SR-1/2004-05

RECHARGE THROUGH EPHEMERAL STREAM - A STATUS REPORT

आपो हिष्टा मयोभुवः

NATIONAL INSTITUTE OF HYDROLOGY
JALVIGYAN BHAWAN
ROORKEE -247 667
2004 - 2005

PREFACE

The Siwalik foothill region, commonly known as Kandi belt, is spread in the north-western states of Jammu and Kashmir, Himachal Pradesh, Uttaranchal, Punjab, and Haryana. Denuded hills, undulating topography, erratic distribution of rainfall in space and time, small land holdings, high soil erosion, coarse textured and infertile soil, and low crop productivity, are typical features of this region. The major problems being faced in the Siwalik hills and Kandi belt include excessive runoff, soil erosion, land degradation and erratic water distribution in space and time.

In arid and semiarid regions there is mounting evidence that recharge is likely to occur in only small portions of a basin, where flow is concentrated, such as depressions and ephemeral stream channels. Recharge along ephemeral channels can be large and play an important role in groundwater-surface water exchange in these regions. However, identification of the processes and dynamics that control this exchange is a challenging problem. In eleventh RCC meeting, organised by the Western Himalayan Regional centre of the Institute at Chandigarh in April 2004, there was concern on the recharge through ephemeral stream in Kandi Belt of Jammu. It was suggested that the recharge through ephemeral stream should be estimated. Keeping above fact in mind, the Western Himalayan Regional Centre has carried out a status review on recharge through ephemeral stream as part of the work program of the centre for the year 2004-2005. In this report, literature related to recharge through ephemeral stream has been reviewed and compiled. It is expected that this report will be useful to the planners, development agencies, researcher and technologists in their efforts for development of the region. This report is prepared by Dr. Vivekanand Singh, Scientist 'C'.

Raj Deva Singh

Director

CONTENTS

LIST OF FIGURE

LIST OF TABLES

ABSTRACT

Ephemeral stream transmission loss represents an important groundwater surface water exchange in arid and semiarid regions and is potentially a significant source of recharge at the basin scale. However, identification of the processes and dynamics that control this exchange is a challenging problem. Specifically, data on the proportion of runoff transmission losses that escapes from near channel transpiration and wetted channel evaporation to become deep groundwater recharge are difficult to obtain. The estimation of transmission losses is also required to provide adequate instream flow requirements to maintain healthy stream ecosystems. In addition, the effect of transmission losses on river flow has direct implications on water supply planning issues such as water consumption, water conservation and groundwater recharge.

In this study, literatures related to recharge through ephemeral stream have been reviewed and compiled. There have been several attempts to quantify ephemeral stream recharge using different methods. The selection of most appropriate method often depends on the circumstances related to the individual study and the availability of the data. Of all the methods reviewed in this report, the combined use of differential equations physical based and regression offer the most promise and seem more realistic as they consider the physical processes related to losses and recharge to study the generic form of the equations and then use regression to develop site specific prediction equations.

CHAPTER 1

1. INTRODUCTION

1.1 General

Rainfall in hilly regions is generally higher than in the plains, and so is the runoff production. It is therefore important to understand the runoff production mechanism on hill slopes, from where most of the flow in the rivers of the world originates. Rainfall reaching the ground surface, after meeting the needs of infiltration and evaporation, moves down the natural slope over the surface and through a network of gullies, streams and rivers to reach the ocean. The portion of the rainfall which by a variety of paths above and below the surface of the earth reaches the stream channel is called runoff. Once it enters a stream channel, runoff becomes stream flow and hence stream may be defined as a natural channel or flow path, which carries rainfall excess/surface runoff from the watershed to the river. About six decades ago, Horton proposed his theory of runoff, wherein runoff begins as soon as rainfall intensity exceeds infiltration rate, and the rate of runoff is equal to the amount by which the rainfall intensity exceeds the rate of infiltration. The runoff was supposed to occur as a thin film of water flowing over land surface. Hewlett had introduced the concept of variable source areas of storm runoff generation. Hewlett & Nutter (1970) has given another mechanism of runoff generation as subsurface flow, where rainfall infiltrates first vertically into the soil and then flows laterally to reach the stream. This mechanism appears to be valid only for deep, well drained soils. Another mechanism of runoff is the water table rises to ground surface as a result of accumulation of rainfall occurring directly over the soil (especially in valley bottoms), or of subsurface flow through the soil from upper slopes. The soil thus attains saturation over its entire depth, and all the rainfall occurring over the saturated area flows on the surface to reach the stream. Subsurface flow from upslope, when it reaches the saturated area, is forced to come to the surface as return flow and runs off to the stream as overland flow. The area over which soil is saturated can expand during the storm and contract towards its end or later.

1.2 Types of streams

Based on the annual hydrographs, streams can be classified into three types as (i) perennial, (ii) intermittent and (iii) ephemeral.

A perennial stream is one which always carries some flow (Figure 1.1). There is considerable amount of groundwater flow throughout the year. Even during dry seasons the water table will be above the bed of the stream. An intermittent stream has limited contribution from the groundwater and flows only at certain time of the year or flows seasonally. During the wet season the water table is above the stream bed and there is a contribution of the base flow to the stream flow. However, during dry seasons the water table drops to a level lower than that of the stream bed and the stream dries up. Excepting for an occasional storm which can produce a short–duration flow, the stream remains dry for the most part of the month (Figure 1.2). An ephemeral stream is one which does not have any base flow contribution. The annual hydrograph of such a river show series of short duration spikes marking flash flows in response to storms (Figure 1.3). The stream becomes dry soon after the end of the storm flow and is generally smaller but is much more numerous than perennial ones. From the divide to the mouth of a drainage basin, the increase in channel size is accompanied by a decrease in the number of channels. Typically an ephemeral stream does not have any well defined channel. Most rivers in arid zones are of the ephemeral kind. Some examples of ephemeral streams are in north-west arid region such as Luni basin, Sukri basin of India which discharges into the Rann of Kachchh, Rio Galisteo and Rio Santa Fe in New Mexico, Walnut Gulch in south-eastern Arizona, Tucson in southern Arizona, western Kansas arid regions of Saudi Arabia, Negev in Israel, etc.

