the potentially significant decrease in recharge caused by the presence of the large DBH trees needed to be included in our analysis. Mesquites often had several main trunks. Diameter was determined by summing the estimated diameters of the main trunks and recording the total as a composite DBH.

Before performing the RCP analysis, it was verified that there were no strong correlations among the variables used to evaluate RCP. A correlation coefficient was calculated for all pairs of continuous variables for both ephemeral-stream channels considered together and separately. Pairs of variables with a correlation coefficient greater than 0.5 were considered to have strong correlations. Not surprisingly, VCP- and HCP-σ_a had a strong positive correlation ($R = 0.86$, $p < 0.001$ for the combined data set). VCP- and HCP-σ_a were both retained in the analysis, however, because the similarities and differences between them contain valuable information related to variations in permeability with depth. The only other significant correlations were found in Coyote Wash between VCP- and HCP-σ_a and incision height ($R = 0.55$, $p < 0.001$ for both). Discontinuous variables were plotted pair wise against all other variables and a visual inspection was made, but no strong correlations were found.

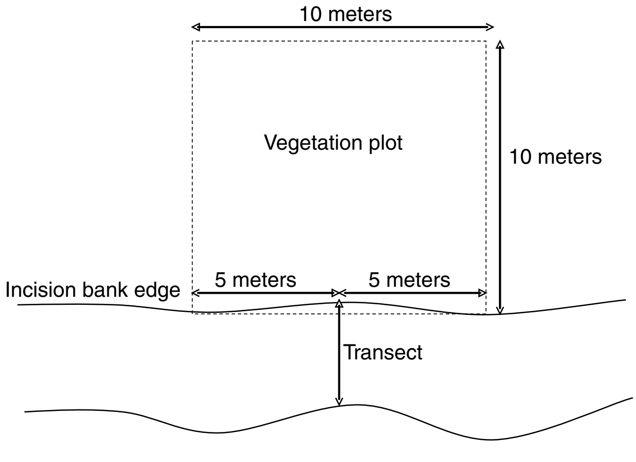


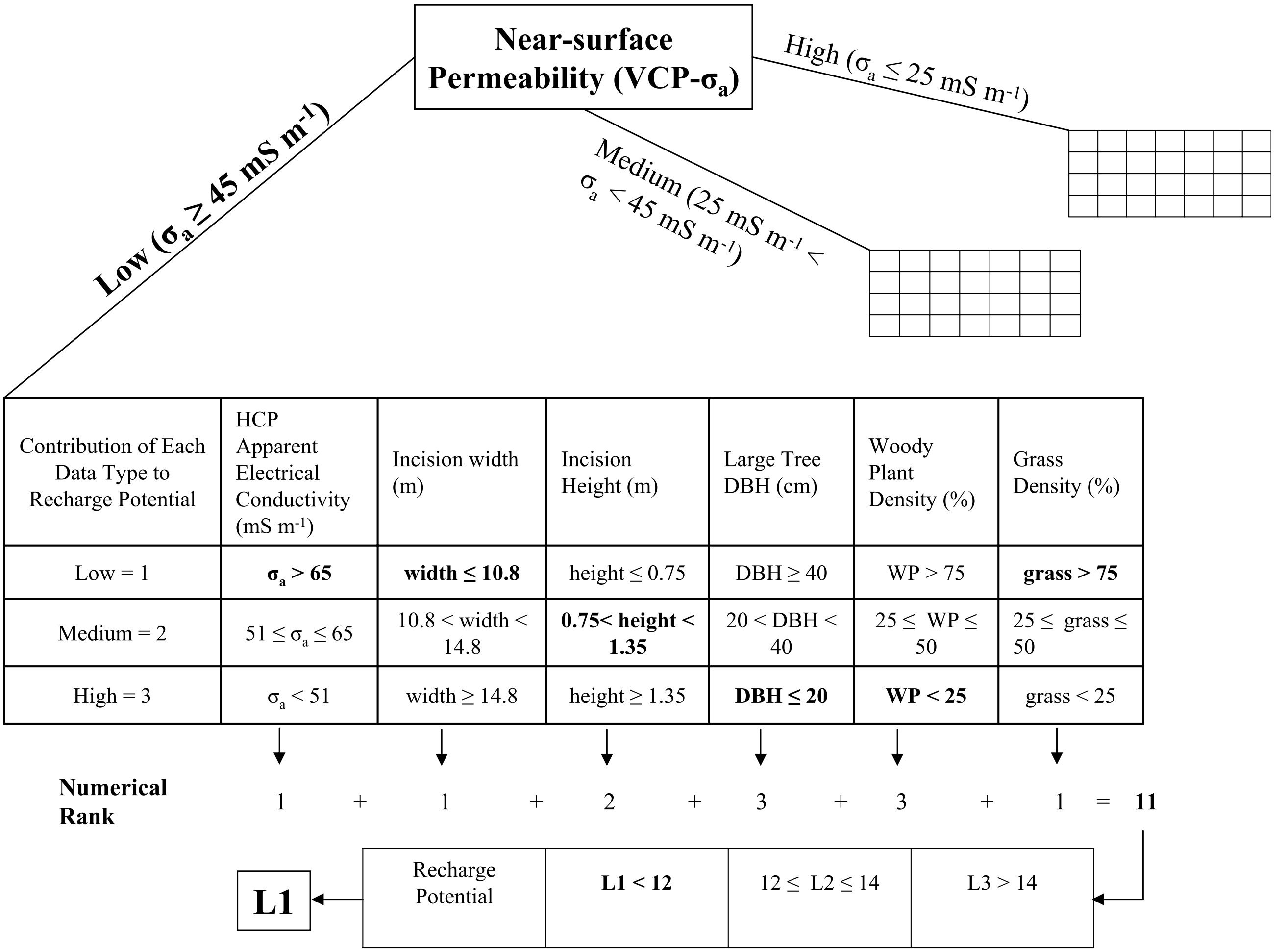
Figure 3 Example of a vegetation evaluation plot showing its dimensions and orientation relative to the ephemeral-stream channel and transect. At each transect, vegetation evaluation plots were done on both banks.

Recharge potential

259 out of 410 vegetation/channel transects were used in the RCP analysis. Those not used were eliminated because of cultural interference. In addition, a RCP classification was made for two USGS and four GSA sites at which previous geohydrologic investigations were done and a comparison with the fractional fine-grain content of the sediment was possible. Measured or estimated hydraulic parameters also were available at most of these sites. Three sites were in Woodcutter's Wash or one of its tributaries (WC1, WC3 and the 3rd Street Channel site); one was in a tributary of Coyote Wash (Summit Channel); and the two remaining sites were in detention basins (Fry and Summit Basins).

