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Ground-water Recharge Estimates in Arid Areas Using Channel Morphology and a Simulation Model

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ABSTRACT: In water-deficient areas, ground-water recharge by transmission loss along ephemeral-stream channels typically is an unmeasured water-budget residual. This value is poorly constrained and alternative approaches are sought. By combining channel-morphology techniques inferred from down-channel changes in streamflow with a simple distributed-parameter simulation model, estimates of recharge from transmission loss are made from direct measurements of watershed variables. Inputs for the simulation model, including rainfall, may be determined indirectly using outflow estimates from selected basins or by estimating downstream changes in discharge as related to channel geometry. Recharge also can be estimated by routing discharge of an index storm down-channel, accounting for channel losses, and adjusting for inter-channel recharge during low-frequency storms.

BACKGROUND

Transmission loss is the abstraction, or loss, of flow in ephemeral- or intermittent-stream channels as discharge migrates downstream. Water loss occurs by infiltration into normally dry (unsaturated) sediment forming the channel bed and banks. Thus, part of the abstraction becomes ground-water recharge. In arid and semiarid regions, where most streamflow is ephemeral and is an important process for recharge, most additions to the ground-water reservoir occur by transmission loss (Lane, 1985; Osterkamp et al., 1995). This part of the arid-lands water balance, which becomes available for recharge, typically is very small compared to evapotranspiration but represents a component of precipitation that is potentially usable for water supply. Hence, the measurement of transmission loss and rates of ground-water recharge are of vital concern to water managers in arid and semiarid regions.

Recharge generally is computed as a remainder after other water-budget components are estimated. This approach is not advised in arid areas where rapid evaporation of rainfall accounts for most water loss and a small error in its estimation may lead to a large error in the estimate of recharge. Hence, alternative techniques to evaluate transmission loss directly, and recharge indirectly, have been proposed in recent decades. A method to determine transmission loss from channel measurements as input to a distributed-parameter simulation model is described here. Examples of its use are given for channels of Abu Dhabi, UAE, and the Amargosa River Basin, western USA.

Previous strategies to evaluate transmission loss directly rely on the downstream routing of inflows or the computation of flow from precipitation records. Examples include loss-rate equations for known inflows to reaches of ephemeral-stream channels (Burkham, 1970a; 1970b), regression equations relating volumes of inflow, outflow, and flow loss (Lane et al., 1971; Sinha and Sharma, 1988), techniques of storage routing as cascading leaky reservoirs (Lane, 1972; Wu, 1972; Peebles, 1975), application of a kinematic-wave model that yields estimates of infiltration (Smith, 1972), and simple differential equations describing rates of transmission loss (Jordan, 1977; Lane, 1980). The approach of Lane (1980) led to the simulation model described here.

APPROACH

This paper describes an empirical water-balance technique to estimate recharge by transmission loss along ephemeral-stream channels. It relies on a distributed transmission-loss model for channelized flow (Lane, 1982; 1985) and evaluates losses using calibrations that relate measures of channel shape and drainage-basin area to discharges, especially flood magnitudes. The input variables for the transmission-loss model, including rainfall, if data are lacking, are geomorphically estimated outflows from selected drainage basins. These input variables are applied to model calculations for other drainage basins. The model inputs for outflow are determined, if feasible, from channel morphology to infer an index event of specified recurrence for the normally flashy streams. The index-event volume is related to long-term flow volume as a means of estimating average-annual

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recharge. Thus, recharge is derived by routing index discharges, if necessary from an index storm, downstream, accounting for channel losses during the flows, and adjusting for interchannel recharge during low-frequency precipitation events.