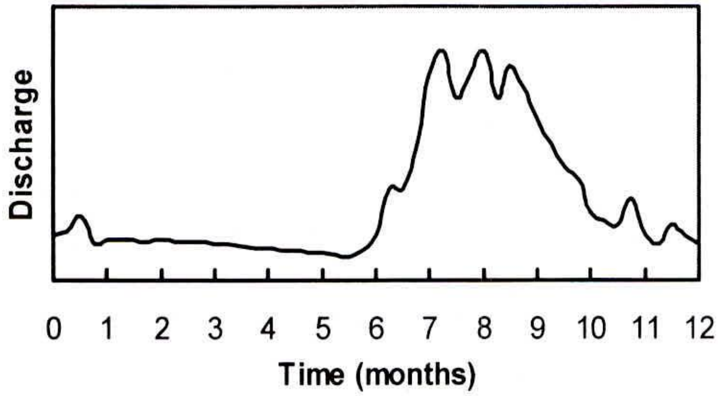

Figure 1.1: Perennial Stream

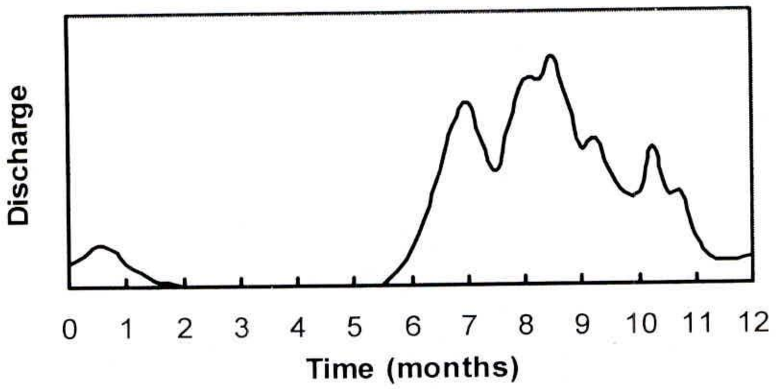

Figure 1.2: Intermittent Stream

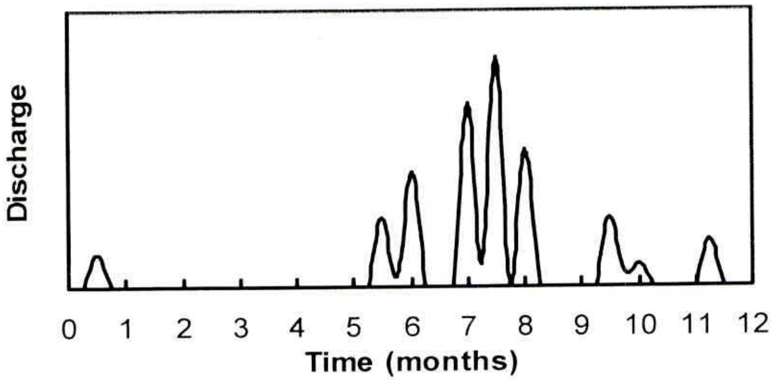

Figure 1.3: Ephemeral Stream

Most of the population in the Kandi belt in Jammu region face water scarcity, especially during summers. Every year there is a hue and cry about water supply in this region, although the Kandi belt receives a fairly high rainfall, and a number of rivulets and torrential streams pass through the area. Many streams are ephemeral in nature and ground water recharge takes place through the streams. Water table is very deep and aquifer is inclined and the recharge water flow downstream of the Kandi belt.

1.3 Losses from Ephemeral Stream

Flow in natural rivers and streams changes its volume, as it travels downstream. If there is no additional volume due to catchment runoff via tributaries or diffused flows within the river reach between upstream and downstream ends, generally there will be a net reduction in flow. This reduction in flow is termed as transmission loss. The two dominant processes included in transmission losses are seepage and evaporation. Seepage loss is the loss of water that infiltrates via the bank and bed of the river. This water may find its way into the underlying groundwater aquifer as recharge or may return later as flow into the river. The evaporation loss occurs when water from a water surface is converted into its gaseous state and transfers from the water surface into the atmosphere. The rate of evaporation from a river depends on meteorological conditions, physical characteristics such as water surface area open to the atmosphere, water depth and to a lesser extent, salinity. Although transmission losses may cause a reduction in flow available for consumption, they support riparian vegetation, and recharge local and regional aquifers. To date, evaporation loss associated with transmission losses has not been studied in detail; even though it has been identified as a dominant process by which water is lost. As it is difficult to obtain accurate evaporation measurements that spatially represent evaporation from natural rivers and streams, few attempts were made to quantify evaporation loss. Furthermore, as it is very difficult to ascertain the fraction of transmission losses attributed to evaporation, it is often ignored, assumed negligible or combined with seepage. However, using crude techniques of estimation, studies such as Peterson (1962), Maunsell and Partners (1981), Abdulrazzak (1994), Shentsis *et al.* (1999) and Gu and Deutschman (2001) did attempt to quantify the evaporation loss.

1.4 Recharge through Ephemeral Stream

Recharge through ephemeral stream is the loss of water that infiltrates into the riverbank and bed of the river. This water may find its way into the underlying groundwater aquifer as recharge. As water resources become more precisely allocated, the ability to accurately manage a surface water system becomes more important. In order to allocate water resources, it is necessary that water planners and operators be capable of determining flow at different locations of the river system and amount of water infiltrated below the river bed and recharge the aquifer. This is often achieved using hydrologic techniques; however, the accuracy of such techniques depends on reasonably accurate estimates of the volumetric transmission loss rates. The estimation of transmission losses is also required to provide adequate instream flow requirements to maintain healthy stream ecosystems. In addition, the effect of transmission losses on river flow has direct implications on water supply planning issues such as water consumption, water conservation and groundwater recharge. Schematic diagram showing rise in water table due to recharge through ephemeral stream is shown in Figure 1.4.

As demands for water resources approach or surpass supplies, due to increasing urban, industrial and agricultural requirements, so does the competition for existing water supplies and pressure to develop new sources of water. To accommodate new demands for water resources whilst securing the existing use, a cap on further water use may need to be introduced. Therefore, in the absence of new sources, new allocations will have to come via water trading, which is a practice currently used in the Australian water industry. Successful arrangements for water trading within and between river basins will rely heavily on improved understanding of the behaviour of natural rivers and streams, including transmission losses and recharge.

There have been several studies undertaken to date that attempt to increase the understanding of transmission losses and recharge in ephemeral streams. Most have been concerned with arid regions of the United States of America and Saudi Arabia, whilst to a lesser extent there have also been studies undertaken in South Africa, India, Israel, United Arab Emirates and Australia. Furthermore, most of the studies were concerned with ephemeral (short lived) streams and very few considered perennial (continuing throughout the whole year) and regulated rivers. However, these perennial and regulated rivers are considered a vital mechanism to convey harvested water from storages to points of demand.

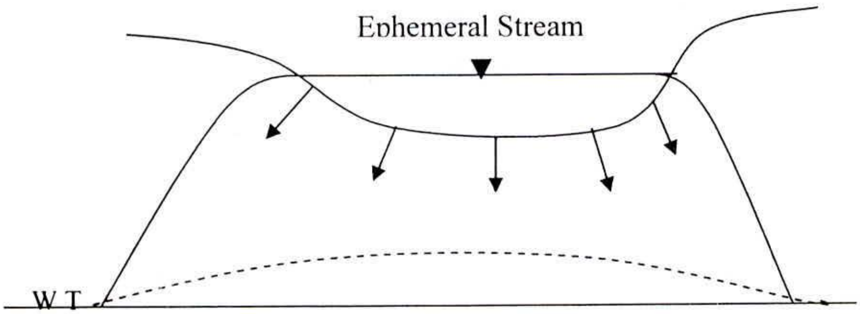

Figure 1.4: Schematic diagram showing rise in water table due to recharge through ephemeral stream.

1.5 Factors affecting recharge

In order to develop some comprehension of the magnitudes of transmission losses and recharge through ephemeral stream, it is essential to understand the factors that affect these losses and recharge. Sharp and Saxton (1962) provide a detailed description of factors affecting seepage, transmission losses and then recharge in natural streams. They include flow regime, soil characteristics of the river bed and banks, topographical characteristics of rivers (e.g. gradient, depth, size, meander, number of channels, etc), and depth to ground water table from river water surface. Vegetation and man made structures along the river channel may also have some hydraulic influence on transmission losses and recharge by varying flow conditions, thus altering the area of inundation. Kraatz (1991) also said that the rate at which water is lost from the river depends on multiple factors which include the type of channel material, channel geometry, wetted perimeter, flow characteristics, depth of groundwater, sediment amount, etc. When considering ephemeral streams, it can also be affected by factors such as antecedent moisture of the channel alluvium, duration of flow, channel bed and bank storage capacity, and the content and nature of sediment in the stream flow.

