A Summary of Published Reports of Transmission Losses in Ephemeral Streams in the U.S.

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Executive Summary

In deciding whether a waterbody that is physically far-removed from a traditionally navigable water should fall under the jurisdiction of Section 404 of the Clean Water Act (CWA), consideration should be given to the frequency and duration with which flow reaches it (i.e., whether ordinary flow reaches the navigable water). One factor, which affects whether flow will reach a navigable water, is "transmission loss."

This report reviews the capabilities of several approaches that are adaptable to a variety of hydrologic evaluations including the prediction of transmission losses. In some cases, these approaches combine statistical and hydrologic models. In other cases, estimates have been derived from field observation. These approaches can be grouped into the following categories:

- **Simple regression equations:** use data on inflow and outflow volumes from a number of events (and potentially from a number of stream reaches) as well as descriptive data about each stream reach in a statistical model to estimate transmission losses.
- **Simplified differential equations:** use simplified differential equations to describe changes in storage. Change in storage is typically in terms of flow rates over time.
- **Combined use of differential equations and regression:** 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 observations and experimentation:** consist of experimental studies carried out at specific locations, requiring additional resources and are usually confined to small areas.
- **Streamflow routing:** is used to predict the temporal and spatial variations of a flood as it moves through a river reach or reservoir. By examining changes in the shape and timing of the hydrograph at different points downstream, the effects of storage and flow resistance within a river reach are explored.
- **Hydrologic budget:** builds from a basic equation describing the change in storage in a reach as a combination of factors including inflow, outflow, evaporation, lateral inflow, bank storage, etc. Each of these components are estimated to reveal information about transmission losses.

About three dozen published studies that predict transmission losses in the United States and abroad using one or several of these approaches have been reviewed. This report notes characteristics of the method, analytical assumptions, limitations in model application and results for each study.

In addition, this document discusses the application of common hydraulic models (e.g. HEC-1, HEC-HMS, and HEC-RAS) for estimation of transmission losses. These models have been developed for streamflow prediction and do not have subroutines to directly determine transmission losses. However, they may have value in determining runoff and flood potential as a component of a transmission loss model.

Nine sets of data on transmission losses, for sites in the Midwest and West of the U.S., are reported in this document. The datasets and estimates of transmission losses have been normalized so that they can be more easily compared. Published reports have estimated transmission losses from single events over a range from less than 0.3 to over 1,500 acre-feet/mile (af/mi).

This evaluation concludes that approaches that combines differential equations and regression analyses have the most promise in new applications for estimating transmission losses. This approach considers physical processes related to transmission losses and uses statistical methods to provide reliable parameter estimates in site-specific prediction equations. When a comprehensive set of site-specific data exists, such as details on flows at tandem gauges in the same stream with no tributary flows between gauges, the estimate of transmission loses have a reasonable potential for success. Where sites do not have such datasets, there appears to be a potential to estimate storm losses by coupling water resources models and transmission loss estimation methods. In such cases, estimates of watershed runoff and streamflow may be used as inputs to models of transmission losses.

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1. Introduction

The CWA defines “navigable waters” as “the waters of the United States.” The Army Corps of Engineers (ACOE) routinely decides whether a non tidal, landscape feature is a water of the U.S. by the presence of an Ordinary High Water Mark (OHWM) with generally no consideration of whether ordinary or any other measurable flows actually reach navigable waters. The CWA defines most anthropogenic conveyances as “point sources.” Increasingly, the ACOE and the U.S. Environmental Protection Agency (EPA), however, have been classifying conveyances, themselves as waters of the U.S., again without consideration of whether flows through them ever reach navigable waters. This literature review examines the state of the science for measuring and predicting the loss of water from morphologically-defined channels as it flows downslope towards navigable waters.

A stream or stream segment can be described as a “losing stream” or a “gaining stream” depending on whether it “loses” water into the ground or “gains” water from ground-water discharge as the flow passes downstream (Heath, 1989). This report focuses research and model development for measuring and predicting transmission losses in ephemeral streams.[1] Transmission losses are important not only with respect to their effect on stage flow reduction, but also as they pertain to groundwater recharge of underground alluvial aquifers.

In general, water is lost through three natural mechanisms as it travels down stream: (1) evapotranspiration (ETo) (in streams, most of which lack vegetation, evaporation plays a greater role than transpiration, with the opposite being true in wetlands); (2) surface storage in depressions in the channel and/or floodplain (and later lost as infiltration or ETo); and (3) ground storage of water that infiltrates into the channel, its banks and/or the floodplain. In most ephemeral streams, transmission losses tend to be a result of infiltration. Accordingly, flow reduction vis-à-vis infiltration is commonly termed transmission loss.