Theory

The differential equation describing transmission loss in a channel reach is based on the assumptions that (1) the volume of loss in a reach is proportional to the volume of upstream inflow, (2) the loss rate is constant, and (3) the rate of lateral tributary inflow is uniform along the channel length during the flow event. The first-order equation is:

$$dV(x,w)/dx=-wc^{*}-wk^{*}V(x,w)+V_{l}/x \qquad (1)$$

in which V(x,w) is flow volume in a channel segment of length x and mean width w, V_l is volume of lateral inflow, and c^* and k^* are empirical parameters. The solution to equation 1 is:

$$V(x,w)=a^{*}(x,w)+b^{*}(x,w)V_{u}+F^{*}(x,w)V_{l}/x \qquad (2)$$

in which V(x,w) becomes the outflow volume, V_u is upstream inflow volume, and $a^*(x,w)$, $b^*(x,w)$, and $F^*(x,w)$ are coefficients. In the absence of lateral inflow, the upstream volume, V_u, is greater than $a^*(x,w)/b^*(x,w)$ or all the inflow is lost in the channel segment and V(x,w) equals 0. If lateral inflow occurs, there must be finite outflow and V(x,w) is greater than 0.

Relations between the coefficients and the parameters are derived as:

$$a(x,w)=[a^{*}/(1-b^{*})][1-b^{*}(x,w)] \qquad (3)$$

in which a^* and b^* are intercept and slope, respectively, for a unit channel,

$$b^{*}(x,w)=\exp(-k^{*}xw) \qquad (4)$$

$$F(x,w)=[1-b^{*}(x,w)]/k^{*}w \qquad (5)$$

$$c^{*}=-k^{*}a/(1-b^{*}) \qquad (6)$$

The values of a^*, b^*, and k^* have been determined for specific measures of effective steady-state hydraulic conductivity (K), mean duration of flow to the reach, and mean volume of inflow to the reach (Lane, 1982). Analyses of data from experimental watersheds in Arizona (Murphey et al., 1977) yielded regression equations to estimate mean duration of flow and mean runoff volume from a watershed area.

Hydrographs for 127 flow events in the western USA were used to calibrate the transmission-loss equation (Lane, 1980). For channels of Abu Dhabi and the Amargosa River, separate calibrations were made for a^*, b^*, and k^*, and inflow durations and volumes were based on flow and rainfall records (Osterkamp et al., 1994, 1995). Because the effective saturated conductivity, K, is the constant hydraulic conductivity of bed sediment under natural conditions of entrapped air and suspended sediment, it is as little as a tenth the conductivity estimated with infiltrometers and clear water. Effective conductivities were derived from total losses for an event divided by length and width of the channel reach and the upstream duration of flow. The estimates were averaged over all flow events for a channel segment to derive mean effective hydraulic conductivity. Values of K based on bed-material classes (Lane, 1982), coupled with values obtained during field activities, provided input values of K for the example studies.

Application

The structure of the model considers a channel network from upland areas to an outlet (Fig. 1). Each primary channel receives input from an upland-flow and two lateral-flow areas (Fig. 1A). Secondary channels of complex watersheds receive input from two, or perhaps one, upstream channels and one or two lateral-flow areas (Fig. 1B). Each upland- and lateral-flow area can have different rainfall and infiltration inputs. Thus, the model is distributed in that a watershed may have discrete upland and lateral-flow areas.

Each primary watershed is described by area above the point of interest (A, Fig. 1A), length of channel segment (AB), average channel width, effective hydraulic conductivity of the bed, upstream area, and lateral areas. Outflow from a channel segment becomes input to a downstream segment until the outlet is reached. Transmission losses for the primary channel segments accumulate to yield loss for an entire basin. The surface-water balance is computed by accounting for all rainfall, infiltration on the upland and lateral-flow areas, transmission loss, and runoff.

Streamflow Estimates

Records defining long-term precipitation in arid areas are scarce and discharge records of sufficient length to give reliable flow indices for ephemeral-stream channels are rare. Two indirect methods to evaluate runoff are the use of channel widths to estimate discharge, and development of area-dependent rainfall/runoff relations for arid regions. For both approaches, either mean discharge is estimated or event-based discharge volumes are estimated that allow computations of mean discharge. Estimates for mean discharge are presumed to result in transmission loss and recharge equal to the sum of flow losses that typically occur in a year. Elaboration is in Osterkamp et al. (1994, 1995).