Despite the fact that the recharge through ephemeral stream can be affected by many of these factors, only few of these factors have successfully been used as parameters in estimating recharge in previous studies.

CHAPTER 2

2. RECHARGE ESTIMATION

Recharge estimates are essential for the sustainable management of groundwater resources, however recharge is arguably the water balance component known with the least certainty. Mounding evidence suggests that in arid and semi arid regions recharge likely occurs in only small portions of the basin where flow is concentrated, such as depressions and ephemeral stream channels; elsewhere little recharge occurs (Heilweil and Solomon, 2004; Plummer et al., 2004; Scanlon et al., 1999 & 2003; Walvoord et al., 2003). Ephemeral channel transmission loss represents a significant water flux in semi-arid and arid regions and therefore is potentially a significant source of groundwater recharge (Renard et al., 1993). Recharge along ephemeral channel can be large and play an important role in groundwater/surface water dynamics in arid and semi arid basins (Goodrich et al., 1997). However, runoff water absorbed by the channel alluvium is subject to several abstractions before it contributes to deep aquifer recharge. Two relatively immediate abstractions are transpiration by near-channel vegetation and evaporation from the wetted channel. At longer timescales (>5 days), impeding subsurface soil and geology may continue to retain channel transmission losses near the surface for vegetation transpiration or divert it down slope to area of discharge or additional vegetation and subsequent transpiration. The measurement of transmission loss is straightforward, when accurate discharge measurements at both ends of the channel reach can be obtained, a number of interdisciplinary challenges must be met to quantify the proportion that escapes near-channel evapotranspiration (ET) and wetted channel evaporation to become groundwater recharge.

2.1 Methods of Recharge Estimation

Many investigations have been undertaken in the past to better understand and attempt to quantify transmission losses and recharge through ephemeral streams. However, most of these studies were focused on transmission losses associated with ephemeral streams and then recharge to underlying local aquifer systems. An extensive literature review in this study showed that there were several types of formulations (or methods) of varying degrees of complexity in quantifying recharge through ephemeral stream. In general, the simplified procedures require less information about the physical features of the channels but are less general in application. The complex procedures may be more physically based, but require correspondingly more data, and more complex computations (Lane *et al.*, 1980). Some of the types of methods used are listed below and classification of these methods has also been shown diagrammatically in Figure 2.1.

1. Differential equations
2. Simple regression equations
3. Combined use of differential equations and regression
4. Field observations and experimentation
5. Stream flow routing
6. Hydrologic budget.

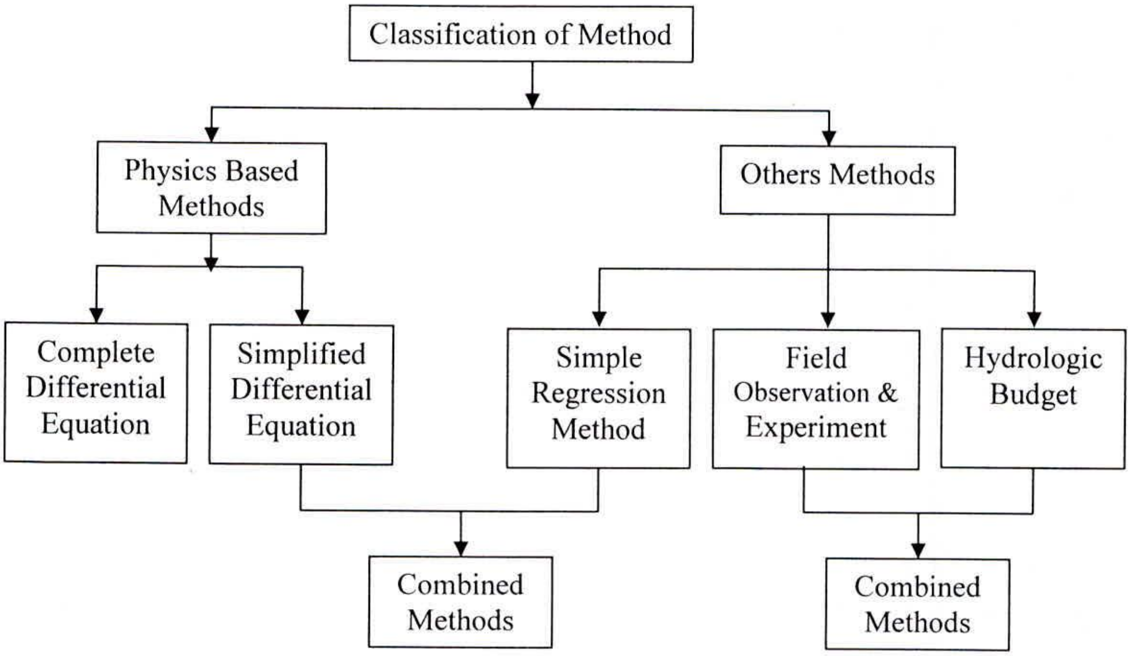

Figure 2.1: Classification of Methods of recharge estimation through ephemeral stream

2.1.1 Differential equations

Hantush, 1967 had estimated the channel recharge using second-order, linear partial differential equations of groundwater mound. The general groundwater flow equation is as follows:

$$T_x \frac{\partial^2 H}{\partial x^2} + T_y \frac{\partial^2 H}{\partial y^2} + Q_s = S \frac{\partial H}{\partial t} \tag{2.1}$$

where, Tx and Ty = transmissivities in x - and y - directions respectively; H = piezometric head; S = storage coefficient; Q_s = net source/sink term. It was described for an interval of constant recharge rate from stream channel represented by a rectangle of channel width and infinite length to an initially level water table. The equation also described a homogeneous, isotropic unconfined aquifer, and includes the Dupuit-Forchheimer assumption of uniform horizontal flow. Decay of the recharge rate could be computed by superposing the solution for an equal but negative recharge rate, beginning when recharge ceases. One could extend the principle of superposition to approximate a time-varying recharge rate by superposing a series of solutions for incremental negative rates thus allowing the recharge rate to decay exponentially rather than end abruptly from an initially constant rate. This represents the gradual dewatering of the material above the aquifer after a recharge season. At some time all material above the water table becomes unsaturated and the recharge rate diminishes rapidly. For simplicity, the rate was set to zero at this point.

Simplified differential equations were also developed by Peebles (1975) and later Peebles *et al.* (1981) to describe a leaky reservoir model capable of representing stream flow recession in an ephemeral stream channel in south-eastern Arizona, USA. The model is described by a continuity equation, and discharge-stage and storage-stage relationships. It was developed assuming a constant loss rate per unit area in the stream, infiltration loss as a function of discharge and time, and high loss at the onset followed by decrease to nearly constant. The general leaky reservoir discharge equation, which is derived using the St. Venant equations with the infiltration term and making certain assumptions, is:

$$-c(Q,t) - Q(t) = \frac{\beta}{\alpha^{p/m}} \frac{d}{dt} [Q(t)]^{p/m} \tag{2.2}$$

in which, c(Q,t) defines functions of discharge and time and is the total reservoir loss rate; Q(t) is outflow from reach, α, β, p and m are constants of the relationship for discharge-storage-stage relationship by assuming kinematic wave approximation as $Q=\alpha h^m$ and $S=\beta h^p$. The model was calibrated using two parameters, reservoir leakage rate and initial storage, and the reservoir was considered a reasonable physical representation of the mechanisms operating in the stream during flow recession.