A weighting scheme was contemplated for the seven variables in the data set. Unfortunately, few ephemeral-stream channel recharge-sensitivity analyses are reported in the literature. Those that have been published do not consider the same set of factors used in the present study. One variable is present, however, in virtually all RCP and contamination-vulnerability studies, and that is the permeability of surficial sediment, rock or soil. Thus, it was decided to weight VCP-σ_a above all others, because it is correlated with the hydraulic permeability of the shallowest sediment. Subsurface factors, the permeability of deeper sediment and those affecting ET, were considered to be of lesser importance, because if water is strongly impeded from entering the subsurface, these factors will play no role. The remaining factors, incision width and depth, directly affect infiltration, but they vary over a much smaller range of values than permeability, which can vary over orders of magnitude. Therefore it is assumed that these factors play a small role when compared with near-surface hydraulic permeability.

To implement the choice of VCP-σ_a as a master variable and to keep the analysis simple (acknowledging the imprecise nature of the RCP designation), we tried to minimize the number of RCP categories. A decision matrix was constructed to categorize a given transect first by the σ_a of shallow sediment (VCP-σ_a measurements). Transects were binned, according to the measured value of VCP-σ_a, as low, moderate, or high (Fig. 4). To do this, VCP-σ_a values were rounded to the nearest integer, ranked according to magnitude, and duplicates (tied values) were removed. The remaining ranked values were counted, divided into three groups, and given a low (*L*), medium (*M*), or high (*H*) designation according to their contribution to RCP, with the lowest VCP-σ_a values having the highest RCP. This categorization of transects was retained throughout the analysis. All subsequent classification was a refinement of RCP within these three initial categories. After the categorization according to near-surface hydraulic permeability, transects within each category were evaluated using each of the six remaining data types. As with VCP-σ_a, values in each



Contribution of Each Data Type to Recharge Potential	HCP Apparent Electrical Conductivity (mS m^{-1})	Incision width (m)	Incision Height (m)	Large Tree DBH (cm)	Woody Plant Density (%)	Grass Density (%)
Low = 1	**$\sigma_a > 65$**	**width ≤ 10.8**	height ≤ 0.75	DBH ≥ 40	WP > 75	**grass > 75**
Medium = 2	$51 \le \sigma_a \le 65$	10.8 < width < 14.8	**0.75< height < 1.35**	20 < DBH < 40	25 ≤ WP ≤ 50	25 ≤ grass ≤ 50
High = 3	$\sigma_a < 51$	width ≥ 14.8	height ≥ 1.35	**DBH ≤ 20**	**WP < 25**	grass < 25

Recharge Potential	**L1 < 12**	12 ≤ L2 ≤ 14	L3 > 14

Figure 4 Example recharge potential calculation for a transect categorized as ''Low Near-Surface Permeability'' as determined by vertical-coplanar apparent electrical conductivity (VCP-σ_a). The other six data types are considered to be of lesser importance, and were used to produce the second level of classification. At each transect, the data in each class were given a numerical rank that depended on the range for all transects. The numerical ranks were summed and fitted into a recharge potential class: *L*1, *L*2 or *L*3.

data type were ranked and classified as low, moderate, or high according to their contribution to RCP. Each class was assigned a number, 1 for low, 2 for moderate, and 3 for high. At each transect, measured values were compared with the rankings for the appropriate data type and assigned a numerical value (1, 2, or 3) based on where they lay in the ranking. These numerical ranks given to the six measurements (data types) at the transect were summed to arrive at a composite recharge value. The composite values were in turn ranked and classified to give nine recharge potential designations. Within the category of low (*L*) VCP-σ_a values, there were three classes: *L*1, *L*2, and *L*3. Within the category of medium (*M*) VCP-σ_a values, there were: *M*1, *M*2, and *M*3. For high values, the classes were: *H*1, *H*2, and *H*3.

Values used for ranking grass, woody-plant density, and DBH were the average of right- and left-bank estimates. In cases where one of the bank estimates could not be made, the one value was assumed valid for both banks. Further, in areas in which the water table is deep, as is the case in our study area, grasses tend to extract water from a depth of less than 1 m below the surface (Cox et al., 1986; Tiller et al., 2000). Thus, grass density was moved into the high-recharge class, if incision depth was greater than 1 m. For incision depth, both for ranking of values and classifying contribution to RCP, the smaller of the two values was used. This was considered to be the maximum non-flood depth of flow.

Results and discussion

About 41 km of ephemeral channels were surveyed resulting in 1665 measurements of σ_a. Of these, 410 were vegetation and channel geometry transects. The bed material of the ephemeral-stream channels was typically sandy and unconsolidated, but there were also clay, indurated calcium carbonate, and consolidated basin fill in some reaches. Velvet mesquite was the dominant species along both channels, followed by desert broom (*Baccharis sarothroides*). Grasses were only identified by genus. Sacaton (*Sporobolus spp.)* and grama (*Bouteloua spp.*) were the dominant genera found.

Measured values of σ_a along Woodcutter's Wash generally increased with distance down the channel indicating fining of channel-bed-sediments, with σ_a ranging from 10 to 25 mS m^{-1} at the west end of the survey and from 30 to

70 mS m^{-1} at the east end (Fig. 5). Values peaked (45–70 mS m^{-1}) between 3 and 4 km down-channel from the west end of the survey, gradually decreased to 15–30 mS m^{-1} at about 9.5 km down-channel, and rose to a high of 80–100 mS m^{-1} at 11 km down-channel. Between 10 and 15 km, the variability of σ_a increased markedly in a pattern of spatially localized deviations from mean σ_a. The deviations may have been caused by stringers of resistive (sand/gravel) or electrically conductive (clay/calcium carbonate).