Measurement of channel width to estimate discharge assumes that alluvial channels adjust to the flows that they convey (Leopold and Maddock, 1953). By measuring channel properties at many sites of known discharge, flows of specified frequency are related to geometry by the continuity equation for stream discharge:

$$Q_i = WDV \qquad (7)$$

in which Q_i is instantaneous discharge, W is flow width, D is mean water depth, and V is mean velocity for a flow at the section. Expanding equation 7 to power form yields:

$$Q_i = kW^bD^fV^m \qquad (8)$$

in which k' is a coefficient and exponents b, f, and m depend on drainage-basin properties including the sizes and flux of fluvial sediment. Equation 7 can be expanded to:

$$Q_i = rW^b \qquad (9)$$

$$Q_i = sD^f \qquad (10)$$

$$Q_i = tV^m \qquad (11)$$

in which r, s, and t are coefficients. Because equations 9, 10, and 11 require measurement of width, depth, and velocity for an instantaneous discharge, their use is impractical for ungauged sites in arid areas. To avoid flow-specific measurements, therefore, discharge estimates are made by considering the channel geometry and the sizes of bed and bank material.

The most reliable relations for arid areas yield mean discharge or a flood discharge from channel widths grouped by properties of sediment, climate, or vegetation (Hedman and Osterkamp, 1982). Using channel-width data from numerous gauged sites, power functions relating width and measures of discharge lead to estimates of streamflow at ungauged sites (Hedman and Osterkamp, 1982). Thus, a flow of specified frequency can be estimated for an ungauged site. If basin area is known and other data required to calculate runoff from a 2-year rainfall are estimated, input values can be evaluated iteratively to replicate the field-determined 2-year flow. Because the model computes water balance as volumes of rainfall, runoff, channel loss, and overland loss (largely evapotranspiration), output too includes volume of streamflow, as estimated by geomorphic techniques and expressed as single flow events, rather than as peak discharge.

Where channels are disturbed and cannot be measured well, application of the geomorphic/distributed-parameter simulation approach can be modified to rely on area-dependent rainfall/runoff relations. Data from ephemeral-stream channels of southwest USA (Osterkamp et al., 1995) gave envelope relations between unit flood discharges and basin areas. Included is a curve for $Q_{2.33}$, a flow of return period 2.33 years that, in desert areas, is assumed to result from the mean-annual precipitation event also of return frequency 2.33 years. For ground-water recharge studies in Abu Dhabi, therefore, available precipitation records were used to define an index storm having a return period of 2.33 years.

Flow data from gauged channels of southwest USA suggest that the volume of $Q_{2.33}$ passing an ephemeral-stream site approximates the volume of mean annual discharge. The mean-annual rainfall (index) event, therefore, is among input data to compute a flow volume about that of mean-annual discharge. Input values, including the index-storm magnitude, are adjusted to yield an outflow volume equaling the mean-annual discharge indicated by the curve for $Q_{2.33}$. Simulation-model output includes flow duration, in hours, as determined by an approach suggested by Ardis (1973) and related to basin area by Murphey et al. (1977); recharge, then, is estimated by routing the 2.33-year index-storm discharge down channel, accounting for transmission loss.

EXAMPLES

Streamflow, transmission loss, and recharge were estimated for channels of Abu Dhabi, UAE, and the Amargosa River Basin, western USA, using the geomorphic, distributed-parameter simulation approach. Summary estimates are in Table 1. Determinations of recharge were computed for 17 basins of Abu Dhabi; the computations were summed to estimate total recharge for the area. In the Amargosa Basin, recharge was estimated by determining channel change along a 130-km reach and for 90 km of main tributaries. The distributed-parameter simulation model was also used by Lane (1982) and Nichols (1999).

Table 1. Estimated drainage area (DA, km^2), average annual precipitation (P, mm), transmission loss (TL, Mm^3), ground-water recharge (G, Mm^3), and recharge as percent precipitation (G%), Al Ain area and Amargosa River Basin.