Jordan (1977) assumed that (1) the rate of loss at any point between the two gauging stations was proportional to the flow at that point; and (2) the channel and valley characteristics were uniform so that the proportionality was the same throughout the reach between gauging stations. Based on these assumptions, Jordan developed a first order differential equation to describe the losses as $V_x = V_A R^x$. Transmission losses between gauging station and transmission loss in the first mile below the upper station were related to the flow at the upper station as below:

$$V_1 = V_A\left(1-\left(\frac{V_x}{V_A}\right)^{1/x}\right) \tag{2.3}$$

in which, V_x is the volume of flow at distance x; V_A is the known volume of flow at location A; R is the ratio of the volume at any location to the volume at a location one unit of length upstream and V_1 is the loss in the first mile. The decision to calculate transmission losses in the first mile was purely to standardize data in an attempt to develop regional equations for use in ungauged rivers and streams. The Jordan (1977) approach would allow for non-linear decrease of flow and variations in distance between gauging stations, and enable better comparison of transmission losses of different rivers and streams. However, the standardization had little effect on the analysis, and some scatter remained as other factors such as antecedent moisture conditions and differences in alluvial material had not been considered. The method was used to determine transmission losses for ephemeral (or intermittent) streams in western Kansas, USA. It was found that the transmission loss in first mile foe medium to large sized stream in Western Kansas averages about 2 % of the flow volume at the upstream. It was developed using events that did not include runoff from the drainage area between gauging stations and used transmission loss data for high flow events only. It was assumed that low or medium flows would be greatly affected by factors not considered in the study such as the continuation of reservoir release after stream bank storage volume was filled. However, by disregarding lateral and/or tributary inflows, transmission loss estimates in this study represented a lower bound.

Flug et al., 1980, has developed a stochastic event-based approach to estimate groundwater recharge from an ephemeral stream assuming that besides several factors in semi arid lands the most important factor affecting recharge of the area underlying an ephemeral stream is the flow duration. The duration of stream flow events is used as an input into a transfer function relating stream flow to groundwater recharge. Flug et al. 1980 concluded that the event-based method can be applied in conjunction with any type of transfer function. However, complex transfer functions will further complicate the calibration process. A simulation procedure, based upon a random number of winter and summer stream flow events, uses the transfer function to generate a long record of annual recharge values. Then a probability density function is fitted to the generated data. The postulated model seems to provide a reasonable estimate of recharge when compared to results from a study using the convolution method to estimate recharge.

2.1.2 Simple regression equations

There have been some attempts to develop simple regression equations based on one or more variables (e.g. upstream flow), giving less consideration to the physical processes governing transmission losses and recharge. Lane *et al.* (1971) developed a regression relationship between transmission losses and inflow volume, and also between inflow and outflow volume for an ephemeral stream channel in south-eastern Arizona, USA. Similarly, Walters (1990) and Sorman and Abdulrazzak (1993) developed regression relationships for ephemeral stream channels in south-western Saudi Arabia. Walters (1990) considered upstream flow volume, channel antecedent condition, channel slope, channel bed material, duration of flow, and active channel width in developing regression equations for transmission losses. The regression on log transformed data identified upstream flow volume and channel width as significant, whilst for the untransformed data only upstream flow volume was significant. Sorman and Abdulrazzak (1993) expressed transmission losses in terms of multiplication of stage height and duration, multiplication of maximum flood width and duration, and groundwater recharge as separate expressions. However, these derived relationships were not strong, and therefore may not be suitable as prediction equations.

Several studies had been undertaken in Australia by Maunsell and Partners (1981) and water authorities, where attempts were made to determine river transmission losses as a function of upstream flow for perennial rivers, often regulated by water resource managers and operators. Almost all studies conducted by water authorities were unpublished. As most of these studies often involved limited data which also contain measurement errors, they had little success in developing meaningful relationships.

The use of these simple regression equations as prediction tools is highly questionable, as they were derived at specific locations, from events subject to local influencing parameters. Furthermore, they do not explain the variability in transmission losses and recharge fully.

2.1.3 Combined use of differential equations and regression

Formulations or methods that involved a combination of differential equations and regression analysis offer some promise and seem more realistic, as they consider physical processes related to transmission losses to study the generic form of the equations and then use regression/optimization to develop site specific equations. However, only few studies were cited in literature and they include Lane *et al.* (1980), Lane (1982, 1985, and 1990), Sharma and Murthy (1994), Osterkamp *et al.* (1994), Osterkamp *et al.* (1995), and Rao and Maurer (1996). All these studies, except Rao and Maurer (1996), had considered transmission losses related to flood events (or loss of water volume during floods) in ephemeral rivers.

Extending the work of Jordan (1977) and assuming the volume of outflow is proportional to the volume of inflow (Lane et al., 1971), Lane et al. (1980) developed a procedure to estimate transmission losses in abstracting stream channels of arbitrary length and width. This was achieved by linking a two-parameter linear regression equation that relates outflow volume of a channel reach to inflow volume with a simplified two-parameter differential equation that describes the transmission loss rate as a function of length and width of the wetted channel. The differential equation of the above procedure was further developed by Lane (1982) and included in the channel component of a distributed model. Lateral inflows were included by assuming a constant rate of lateral inflow per unit length of channel. This differential equation also assumes the volume of losses in the reach is proportional to the volume of upstream inflow and a constant or steady-state loss rate (Lane, 1990). Transmission loss rates were also assumed to vary directly with the surface area of the river bed and bank wetted by a passing flood wave through a channel reach. This model was used in several subsequent studies including Lane (1985, 1990), but was limited to stream flow in ephemeral stream channels with infiltrating losses. The model has only been evaluated using flood peak data for conditions represented by small semiarid watersheds in southeastern Arizona, USA. Although, the model was unable to fully describe the dynamic nature of transmission losses and recharges, it requires a minimum amount of observed data, considers lateral inflow and can be used to estimate transmission loss in ungauged catchments. This approach was further used by Sharma and Murthy (1994) to evaluate transmission losses in ephemeral streams in north-west arid India where results were compared with those obtained by previous studies undertaken in arid regions of Saudi Arabia and the USA. Despite some scatter, the results were generally consistent.

Osterkamp *et al.* (1994) combined this approach with channel-morphology techniques used to determine stream flow to determine transmission losses, used to estimate recharge for the Amargosa River basin, above Shoshone, California, USA. Similarly Osterkamp *et al.* (1995) used this approach to estimate groundwater recharge for ungauged basins in arid/semi-arid areas of Oman and Abu Dhabi, United Arab Emirates.