Incision width in Woodcutter's Wash ranged from 5.6 to 33 m and peaked near 2 km down-channel, but did not correlate well with either σ_a or incision depth (Fig. 5). Along the channel, incisions widths were scattered, but generally ranged from 5 to 20 m. Constant, adjacent values of width and depth were caused by stretches of channel lined with concrete. In general, incision depth (ranging from 0.2 to 3.0 m) varied widely to about 7.5 km down-channel, and did not apparently correlate with σ_a. Beyond this point, incision depth was small and remarkably uniform to just past 10 km. In this reach, small incision depth corresponded to a zone of low σ_a. The channel sides and bottom were sandy and unconsolidated, which, if the sandy material were laterally and vertically extensive, could explain the small values of channel depth and σ_a. Down-channel of this zone, incision depth was markedly variable, possibly caused by variation in the degree of consolidation of the sediment through which the channel cut. Large-tree DBH ranged from 0.08 to 1.0 m. DBH followed a somewhat cyclic pattern along the length of the channel with increasingly high peaks in the down-channel direction (Fig. 6). The most prominent peaks occurred 2–4 km, 8–10 km, and 13–15 km down-channel. Woody-plant density increased slightly down-channel, with no clear trend in grass density.

Along the main channel of Coyote Wash, σ_a measured with both VCP and HCP instrument orientations increased from about 5 to 25 mS m^{-1} at the west end and from 15 to 55 mS m^{-1} at the east end (Fig. 7). There was considerable

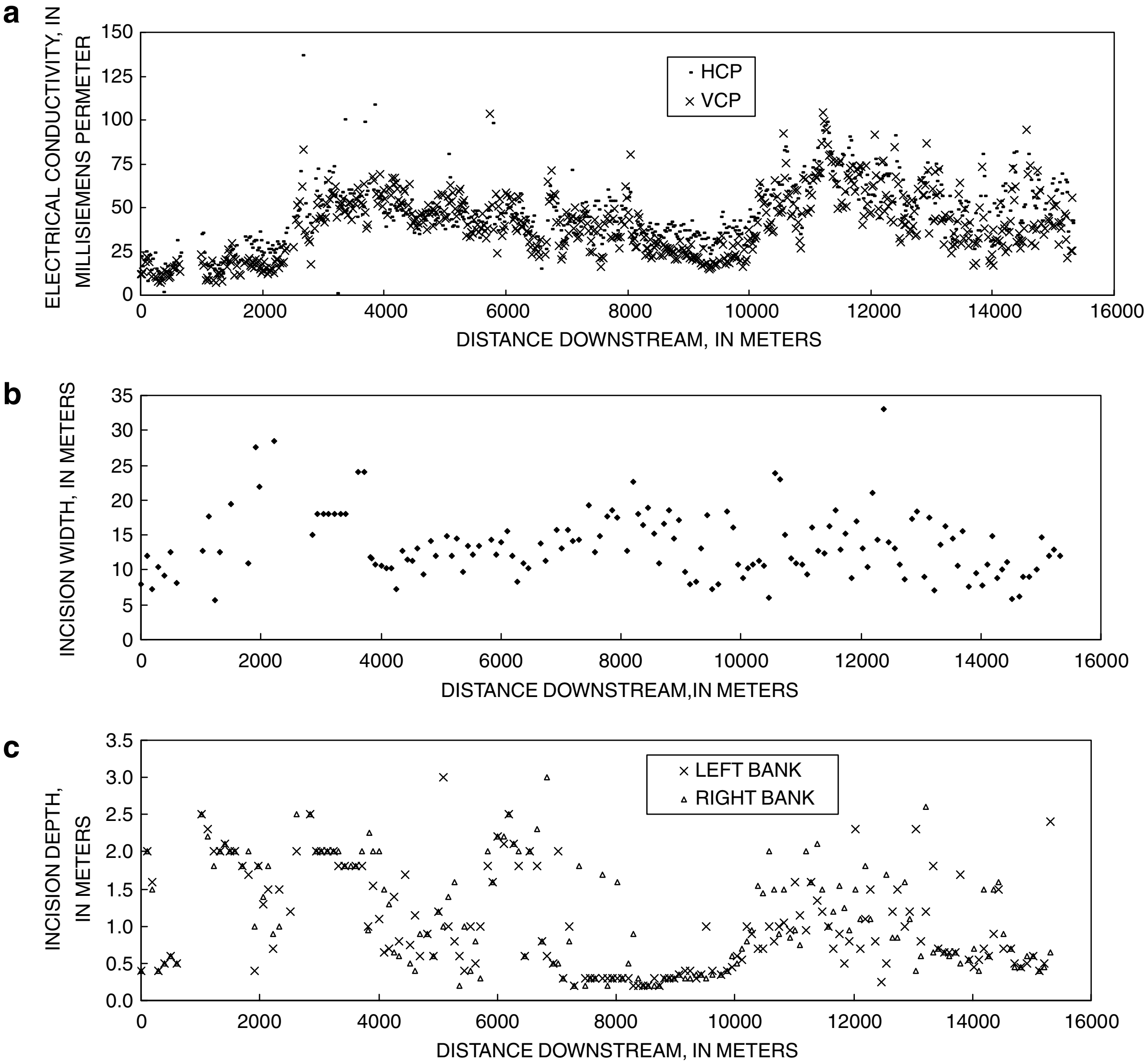


Figure 5 Data summary Woodcutter's Wash: Comparison of (a) electrical conductivity measured in both horizontal and vertical coplanar coil orientations, (b) incision width, and (c) left and right bank incision depths.