	Estimated drainage area (km^2)	Average annual precipitation (mm)	Transmission loss (mm^3)	Groundwater recharge (mm^3)	Recharge Precipitation (%)
Al Ain area	6290	130	46.1	55.3	6.8
Amargosa Basin	3980	180	18.4	20.5	1.6

Abu Dhabi, United Arab Emirates

Investigations to evaluate and model ground-water resources near Al Ain, Abu Dhabi, UAE, required modeling of a water budget, including estimates of ground-water recharge. Most stream channels (wadis) of the area, west of the Oman Mountains, are altered and thus measures of shape do not indicate discharges. In bottomlands of the mountains, highly braided channels are typically floored with coarse debris and the hillslopes often expose bedrock but little vegetation (Fig. 2). Many flow-input volumes to the simulation model, therefore, were computed from relations of rainfall and runoff for simple or complex watersheds (Fig. 1). Transmission loss was assumed complete downstream, where no channel definition was apparent; hence, all ground-water recharge was inferred to occur above these sites.

The study area had 17 basins discharging water from gaps along the western edge of the Oman Mountains at 26 sites; seven basins had two or more primary channels and were modeled as complex watersheds (Fig. 1B). To generate input volumes of streamflow and rates of transmission loss above and below gaps, a rainfall/runoff relation was developed from isohyetal data for the Oman Mountains:

$$R_a = 0.755P_p - 10.6 \qquad (12)$$

in which R_a and P_p, in mm, are runoff volume and annual peak precipitation (Osterkamp et al., 1995). Model results of average annual ground-water recharge (millions of cubic meters, Mm^3) were adjusted to account for inter-channel additions by high-intensity storms (Lane and Osterkamp, 1991).

The study indicated that about 55 Mm^3 are recharged annually to the ground-water reservoir in the Al Ain area, about 93% of which occurs above gaps in the Oman Mountains. Computed average-annual recharge, as water depth, was 18 mm in basins of the mountains (2870 km^2) and 1.1 mm on fans (3420 km^2) west of the mountains. Assuming average-annual precipitation of the area to average 130 mm, recharge is nearly 7% of rainfall (Table 1).

Amargosa River Basin in Nevada, USA

As part of safety programs for the Nevada Test Site, USA, transmission losses were computed in support of a water-balance model for the Amargosa River (Osterkamp et al., 1994). As for the Al Ain area, the goal was to estimate transmission loss and recharge along ephemeral-stream channels of the basin.

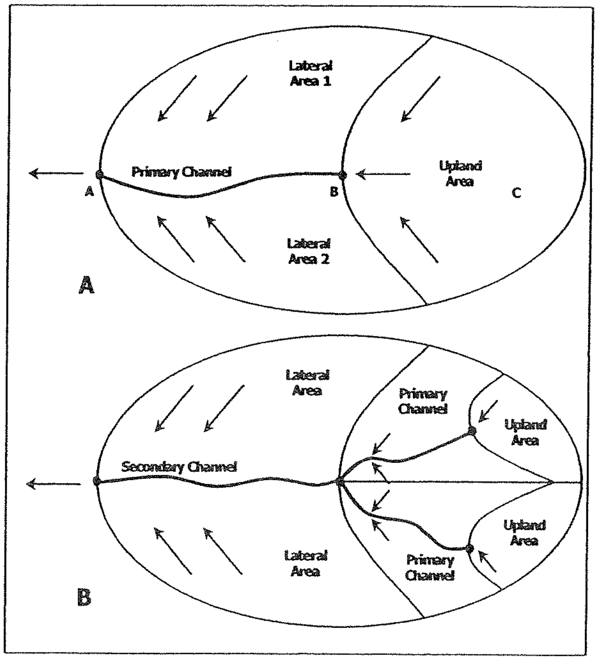

Figure 1. Schematic diagram illustrating physical elements for model input to a simple watershed (A) and a complex watershed (B). Arrows indicate streamflow and runoff directions from contributing parts of the watershed to a primary or secondary channel.