Rao and Maurer (1996) also combined a differential equation with regression to predict daily transmission losses in a stream channel. They coupled a seepage function with a stage-discharge relationship representing the river reach to produce a combined differential equation which, when integrated over the entire reach produced a one-parameter seepage loss model that can be easily calibrated using measured flow data. This approach, the only significant study based on a non-ephemeral river, lumps all individual losses (e.g. deep percolation, use by phreatophytes, evaporation) into a single loss term, whilst retaining the simulation of the non-linear relationship of seepage to flow. However, the model can only be applied to a losing stream and requires that all lateral inflows, ungauged tributary inflows and water diversions be accounted for in the inflow or the outflow term. Nevertheless, the basic methodology can be applied worldwide and is not site-specific in application. Rao and Maurer used flow as the variable, rather than the volume of water associated with a particular hydrological event. They successfully separated their analysis to isolate changing patterns of transmission losses due to seasonal irrigation practices, and other activities related to consumptive use and drainage in the area, near Lompoc, California, USA. This approach can be easily applied to regulated rivers free of storages and flowing under gravity, which are used to convey large amounts of water that are of interest to water resource planners, operators and communities around the world. The method can be used with any flow regime (high/moderate/low, summer/winter) and with different time intervals such as day/week/month.

Goodrich et al., 2004 also used Soil-temperature profiles method to estimate one-dimensional infiltration fluxes in the vadose zone below ephemeral streambeds while comparing the different methods of recharge estimation in Walnut Gulch channel. Two approaches were utilized to estimate infiltration flux using heat as a water tracer. An analytical method (Taniguchi and Sharma, 1996; Constantz and Thomas 1996) was used as a first approximation of infiltration flux from measured soil temperatures at each site. A more comprehensive, rigorous numerical approach was also used, when possible, to account for heat transport with water flow into the vadose zone. The numerical code VS2DH (Healy and Ronam, 1996) was used to simultaneously solve for conductive and advective heat transport with variably saturated water flow. The numerical model simulations were calibrated by adjusting the specified water flux at the upper boundary to minimize the difference between the calculated and measured soil temperatures at depth. Estimated infiltration rates can than be scaled to calculate the annual infiltration volume for the entire length of channel in between. Annual channel recharge is then estimated by subtracting the annual water lost due to open channel evaporation and near channel transpiration from the annual infiltration volume.

2.1.4 Field observations and experiments

Studies involving field observation and experiment have also been adopted as a means for estimating transmission losses and recharge. Wallace and Renard (1967) used observation wells to measure the effect of transmission losses on recharge to underlying aquifers of ephemeral streams in southeastern Arizona, USA. Transmission losses from flow events in this region were considered a primary source of recharge as direct recharge through the soil profile was almost non-existent because of the high potential evaporation and low precipitation. Such a phenomenon is also true for other arid regions of the world including the eastern Cape Province of the Republic of South Africa, where Hughes and Sami (1992) presented some transmission loss estimates based on moisture observations of the alluvium material using neutron probe access tubes. While their results were based on extrapolation from a limited number of observations, the estimated losses should at least be of the correct order of magnitude.

Dunkerley and Brown (1999), and Parsons *et al.* (1999) also analyzed transmission losses using field observation and experimentation. Dunkerly and Brown (1999) used direct observation to assess transmission losses in a single small (sub-bank-full) flow event in an ephemeral dry land stream in western NSW, Australia. Parsons *et al.* (1999) studied transmission losses through the beds of hill slope rills in the semi-arid south-western United States. Experimental studies of this nature are often carried out at specific locations, requiring additional resources and are usually confined to small areas. Therefore, the results of such studies are not useful as estimating tools for water supply planners.

Pool and Schmidt, 1997 has used repeat microgravity surveys to monitor changes in subsurface water storage and recharge near ephemeral channels in Arizona. In this method, changes in subsurface mass are measured by applying Newton's law of gravitation to variations in the results of repeated gravity surveys of a network of stations. Changes between stations are interpolated from the measured stations and integrated across the area of interest to determine total mass change. Measurements were made using a Lacoste and Romberg Model D relative gravity meter and referenced to a station near Tombstone, Arizona, where the absolute acceleration of gravity was measured periodically. The changing subsurface distribution of water mass was simulated using two-dimensional gravity models. This method estimates recharge assuming steady state or pre-summer conditions existed during the final survey.

Goodrich et al., 2004 also used the Chloride concentration and stable Isotopes methods for the recharge estimation in Walnut Gulch channel by measuring stable isotopes of hydrogen and oxygen along with Cl and SO4 concentrations to identify and quantify the source of water to the aquifer. Isotopic variation is useful for identifying the origin, seasonal timing, and mechanisms of recharge to aquifer in arid and semi arid areas (Allison et al., 1994; Mathieu and Bariac, 1996; Pool and Coes, 1999). Likewise, because plant do not take up appreciable amounts of Cl and evaporation leaves behind dissolved solids, increase Cl concentrations from rain to runoff to groundwater can be used to estimate the proportion of rain and runoff water which are abstracted from potential recharge due to ET. As applied in this study, this assumes that the observed increase in chloride concentration assumes that the observed increase in chloride concentration is the result of near-channel vegetation transpiration and open channel evaporation and that no appreciable groundwater inflow occurs from distant sources that may have different Cl concentrations. The method should only be interpreted as providing a long-term (>one year) integrated estimate of the amount of surface waters abstracted by transpiration and evaporation.

2.1.5 Stream flow routing

Few studies have also used stream flow routing techniques of varying degrees of complexity to estimate transmission losses. The complete hydrodynamic differential equations for one-dimensional channel flow routing are as follows:

$$\frac{\partial Q}{\partial x}+\frac{\partial A}{\partial t}-q-w(r-f)=0 \tag{2.4}$$

$$\frac{\partial v}{\partial t}+v\frac{\partial v}{\partial x}+g\frac{\partial h}{\partial x}+\frac{vq}{wh}+g(S_f-S_o)-\frac{v}{h}(r-f)=0 \tag{2.5}$$

where, Q = discharge; A = channel cross-sectional area; v = flow velocity; h = flow depth; q = lateral inflow per unit width; So = frictional slope; So = Bed slope; w = cross-section width; r = rainfall intensity; f = infiltration rate; g = acceleration due to gravity; x = horizontal distance.

Smith (1972) used the kinematic wave model to route hydrographs in channels of ephemeral streams and demonstrated the decrease of the hydrograph peak in the downstream direction due to infiltration. Knighton and Nanson (1994) used the three parameter Muskingham procedure to estimate outflow hydrographs (and therefore transmission losses) for a 32km reach of an arid zone river in Australia. With minimal tributary contribution downstream, output was largely controlled by upstream input.

Sharma and Murthy (1995) stated that the accuracy of the hydrologic flow routing methods depended on reasonable accurate estimates of the volumetric transmission loss rates. With this in mind, they developed an empirical method to estimate time-dependent transmission loss to be used in hydrologic routing of flow in an ephemeral channel in arid northwest India. The continuity equation was modified by introducing a nonlinear volumetric transmission loss rate, which was empirically determined from the observed inflow-outflow data for a channel reach.

El-Hames and Richards (1998) used the St Venant equations and the Kinematic wave equation for channel routing and overland flow, respectively and coupled this with Richards' equation to account for infiltration losses into channel beds. The coupled model was able to simulate the dynamic transmission loss as the hydrograph passed downstream. This was believed to be the first physically based model capable of modelling transmission losses dynamically. The model was tested in arid regions in south-western Saudi Arabia and produced reasonable transmission loss simulation with little calibration. It was observed from sensitivity analysis that the initial soil moisture content, soil saturated hydraulic conductivity and Manning's roughness coefficient are the most effective factors interms of affecting the outflow hydrograph's shape and volume. Although stream flow routing has been used to estimate transmission losses in these studies, they are often more complex and are event based. Therefore, they are less useful for transmission loss estimation of rivers and streams with varying flow regime, which are not dominated by events.