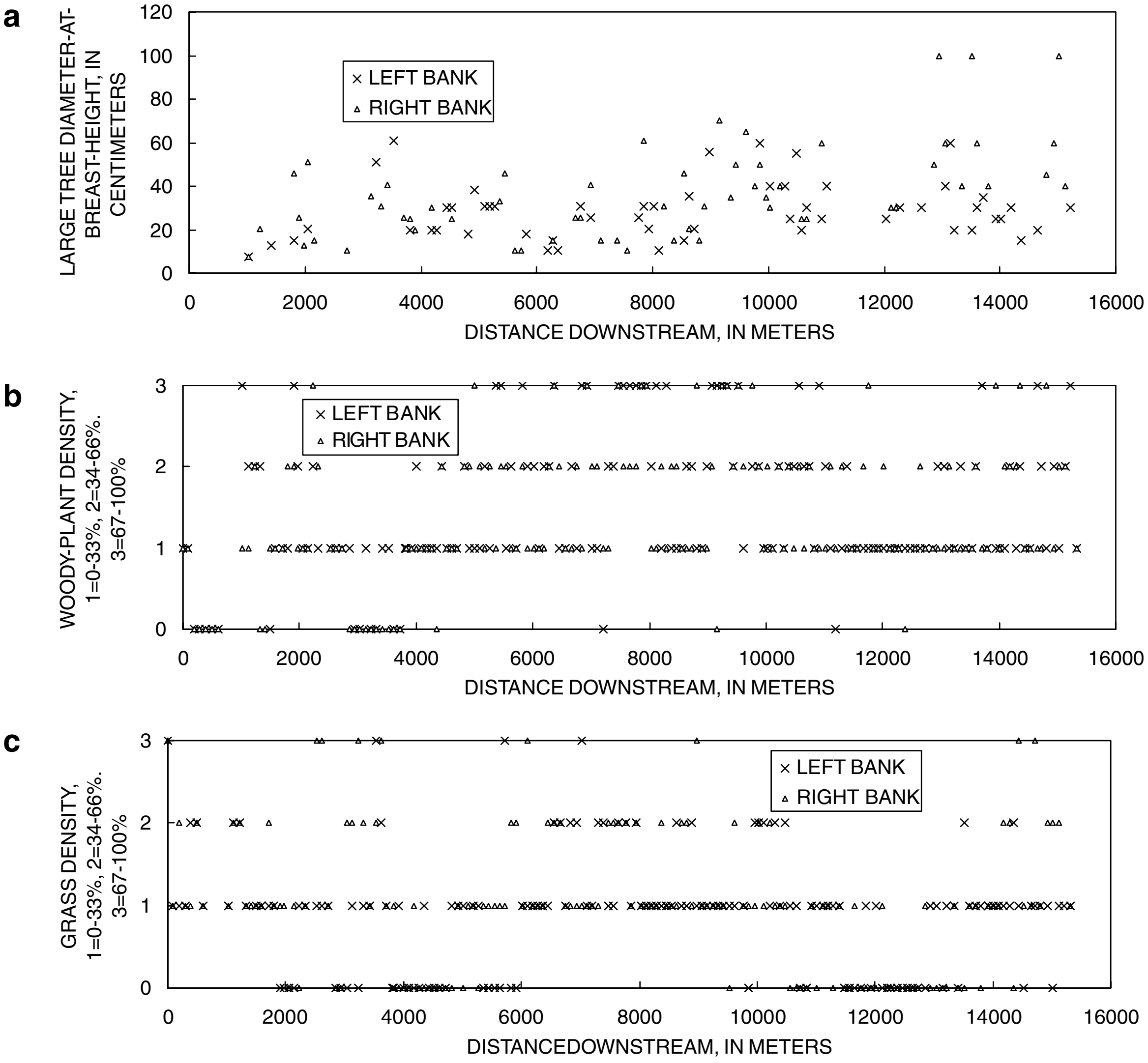


Figure 6 Data summary Woodcutter's Wash: Comparison of (a) large tree diameter-at-breast-height, (b) woody plant coverage, and (c) grass coverage.

variation, however, which in the upper reaches could be controlled by the depth and clay content of consolidated sediment (the ''basin fill'' of Coes and Pool, 2005). In the lower reaches, there were a series of peaks and troughs in σ_a. The troughs were separated by a distance of 1–1.3 km. This pattern of peaks and troughs could have been caused by the channel passing through layers of sediment with different particle-size distributions or layers of indurated calcium carbonate as the channel elevation decreased. The channel's incision width ranged from 1 to 34.8 m and increased down-channel. Incision-width variability increased notably beyond 10 km down-channel. The increase in variability could have been related to the same changes in layer composition that affected σ_a. Incision depth ranged from 0.2 to 3.2 m. The degree of scatter in incision depth was generally consistent along the channel, but the average appeared to increase slightly in the down-channel direction. The cyclic pattern visible in the incision-depth data did not correspond to that of σ_a. DBH of large trees ranged from 0.05 to 1.0 m, but exhibited no marked trend (Fig. 8). Woody-plant coverage increased down-channel, and grass coverage decreased.

A RCP classification matrix was constructed using data from 259 transects (Table 1). RCP as used in this study is a relative term, the values of which are based on the range of measured-parameter values in the study area. To evaluate RCP, each transect was categorized first according to VCP-σ_a as having low (*L*), moderate (*M*), or high (*H*) near-surface permeability. Each of these categories was subdivided into three classes, low (1), medium (2) or high (3), using the 6 other data types available, to give 9 RCP classes with designations combining the above abbreviations: *L*1, *L*2, *L*3; *M*1, *M*2, *M*3; and *H*1, *H*2, *H*3 (Table 2). In Woodcutter's Wash, the highest RCP transects clustered in the upper reaches (Fig. 9) where factors including small DBH, low σ_a, few woody plants, and grass converge. There was another zone of high RCP transects 7–9.5 km from the west end of the survey. Low RCP transects dominated in the intervals, 4–7 km, and 10–12.5 km. The low to moderate RCP sites at the east end of the survey were caused by the presence