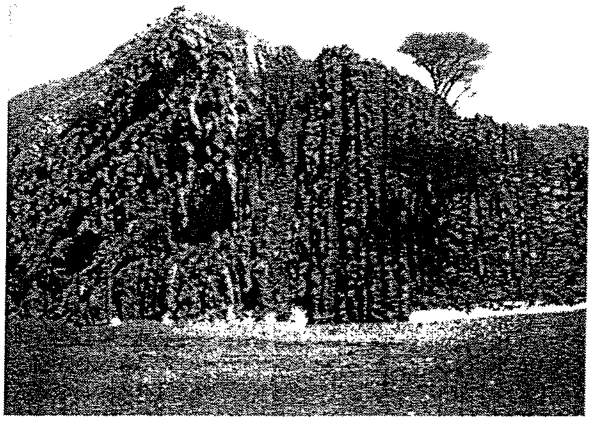

Figure 2. Photograph showing coarse alluvial deposits of a stream channel and bedrock sideslope, western Oman Mountains.

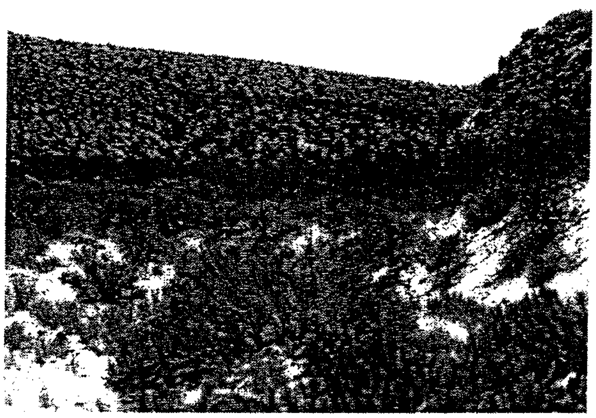

Figure 3. Photograph showing headwaters area of Amargosa River Basin, Nevada, USA.

Channels of the Amargosa Basin are generally undisturbed; thus flows based on channel widths, and calibrated by records from 12 stream gauges, were input directly to the simulation model. Accounting for inflows from lateral areas (Fig. 1A) based on rainfall and inferred infiltration potential, discharges were routed along channels of the Amargosa River and its main tributaries. Reductions in mean discharge, as suggested by net decreases in channel size, led to computed volumes of recharge through transmission loss. Total recharge included additions by infiltration in inter-channel areas during low-frequency storms (Lane and Osterkamp, 1991).

Average-annual recharge in the modeled area (3980 km^2) was estimated to be 20.5 Mm^3 (Table 1), suggesting mean-annual recharge of 5.2 mm. Study results indicate that net abstraction of water occurs downstream along most channel reaches. Where a channel is near mountains with elevated rates of rainfall and runoff, the mean rate of streamflow may increase and thus recharge by transmission loss also increases. As for the Al Ain area, recharge rates appear to be much greater in mountainous parts of the basin (Fig. 3) than in the lower interior. About 90% of recharge in the Amargosa Basin occurs by abstraction along ephemeral-stream channels, the rest results from infrequent rainfalls and infiltration through soil of upland and inter-channel areas.

CONCLUSION

Model results for ground-water recharge in the Al Ain area and the Amargosa River Basin differ much but may not be contradictory. Computed depths of average annual recharge for the two areas are, respectively, 8.8 and 5.2 mm despite evidence that mean annual rainfall in the Al Ain area is 50 mm less than in the upper Amargosa Basin. Al Ain watersheds have few plants to transpire soil moisture, and headwater areas of the Oman Mountains have much bare-rock surface from which runoff readily flows to alluvium of high hydraulic conductivity. The upper Amargosa Basin has greater vegetation cover, less bare-rock area to enhance runoff, and more soil areas of lower hydraulic conductivity than does the Al Ain area. Because the transmission-loss model accounts for rainfall, runoff, and infiltration, results obtained for the two example areas may offer reasonable inputs for the larger water-budget studies.

The simulation model upon which ground-water recharge was computed for the Al Ain and Amargosa areas are event-based and originally unintended for long-term estimates of recharge. The work described here, with field-based (geomorphic) techniques for its use, permits integration to larger scales of space and time and, therefore, inputs to models of large ground-water systems. Extension of these techniques could include addition of sediment-transport algorithms to estimate sediment discharge by otherwise unsampled flows in ephemeral-stream channels.

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