2.1.6 Hydrologic budget

The simplest (although often considered as the crudest) method of estimating transmission losses and recharge in rivers and streams would be the use of a hydrologic budget approach (also known as mass/volume balance). However, if the use of complex methods does not improve estimates, then the use of a hydrologic budget approach may be a viable option, depending on the amount and quality of data available. The channel reach water balance equation is as follows:

$$R = P + Q_i + Q_l - Q_o - E - T \qquad (2.6)$$

where, P = Precipitation; Q_i = measured inflow into the study reach; Q_l = lateral inflow into the reach; Q_o = measured out flow; E = Estimates of channel evaporation; and T = Scaled sap flow estimates of near-channel transpiration.

McIntosh and Langford (1978) determined the upper limit of the transmission losses for a perennial river in Victoria, Australia. Although they attempted to include major tributary inflow into their analysis by collecting data from stream gauging stations, the tributary gauging sites were often quite some distance away from the confluence to the river being analyzed. Therefore the potential transmission losses between these gauges and the river were not included or considered insignificant in the hydrological budget.

Abdulrazzak (1994), and Abdulrazzak and Sorman (1994) used a simple mass balance approach to determine transmission losses for ephemeral streams in a typical arid region in southwestern Saudi Arabia. They were able to include both tributary flows and evaporation in their analysis by using simplified estimation techniques. A runoff coefficient procedure was used to estimate the tributary runoff between upstream and downstream gauging stations, whilst evaporation losses were estimated using pan evaporation data of a nearby meteorological station, the duration of storm and the average channel flow area. Regression analysis was then used to relate transmission losses to the controlling parameters such as upstream inflow, channel flow width and antecedent soil conditions. These regression equations can be used indirectly to estimate transmission losses in arid catchments having similar hydrological and morphological characteristics to the ones used in above regression analysis. However, since the regression equations were developed using a limited set of data, they require further verification.

Taylor and Howard (1996) predicted the magnitude of groundwater recharge using soil moisture balance approach which was supported by stable isotope data and groundwater flow modeling in the Aroca catchment of Uganda in Africa. It was revealed that recharge is more dependent on the number of heavy rainstorm events of the monsoon.

Arnold and Allen (1999) had compared the recharge obtained with automated recession curve displacement method to the field based water balance methods. Monthly estimates of recharge using this method were problematic and not advocated for use at except for assessment of general trend in recharge. This approach provided a valuable tool for estimating annual groundwater recharge over large area and assist in the calibration of regional ground water models when applied in a conscientious manner to flow systems.

Shentsis *et al.* (1999) developed a hydrological-lithostratigraphical model for the assessment of transmission losses and groundwater recharge from runoff events in arid water courses in Negev, Israel where hydrological and meteorological records were incomplete. Transmission losses were estimated using water balance equations that included lateral tributary inflows that could only be estimated indirectly. Nevertheless, this was one study, if not the only study, that subdivided transmission losses into various components. The losses were subdivided into channel moistening, which subsequently evaporates, and groundwater recharge. Estimation of actual evaporation from channel alluvium indicated that evaporation was substantially smaller than the transmission losses (approximately 1-2% of the transmission losses), implying that most of the loss became groundwater recharge for runoff events. The hydrologic budget approach was also considered the most appropriate approach to assess transmission losses in a river of a proposed diversion project in North Dekota, USA by Gu and Deutschman (2001).

Jothiprakash (2003) used a water balance model for estimating the water loss/gain in Tambiraparani river in India. Water loss/gain included was return flow, transmission loss, and tributary contribution. It was found that the Tambiraparani river losing water during June to September and gaining during rest of the months.

Goodrich et al. (2004) used a channel reach water balance approach assuming that ephemeral channel recharge equals channel transmission losses less the abstractions from near channel vegetation transpiration and channel evaporation. However, it is very difficult to quantify the proportion of transmission losses that escape from near-channel evapotranspiration (ET) and wetted channel evaporation to become groundwater recharge. Channel transmission losses from the main channel stem were calculated using measured flow volumes and lateral inflow into the main stem estimated using KINEROS2.

Although the hydrologic budget approach of estimating transmission losses may seem crude at times, it offers flexibility, and can be used for non-ephemeral streams with long losing or gaining reaches, with varying time intervals. This method can easily include evaporation estimates and lateral flows, either as tributary inflow and/or diversions, and often present in channels used to deliver irrigation water. However, the method is site specific, does not consider the dynamic nature of transmission losses and requires sufficient data in order to establish reasonable estimates.

Goodrich et al. 2004 estimated the ephemeral stream recharge using several independent methods, which includes a reach water balance approach, with near-channel ET estimated using sap flux and micrometeorological measurements; geochemical methods such as chloride mass balance; modelling of changes in groundwater level or microgravity measurements; and vadose zone water and temperature transport modelling in Walnut Gulch, Arizona. They concluded with the remarks that the recharge estimates from all the methods fall within a factor of three. Individual methods yielded important results. The reach water balance revealed the limited size of ET loses (≈ 20 %) and limited area of inundated channel. For the Cl mass balance method, (Cl)/(SO4) ratios were found to be useful for distinguishing ephemeral channel recharge from regional groundwater. In terms of wider applicability, the data requirements for reach water balance and vadose zone temperature modelling will limit their use for recharge estimates. However, because data for these methods is collected on an event basis, they will yield process level insights. In contrast, methods that integrate over time and space, such as microgravity, groundwater mound modelling, and Cl mass balance will find wider applicability for estimating ephemeral channel recharge. It was found that the range of ephemeral channel recharge estimated from these methods differed by a factor of less than three during the relatively wet and average monsoon seasons. A rough scaling for the entire basin of San Pedro Basin indicates that ephemeral channel recharge constitutes between ≈15 % and ≈40 % of the total annual recharge to the regional aquifer as estimated from a calibrated groundwater model.

2.2 Data Requirement

Selection of particular method mainly depends on the data requirement of that particular method and data availability for the study area. Different methods require different set of data but in general data requirements are as follows:

1. Meteorological data (Precipitation, Relative humidity, air temperature, wind velocity)
2. Pan evaporation value and evapotranspiration
3. Hydraulic conductivity values
4. Discharges at inlet and outlet of the reach of stream
5. Infiltration rate from the bed of the stream
6. Length and width of the stream
7. Flow parameters of the catchment.

2.3 Comparison of Different Methods

In general, the differential equation may be more physically based but require correspondingly more data and more complex computations and is more general in application (Lane *et al.*, 1980). The simplified procedures require less information about the physical features of the channels but are less general in application. Some of the types of methods used are listed below. The simple regression equations based on one or more variables (e.g. upstream flow), gives less consideration to the physical processes governing transmission losses and recharge. The use of these simple regression equations as prediction tools is highly questionable, as they were derived at specific locations, from events subject to local influencing parameters. Methods which involve a combination of differential equations and regression analysis offer some promise and seem more realistic, as they consider physical processes related to transmission losses to study the generic form of the equations and then use regression/optimization to develop site specific equations. Field observation and experimental methods are often carried out at specific locations, requiring additional resources and are usually confined to small areas. Therefore, the results of such studies are not useful as estimating tools for water supply planners. This method is more expensive as it requires expensive instruments for measuring data. Hydrologic Budget method is conceptual and simple method of estimating transmission losses and recharge in rivers and streams. However, if the use of complex methods does not improve estimates, then the use of a hydrologic budget approach may be a viable option, depending on the amount and quality of data available. Comparative merits/strength and demerits/weaknesses of different methods are presented in Table 2.1.