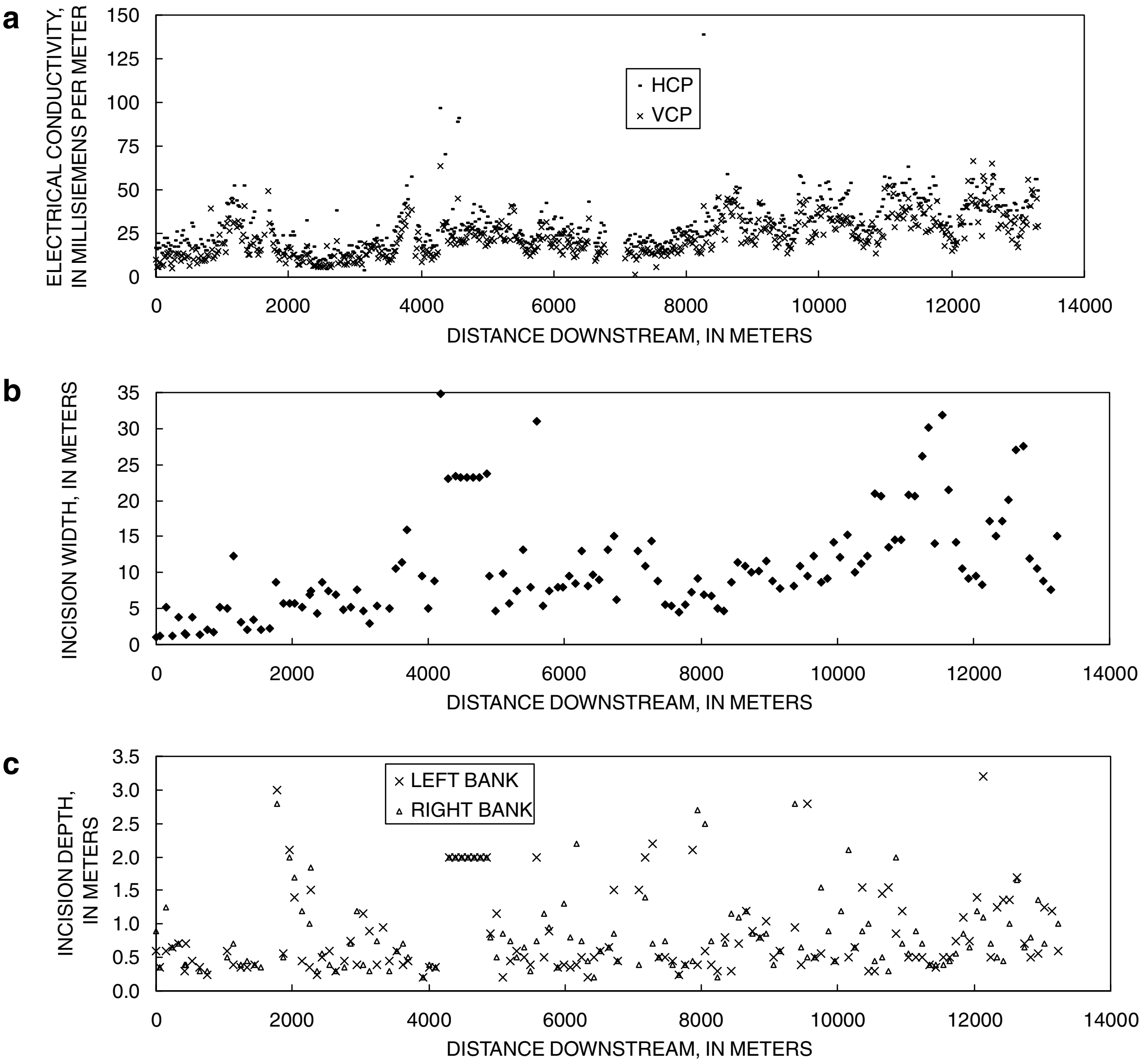


Figure 7 Data summary Coyote Wash: Comparison of (a) electrical conductivity measured in both horizontal and vertical coplanar coil orientations, (b) incision width, and (c) left and right bank incision depths.

of large diameter trees, high σ_a, and high woody-plant and grass density. Coyote Wash was dominated by high RCP values. With some exceptions, they were relatively uniformly dispersed along the main channel and its tributaries. Low RCP values were concentrated in three locations: near the confluence of the two tributaries south of the main channel, 9–13 km on the main channel, and about 1.5 km up-channel of the confluence of the main and northern branches of Coyote Wash. Within permeability groups, despite increases in incision width and depth, there was a general decrease in RCP down-channel caused by an increase in HCP-σ_a, large diameter trees, and density of woody plants and grasses.

RCP also was evaluated at two USGS sites (WC1 and WC3; Coes and Pool, 2005) and four GSA sites (3rd Street Channel, Summit Channel, Mall Basin, and Fry Basin; GSA, 2001, 2004). The rankings developed for the ephemeral-stream channel data set were used to categorize and classify the RCP of these sites. Apparent electrical conductivity was compared with measurements made by previous investigators of saturated hydraulic conductivity, cylinder infiltrometer flux, and fines (silt plus clay, in percent) of which only a few were available for each site. Borehole-averaged fines showed a moderate correlation with both shallow (VCP) and deep (HCP) σ_a measurements (Fig. 10). At WC1, percent fines was less than or equal to 3.5 at the surface and at 2.1 m depth with K_{sat} in the range of 10^{-2}–10^{-1} cm s^{-1}. Fines increased to about 18% at 3.7 and 6.7 m depth with K_{sat}'s of 10^{-2} and 10^{-6} cm s^{-1}, respectively. Perched water existed at depths ranging from 6.6 to 8.3 m during a period of about 18 months. Apparent electrical conductivity measured for this study increased with depth (VCP to HCP) from 25.2 to 42.4 mS m^{-1}. Though the increase in percent fines with depth is modest, the saturation of deeper sediment, and low K_{sat} at 6.7 m could explain the increase in σ_a with change in coil orientation. Recharge potential at WC1 was categorized as *M*2. The discrepancy between the low near-surface percent fines and the medium permeability designation has at least two possible causes. First, the LIN FEM instrument may have included in its sample volume some shallow, fine-textured sediment not evident in the