Table 2.1: Comparison of different methods for estimating recharge through ephemeral streams

Methods	Merits/Strength	Demerits/Weakness
Differential Equations	More physical based More general application.	Requires more information & complex computations.
Simplified Differential Equation	Requires less information about physical features.	Less general application.
Simple Regression equation	Based on one or more variables.	Less consideration to physical processes, specific location & subjected to local influencing parameters.
Field Observation & Experimentation	Realistic estimate.	Extensive instruments & expensive.
Hydrologic Budget	Conceptual & simplest method.	More uncertainties, quantifying input and output can be expensive and challenging, more error.
Combined Method (differential & regression)	More realistic as considered physical processes.	More computations.

CHAPTER 3

3. SUMMARY AND CONCLUSIONS

There have been several attempts to quantify ephemeral stream recharge using different approaches. These include differential equations, simple regression equations, combined use of differential equations and regression, field observation and experimentation, stream flow routing and hydrologic budget. The most appropriate approach to use often depends heavily on the circumstances related to the individual study and the availability of the data.

Most of the studies conducted in the past related to transmissiòn losses and then recharge were based on empirical analysis of flow data and were mainly concerned with ephemeral streams in arid regions of the world. Often they did not include lateral flows entering or leaving the study reaches. Tributary runoff contributions were frequently ignored and often assumed negligible. Furthermore, most studies were event based and involved comparing inflow and outflow hydrographs to determine transmission losses and from transmission losses recharge was computed. Being event based, these methods cannot provide useful long term estimates of recharge. They are not necessarily useful when considering highly variable less natural (or regulated) flows, common in most perennial rivers around the world still being used to deliver water to areas of demand. These rivers often carry base flow and do not have the same hydrograph characteristics as flood events. There is only one study, which considered the physically based model to estimate the transmission losses, but this type of model is computationally expensive and takes more computational time. This type of model can be used to estimate the recharge or infiltration below the river bed.

Of all the approaches reviewed in this report, the combined use of differential equations physical based and regression offer the most promise and seem more realistic as they consider the physical processes related to losses and recharge to study the generic form of the equations and then use regression to develop site specific prediction equations. However, water budget method is used in most of the studies as it is conceptual and simplest method.

REFERENCES

1. Abdulrazzak M. J. (1994). Losses of flood water from alluvial channels. Arid Soil Research and Rehabilitation, 9, pp. 15-24.
2. Abdulrazzak M. J. and Sorman A. U. (1994). Transmission losses from ephemeral stream in arid region. Journal of Irrigation and Drainage Engineering, 20, 3, pp. 669-675.
3. Allison, G.B., G.W. Gee. And S. W. Tyler (1994), Vadose-zone technique for estimating groundwater recharge in arid and semiarid regions, Soil Science Society of American Journal vol. 58, pp. 6-14.
4. Arnold, J.G. and P.M., Allen, (1999), Automated Methods for estimating base flow and ground water recharge from stream flow records, J. of American Water Resources Association, 35(2), pp. 411-424.
5. Constantz, J. and C.L. Thomas, (1996), The use of stream bed temperature profiles to estimate the depth, duration and rate of percolation beneath arroyos, Water Resources Research, 32, pp. 3597-3602.
6. Dunkerley D. and Brown K. (1999). Flow behaviour, suspended sediment transport and transmission losses in a small (sub-bank-full) flow event in an Australian desert stream. Hydrological Processes, 13, pp. 1577-1588.
7. El-Hames A. S. and Richards K. S. (1998). An integrated, physically based model for arid region flash flood prediction capable of simulating dynamic transmission loss. Hydrological Processes, 12, pp. 1219-1232.
8. Flug, M., G.V. Abi-Ghanem, and L. Duckstein. An Event Based Model of Recharge From an Ephemeral Stream. Water Resources Research; 1980; 16(4): 685690.
9. Goodrich , D.C. , L.J. Lane, R.A. Shillito, S.N. Miller, K.H. Syed, and D.A. Woolhiser, (1997), Linearity of Basin Response as a Function of Scale in a Semi-Arid Watershed, Water Resources Research 33, 2951-2965.
10. Goodrich , D.C. , D.G. Williams, C.L. Unkrich, J.F. Hogan, R.L. Scott, K.R. Hultine, D. Pool, A.L. Coes, and S. Miller, (2004), Comparison of methods to estimate ephemeral channel recharge, Walnut Gulch, San Pedro River Basin, Arizona, in Groundwater Recharge in a Desert Environment: The Southwestern United States, edited by J.F. Hogan, F.M. Phillips, and B.R. Scanlon, Water Science and Applications Series, vol. 9, American Geophysical Union, Washington, D.C., 77-99.
11. Gu R. and Deutschman M. (2001). Hydrologic assessment of water losses in river. Journal of Water Resources Planning and Management, Jan/Feb, pp. 6-12.
12. Hameed T., Marino M. A. and Cheema M. N. (1996). Time series modeling of channel transmission losses. Agricultural Water Management, 29, pp. 283-298.
13. Hantush, M.S., (1967) Growth and decay of groundwater-mounds in response to uniform percolation, Water Resources Research, Vol. 3, pp. 227-234.
14. Healy, R. W. and A.D. Ronan, (1996), Documentation of computer program VS2DH for simulation of energy transport in variably saturated porous media-Modification of the U.S. Geological Survey's computer programVS2DT, U.S. Geol. Surv. Water Resources Invest. Rep. 96-4230, pp. 36.
15. Heilweil, V.M., and D.K. Solomon, (2004), Millimeter- to kilometer- scale variations in vadose-zone bedrock solutes: implications for estimating recharge in arid settings, in Groundwater Recharge in a Desert Environment: The Southwestern United States, edited by J.F. Hogan, F.M. Phillips, and B.R. Scanlon, Water Science and Applications Series, vol. 9, American Geophysical Union, Washington, D.C.,49-67.

16. Hughes D. A. and Sami K. (1992). Transmission losses to alluvium and associated moisture dynamics in a semiarid ephemeral channel system in southern Africa. Hydrological Processes, 6, pp. 45-53.
17. Jordan P. R. (1977). Stream flow transmission losses in Western Kansas. Journal of the Hydraulics Division, Proc. A. S. C. E., 103 (HY8), pp. 905-919.
18. Jothiprakash, V. (2003), Water balance model to assess the water loss/gain in a river system, Jl. of Institution of Engineers (I), Vol. 84, Nov., pp. 196-200.
19. Kraatz D. B. (1991). Irrigation canal lining, FAO Irrigation and Drainage Paper No. 2, Food and Agriculture Organization of the United Nations, Rome, 170 pp.
20. Knighton A. D. and Nanson G. C. (1994). Flow transmission along an arid zone anatomising river, Cooper Creek, Australia. Hydrological Processes, v. 8, pp. 137-154.
21. Lane L. J., Diskin M. H. and Reynard K. G. (1971). Input-output relationships for an ephemeral stream channel system. Journal of Hydrology, 13, pp. 2-40.
22. Lane L. J., Ferreira V. J. and Shirley E. D. (1980). Estimating transmission losses in ephemeral stream channels. Hydrology and Water Resources in Arizona and the South West, Proc. 1980 meeting Arizona Section, A. W. R. A and Hydrology Section Arizona Nevada Academy of Science, pp. 193-202.
23. Lane L. J. (1982). Distributed model for small semiarid watersheds. Journal of the Hydraulics Division, A. S. C. E., 103 (HY10), Oct., pp. 1114-1131.
24. Lane L. J. (1985). Estimating transmission losses. Proc. Spec. Conf., Development and Management Aspects of Irrigation and Drainage Systems, Irrig. And Drain. Engr. Div., A. S. C. E., San Antonio, Texas, pp. 106-113.
25. Lane L. J. (1990). Transmission losses, flood peaks, and groundwater recharge. Hydraulics/Hydrology of Arid Lands (H^2AL), Proc. Int. Symp., R. H. French, ed., A. S. C. E., Reston, VA., pp. 343-348.
26. Leopold, L.B. and Miller, J.P. (1956), Ephemeral streams - hydraulic factors and their relation to the drainage net: USGS Professional Paper 282-A.
27. Mathieu, R. and T. Bariac, (1996), An isotopic study (H and O) of on water movements in clayey soils under a semiarid climate, Water Resources Research, 32,779-789.
28. Maunsell and Partners (1981). River Murray study of transmission and operational losses. River Murray Commission, Summary, Feb.
29. McIntosh J. R. and Langford K.J. (1978). Transmission losses in the Yarra River upstream of yering gorge. Report No. MMBW-W-0030, Melbourne and Metro. Board of Works, 43 pp.
30. Osterkamp W. R., Lane L. J. and Savard C. S. (1994). Recharge estimates using a geomorphic/distributed-parameter simulation approach, Amargosa river basin. Water Resources Bulletin, American Water Resources Association, 30, 3, pp. 493-507.
31. Osterkamp W. R., Lane L. J. and Menges C. M. (1995). Techniques of ground-water recharge estimates in arid/semi-arid areas, with examples from Abu Dhabi. Journal of Arid Environments, 31, pp. 349-369.
32. Parsons A. J., Wainwright J., Stone P. M. and Abrahams A. D. (1999). Transmission losses in rills on dry land hill slopes. Hydrological Processes, 13, pp. 2897-2905.
33. Peebles R. W. (1975). Flow recession in the ephemeral stream. PhD diss., Univ. Arizona, Tucson, 96 pp.
34. Peebles R. W., Smith R. E. and Yakowitz S. J. (1981). A leaky reservoir model for ephemeral flow recession. Water Resources Research, 17, 3, pp. 628-636.
35. Plummer, L.N., W.E. Sanford, L.M. Bexfield, S.K. Anderholm, and E. Busenberg, (2004), Using geochemical data and aquifer simulation to characterize recharge and groundwater flow in the Middle Rio Grande Basin, New Mexico, in Groundwater Recharge in a Desert Environment: The South-western United States, edited by J.F.

Hogan, F.M. Phillips, and B.R. Scanlon, Water Science and Applications Series, vol. 9, American Geophysical Union, Washington, D.C., 185-216.

36. Pool, D. R., and A. L. Coes, (1999), Hydrologic investigations of the Sierra Vista sub watershed of the upper San Pedro basin, Cochise Country, southeast Arizona, USGS Water Resources Investigations Report 99-4197.
37. Pool, D. R., and W. Schmidt, (1997), Measurement of ground water storage change and specific yield using the temporal gravity method near Rillito Creek, Tucson, Arizona: U.S. Geological Survey Water-Resources Investigations Report 97-4125, pp. 30.
38. Rao C. X. and Maurer E. P. (1996). A simplified model for predicting daily transmission losses in a stream channel. Water Resources Bulletin, 32, 6, Dec., pp. 1139-1146.
39. Renard, K.G., L.J., Lane, J.R. Simanton, W.E. Emmerich, J.J. Stone, M.A. Weltz, D.C. Goodrich and D.S. Yakowitz, (1993), Agricultural impacts in an arid environment: Walnut Gulch case study, Hydrol. Sci. Tech., 9, pp. 145-190.
40. Scanlon, B.R., R.P. Langford and R.S. Goldsmith, (1999), Relationship between geomorphic setting and unsaturated flow in an arid setting, Water Resources Research, 35, 983-999.
41. Scanlon, B.R., K. Keese, R.C. Reedy, J. Simunek and B.J. Andraski, (2003), Variations in flow and transport in thick desert vadose zones in response to paleoclimatic forcing: field measurements, modelling and uncertainties, Water Resources Research, 39, 1179.
42. Sharma K. D. and Murthy J.S.R. (1994). Estimating transmission losses in an arid region. Journal of Arid Environments, 26, pp. 209-219.
43. Sharma K. D., Murthy J. S. R. and Dhir R. P. (1994). Stream flow routing in the Indian arid zone. Hydrological Processes, 8, pp. 27-43.
44. Sharma K. D. and Murthy J. S. R. (1995). Hydrologic Routing of flow in Arid ephemeral channel, Journal of Hydaulic Engineering, Vol.121, No. 6, pp. 466-471.
45. Sharp A. L. and Saxton K. E. (1962). Transmission losses in natural stream valleys. Journal of the Hydraulics Division, A. S. C. E., 88 (HY5), pp. 121-142.
46. Shentsis I., Meirovich L., Ben-Zvi A. and Rosenthal E. (1999). Assessment of transmission losses and groundwater recharge from runoff events in a wadi under shortage of data on lateral inflow, Negev, Israel. Hydrological Processes, 13, pp. 1649-1663.
47. Smith R. E. (1972). Border irrigation advance and ephemeral flood waves. Journal of the Irrigation and Drainage Division, A. S. C. E, 98, pp. 289-307.
48. Sorman A. U. and Abdulrazzak M. J. (1993). Infiltration-recharge through wadi beds in arid regions. Hydrological Sciences-Journal-des Sciences Hydrologiques, 38, 3, 6, pp. 173-186.
49. Taniguchi, M. and M.L. Sharma, (1996), Solute and heat transport experiments for estimating recharge rates, J. of Hydrology, 119, 57-69.
50. Taylor, R.G. and K.W.F. Howard, (1996), Groundwater recharge in the Victoria Nile basin of east Africa: support for the soil moisture balance approach using stable isotope tracers and flow modelling, Jl. of Hydrology, 180, pp. 31-53.
51. Wallace D. E. and Renard K. G. (1967). Contribution to regional water table from transmission losses of ephemeral streambeds. Transactions of A. S. A. E., 10, pp. 786-789 and 792.
52. Walters M. O. (1990). Transmission losses in arid region. Journal of Hydraulic Engineering, 116, 1, pp. 129-138.
53. Walvoord, M., F.M. Phillips, S.W. Tyler and P.C. Hartsough (2003), Deep arid system hydrodynamics part 2: application to paleohydrologic reconstruction using vadose-zone profiles from the Northern Mojave Desert, Water Resources Research (in press).

Director : Dr. K. D. Sharma

Coordinator : Dr. S. K. Jain

Head : Dr. Vijay Kumar

STUDY GROUP : Dr Vivekanand Singh, Sc ‘C’

Supporting Staff : Mr Shobha Ram, PRA