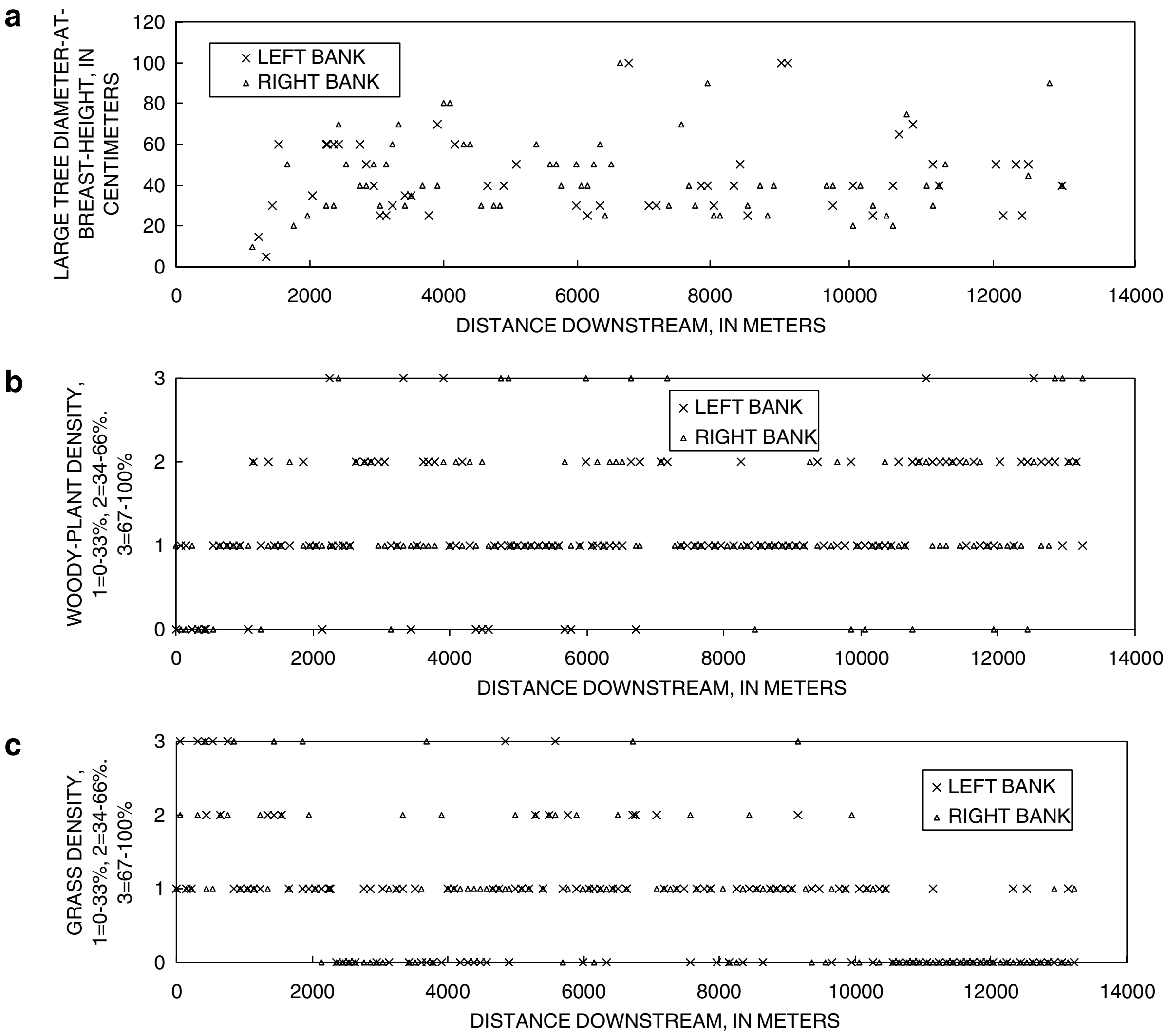


Figure 8 Data summary Coyote Wash: Comparison of (a) large tree diameter-at-breast-height, (b) woody plant coverage, and (c) grass coverage.

USGS borehole. Second, the higher σ_a of the saturated sediment could have affected (increased) the shallower VCP-σ_a measurement.

At WC3, percent fines ranged from 16 at 0.9 m to 2.6 at 8.2 m depth. K_{sat} ranged from about 10^{-4} at 1.5 m depth to 10^{-3} cm s^{-1} at 8.2 m depth. Coes and Pool (2005) attempted to use temperature and tritium to estimate K_{sat} at WC3, but temperature changes were too small to allow for a flux calculation, indicating that flux is small. Tritium data indicated a flux of about 10^{-9} cm s^{-1}. Apparent electrical conductivity values fell into the high end of the moderate permeability category (>40 mS m^{-1}) for both coil orientations. Although the RCP designation for this site was also *M*2, the Coes and Pool data suggest a lower permeability value for the site. Measured σ_a places the transect nearly into the low permeability category for both VCP and HCP measurements, and nearby sites along the channel are in this category suggesting that, for example, this would not be a favorable location for a detention basin. This underscores the benefit of the wide spatial coverage of this method, in that any site may be compared to neighboring sites to determine if the RCP designation is anomalous.

There were four sites along Coyote and Woodcutter's Washes that were investigated by GSA for a stormwater-recharge feasibility study (Fig. 9). At the 3rd Street Channel site, the GSA data indicated a moderate to low hydraulic permeability. Borehole samples ranged from 21% fines and a K_{sat} of about 10^{-3} cm s^{-1} (1.7–2.7 m depth) to 55% fines and a K_{sat} of about 10^{-4} cm s^{-1} at about 7 m depth (GSA, 2001). Surface infiltration flux was 10^{-4} cm s^{-1} (GSA, 2004). In contrast to these findings, σ_a (ranging from 23.9 mS m^{-1} (VCP) to 33.2 mS m^{-1} (HCP)) suggested high to moderate permeability. Recharge potential at this site fell into the high permeability category *H*2. At the Summit Channel site, laboratory K_{sat} values were about 10^{-4} cm s^{-1} between 2.0 and 6.7 m depth, but increased to 10^{-2} cm s^{-1} at a depth of about 9 m. Surface infiltration was found to be about 10^{-3} cm s^{-1}. Fines varied considerably with depth, ranging from 16% to 72%. Apparent electrical conductivity values were low (VCP = 19.8 mS m^{-1}, HCP = 14.8 mS m^{-1}) suggesting a high permeability between 0 and 6 m depth.

Table 1 Ranges and classification of parameter values used in calculating recharge potential

Contribution of data types to recharge potential Numerical Rank	HCP apparent electrical conductivity (mS m^{-1})	Incision width (m)	Incision depth[a] (m)	Large tree DBH[b] (cm)	Woody plant density[b] (%)	Grass density[b,c] (%)
Low (*L*) Permeability (VCP-$\sigma_a \geqslant 45$ mS m^{-1})						
Low = 1	$\sigma_a > 65$	Width $\leqslant 10.8$	Height $\leqslant 0.75$	DBH $\geqslant 40$	WP > 75	Grass > 75
Medium = 2	$51 \leqslant \sigma_a \leqslant 65$	$10.8 <$ width < 14.8	$0.75 <$ height < 1.35	$20 <$ DBH < 40	$25 \leqslant$ WP $\leqslant 50$	$25 \leqslant$ grass $\leqslant 50$
High = 3	$\sigma_a < 51$	Width $\geqslant 14.8$	Height $\geqslant 1.35$	DBH $\leqslant 20$	WP < 25	Grass < 25
Moderate (*M*) Permeability (25 mS m^{-1} < VCP-σ_a < 45 mS m^{-1})						
Low = 1	$\sigma_a > 47$	Width $\leqslant 9.6$	Height $\leqslant 0.55$	DBH $\geqslant 46$	WP > 75	Grass > 75
Medium = 2	$38 \leqslant \sigma_a \leqslant 47$	$9.6 <$ width < 14.7	$0.55 <$ height < 1.2	$28 <$ DBH < 46	$25 \leqslant$ WP $\leqslant 50$	$25 \leqslant$ grass $\leqslant 50$
High = 3	$\sigma_a < 38$	Width $\geqslant 14.7$	Height $\geqslant 1.2$	DBH $\leqslant 28$	WP < 25	Grass < 25
High (*H*) Permeability (VCP-$\sigma_a \leqslant 25$ mS m^{-1})						
Low = 1	$\sigma_a > 29$	Width $\leqslant 6.8$	Height $\leqslant 0.55$	DBH $\geqslant 50$	WP > 75	Grass > 75
Medium = 2	$19 \leqslant \sigma_a \leqslant 29$	$6.8 <$ width $\leqslant 11.3$	$0.55 <$ height $\leqslant 1.00$	$30 <$ DBH < 50	$25 \leqslant$ WP $\leqslant 50$	$25 \leqslant$ grass $\leqslant 50$
High = 3	$\sigma_a < 19$	Width > 11.3	Height > 1.00	DBH $\leqslant 30$	WP < 25	Grass < 25

Recharge potential of each transect was classified first by hydraulic conductivity estimated from vertical coplanar orientation apparent electrical conductivity (VCP-σ_a): low (*L*), moderate (*M*), high (*H*). These three categories were subdivided using measurements from six additional data types. The measurements were classified and given a numerical rank of low (1), medium (2) or high (3) according to their contributions to recharge potential. The range of values for each rank is listed under each data type.

[a] Incision depth is the elevation difference between the lower of the two banks and the thalweg.

[b] For DBH, woody plant density and grass density, if measurements were made for both left and right banks, the values were averaged.

[c] Grass is counted only if Incision Depth < 1 m.

Table 2 Ranges of recharge-potential values and their classification

	Low (*L*) Permeability (VCP-$\sigma_a \geqslant 45$ mS m^{-1})			Moderate (*M*) Permeability (25 mS m^{-1} < VCP-σ_a < 45 mS m^{-1})			High (H) Permeability (VCP-$\sigma_a \leqslant 25$ mS m^{-1})		
Recharge potential category	$L1 < 12$	$12 \leqslant L2 \leqslant 14$	$L3 > 14$	$M1 \leqslant 11$	$11 < M2 < 15$	$M3 \geqslant 15$	$H1 \leqslant 11$	$11 < H2 < 15$	$H3 \geqslant 15$

Transect recharge potential was categorized by the magnitude of the vertical coplanar (VCP) measurement of apparent electrical conductivity (σ_a) as High (*H*), Medium (*M*) or Low (*L*). The numerical ranks given to the values of each data type measured at the transect are summed. The sum is ranked and classified within each VCP-σ_a category as High (3), Medium (2) or Low (1) to give nine recharge potential classes: *L*1, *L*2, *L*3, *M*1, *M*2, *M*3, *H*1, *H*2 and *H*3.

The low permeability layer intersected by the borehole may have been too thin or laterally limited to influence the volumetric average of the σ_a measurement. RCP was in the *H*3 category, the highest among the comparison sites. The Mall Detention Basin site had low laboratory K_{sat} and surface infiltration values (10^{-5} to 10^{-4} cm s^{-1}) and high percent fines (37–47%). These values indicate a low permeability for the site in contrast to the moderate RCP designation, *M*2. Average σ_a across the basin was moderate at shallow depth (35.3 mS m^{-1}) and high at depth (50.8 mS m^{-1}). At the Fry Detention Basin, the 9.8–10.2 m depths contained 41% fines. The K_{sat} measurements from the same interval were about 10^{-4} cm s^{-1} and surface-infiltration flux was about 10^{-6} cm s^{-1}. These results indicate low permeability at this site. The average of 18 measurements of σ_a across the basin, was 22.6 mS m^{-1} (VCP) and 34.2 mS m^{-1} (HCP). The RCP designation was *H*2. The high near-surface permeability designation for the site is in marked contrast to the GSA findings. This difference could indicate a potential disadvantage of the RCP method. In contrast to open channels, outflow in detention basins is restricted and material in suspension is deposited because of the decreased flow velocity. Thus, a clogging layer has probably developed in each of the basins (Schuh, 1990). Though thin, clogging layers can significantly decrease surface hydraulic permeability and therefore RCP. Being thin relative to the depth averaging of the LIN FEM instrument, a clogging layer would generally be undetectable.

In summary, comparison of σ_a with *point* measurements of fines, infiltration rate and hydraulic permeability at the comparison sites showed generally poor correlation. However, when fines were averaged over the borehole, they correlated moderately well with σ_a (Fig. 10). Many factors affect permeability and the relations among these factors and with σ_a are not necessarily linear. Comparison with laboratory-determined K_{sat}, percent fines and infiltration flux is problematic given small numbers of samples, the heterogeneity of many systems, difficulty in obtaining representative cores, and the small sample size of these measurements relative to that of σ_a. These measurement types should com-

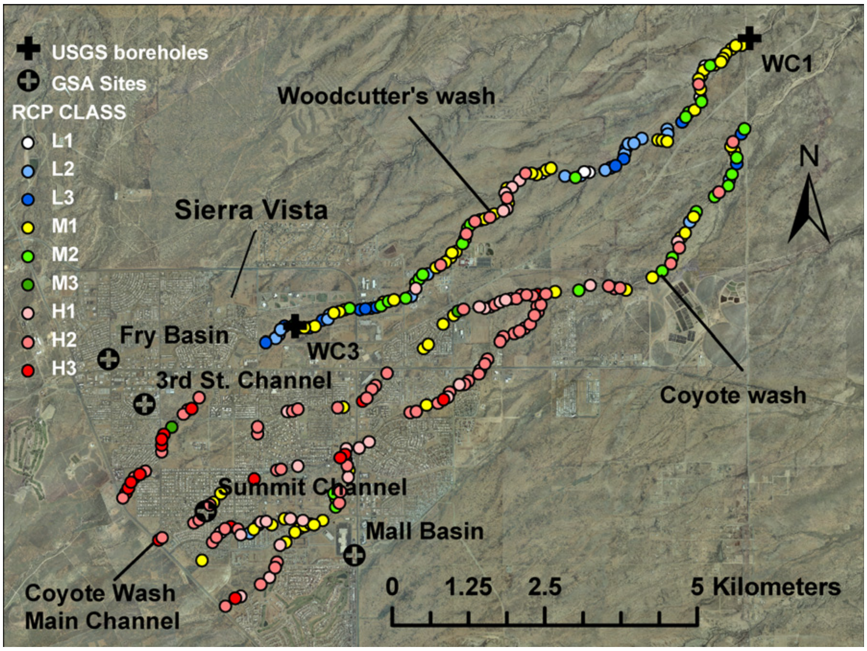


Figure 9 Map of recharge potential in Coyote and Woodcutter's Washes. Red = high (*H*), green = moderate (*M*) and blue = low (*L*) near-surface permeability derived from VCP-σ_a. Shades of color within each permeability category are derived from the six other data types collected. These shades denote magnitude of recharge potential, with paler colors indicating lower recharge potential and darker colors indicating higher.

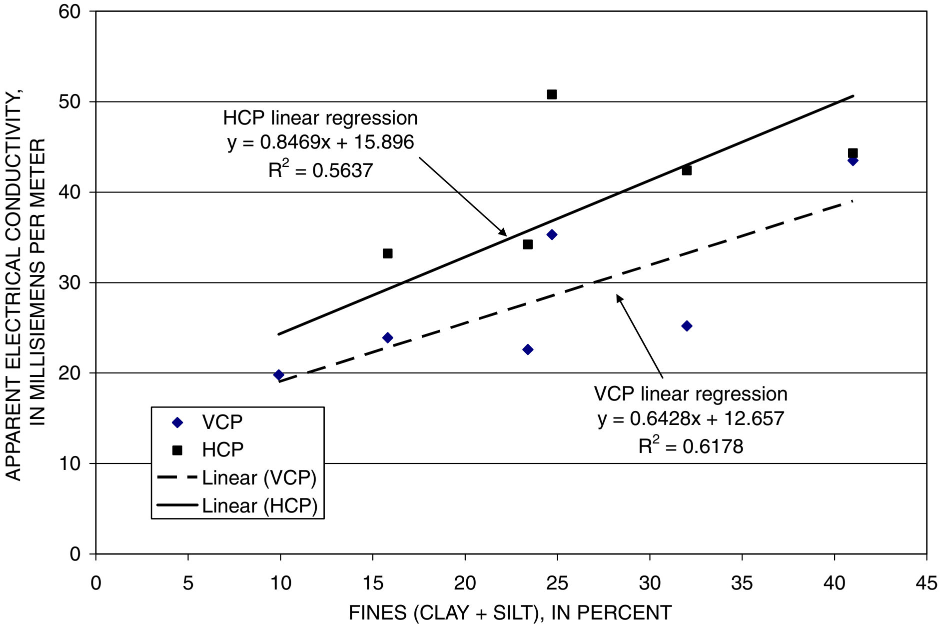


Figure 10 Plot of linear regression lines for average percent fines versus apparent electrical conductivity measured with vertical-coplanar (VCP) and horizontal-coplanar (HCP) coil orientations in the six comparison sites. Fines were field estimated, but at the four GSA sites, they were corrected using laboratory-measured fines. Data sources Coes and Pool (2005) and GeoSystems Analysis, Inc. (2001, 2004).

pare well at sites with low vertical and horizontal heterogeneity, or if spatially-adequate sampling and averaging of soil physical and hydraulic properties are carried out. However, the comparison contrasts the potentially mis-representative, but common, point methods with the relatively rich and spatially extensive information available through RCP analysis. In arid and semiarid regions, the RCP method presented here is more efficient in terms of time and money than regional studies, because it focuses effort on that part of the landscape at which recharge is most likely to occur.

Thin layers such as clogging layers in the upper few centimeters of detention basins will not normally be detected by LIN FEM instruments. This lack of detection may cause a site to be categorized incorrectly with respect to RCP. If a site is deemed particularly important, for example for the construction of a detention basin, then coring at multiple points is recommended to explore spatial variability of physical and hydraulic parameters. Despite limitations, the RCP evaluation method developed here gives insight into the combined factors influencing recharge along ephemeral-stream channels that is difficult or impossible to achieve with traditional methods for estimating recharge.

Conclusions

A study was carried out to develop a method for assessing recharge potential (RCP) at transects in ephemeral-stream channels. Mapping the recharge potential of ephemeral-stream channels in arid regions is well-suited to study by measurements of apparent electrical conductivity (σ_a), and channel and vegetation characteristics, because these factors account for the majority of significant factors affecting recharge in a channel reach. These are infiltration (transmission loss) through bed-sediment, the presence of confining layers, evapotranspiration, wetted area, and flow depth. Factors affecting runoff were beyond the scope of this study, as information extending to the surface water divide is required. These factors may certainly be estimated, however, and added to the RCP evaluation if so desired. Data types that were used included σ_a measured over two depth intervals (0–3 m (VCP-σ_a) and 0–6 m (HCP-σ_a)), channel-incision width and depth, and on-the-ground estimates of diameter-at-breast-height (DBH) of the largest tree, grass density, and woody-plant density. RCP as defined in this study is a relative parameter, that is completely dependent upon the ranges of data measured in the study area. VCP-σ_a was used as the first level of categorization of transects, because it provides a measure of the texture and hydraulic permeability of shallow channel-bed sediment. Shallow bed-sediment (or rock or soil) permeability is widely recognized as a master variable in the control of recharge. Based on VCP-σ_a, the transects were categorized as having high (*H*), medium (*M*), or low (*L*) permeability. The other six data types were combined to refine further the RCP classification within each of the permeability categories, and classified as low (1), medium (2), or high (3) RCP. This resulted in nine possible RCP classes: *L*1, *L*2, *L*3; *M*1, *M*2, *M*3; and *H*1, *H*2, *H*3.

The data were collected in two ephemeral-stream channels in and downstream of Sierra Vista, Arizona: Coyote and Woodcutter's Washes. These channels were targeted because of interest in the construction and siting of detention basins in favorable channel reaches, as well as an interest in laying the groundwork for studies to quantify enhanced recharge due to urbanization. Coyote Wash generally had higher RCP, than did Woodcutter's Wash, but each channel contained at least two high RCP zones that could be suited to the installation of recharge-enhancing structures. Six sites in the study area were used for comparison of RCP with measured values of saturated hydraulic conductivity (K_{sat}), cylinder infiltrometer flux, and percentage of fines from previous investigations. Variations in factors that could confound interpretation of the results were generally absent except that thin, low permeability layers that would not be detected by the LIN FEM instrument may have been present at several of the sites. Values of σ_a were moderately correlated with fines at six comparison sites, but were poorly correlated when compared with point measurements of infiltration flux, K_{sat} and particle size from soil cores probably because of the different scale of the measurements. Direct comparison of RCP with the previously measured data underscored the fact that RCP is a more complete source of information about the flow system than are data measured with more traditional methods, because in addition to hydraulic permeability RCP contains information on ET, wetted area, and flow depth.

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