Infiltration is the movement of water into soil. The rate at which water can enter the soil at a given set of temperature and soil moisture conditions is known as infiltration capacity. When the infiltration capacity is greater than the rate at which rain falls, all of the rainfall will enter the soil. When the rate of rainfall or stream flow exceeds the infiltration capacity, runoff will occur or, in the case of a stream, the stream will flow. Although water may be flowing over the surface of the land or in a channel, it does not necessarily mean that infiltration has stopped.

Infiltration of water into a soil or the substrate of a stream is driven by gravity, and in the initial phases, by capillary attraction. After a soil or other material is saturated, water movement is driven solely by gravity. Water flow through porous material such as sand can be explained by Darcy’s Law, which states that flow is proportional to the hydraulic conductivity of the fluid and the gradient or slope between the point where flow begins and the point where the water exits the porous material. Darcy’s Law describes water movement in any environment - dryland or humid. Since precipitation is a major force in erosion processes, drylands soils generally tend to be less finely eroded than in more humid climates. This coarseness of texture often leads to very high rates of hydraulic conductivity and accordingly, high rates of transmission losses.

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[1] Approaches for predicting transmission losses in ephemeral streams may be adaptable for estimation in perennial and intermittent streams in most cases. However, this could depend on the significance of additional parameters, especially those related to groundwater effects.

The rate of transmission loss from a river reach is a function of the characteristics of the channel alluvium, channel geometry, wetted perimeter, flow characteristics, and depth to groundwater. In ephemeral streams, factors influencing transmission losses (and by extension, infiltration) include antecedent moisture of the channel alluvium, duration of flow, storage capacity of the channel bed and bank, and the content and nature of sediment in the streamflow. The total effect of each of these factors on the magnitude of the transmission loss depends on the nature of the stream, river, irrigation canal or even rill being studied (Vivarelli and Perera, 2002). Published reports have estimated transmission losses from single events over a range from less than 0.3 to over 1,500 acre-feet/mile (af/mi).

2. Methodology and Document Overview

This report attempted to identify and assess the state-of-the-art and historical development in approaches to predicting transmission losses. Studies that were included in this report are those that are applicable in conditions where site-specific data is available and where there is a manageable number of unknown parameters. Over three dozen papers were reviewed for this report. Some papers directly studied transmission losses resulting from single rain events. Other papers examined transmission losses indirectly as part of a study on groundwater recharge in arid areas. Additional papers were reviewed but are not reported here because they did not provide information directly pertinent to this topic.

Varying methods were employed in these research papers according to the data available and purpose for analysis. The modeling approaches fall generally into these six categories:

A. Simple regression equations
B. Simplified differential equations
C. Combined use of differential equations and regression
D. Field observations and experimentation
E. Streamflow routing
F. Hydrologic budget

An overview of each modeling approach is provided in Section 3 under its respective heading. Individual papers that utilize one of these approaches are reviewed separately under each subsection. For each paper, the review includes a brief description of the data and site, modeling approach and results, analytical assumptions, limitations in model application and estimated transmission losses. Section 4 discusses the applicability of water resources models such as HEC-1 and SWMM for site specific applications. An evaluation of specific applications of these was not undertaken because conditions vary from site to site.

Published data on transmission losses are available from many streams in the Midwest and Western U.S. These data are summarized in Section 5. The tables include transmission loss estimates for flow losses from single events, seasonal periods, and annual averages. These measures of transmission loss differed in part because of the data availability of the site studied. In addition, different methods were applied with the different types of data.

3. Modeling Approaches and Research Papers

A. Simple regression equations

Simple regression equations explore the influence of one or more covariates ("explanatory variables") on a dependent variable. Transmission losses are typically modeled as a dependent variable. Another dependent used in these papers is outflow volume. Covariates include upstream flow volume, channel antecedent condition, channel slope, channel bed material, duration of flow, and active channel width. In some cases, the dependent variable and covariates are log-transformed (that is, the log of the data is used in the analysis) to provide a better fit of the data. Significant relationships have been found between transmission losses and inflow volume (Lane *et al.,* 1971). Others found that log transformed data of upstream flow volume and channel width has a significant relationship (Walters, 1990, Sharma & Murthy, 1994a). In general, regression models are straightforward to implement. The models however lack a direct connection to the specific physical processes governing transmission losses. Predicting transmission losses with regression equations is limited because models are applied to only a series of events from the same location. Accordingly, variability in losses at sites not in the dataset cannot be determined.

Lane, et al. (1971) "Input-output relationships for an ephemeral stream channel system."

Site and Data Information

- Walnut Gulch (AZ)
- Research site was between flumes 11 and 8
- Data included volume of runoff, peak discharge, duration of runoff, time to peak, time to the centroid of the hydrograph

Method Details

- Improved upon Renard & Keppel (1966) and Keppel & Renard (1962)
- Developed a method to predict the outflow hydrograph from the volume of inflow hydrograph using a 3-parameter gamma distribution.
- Inflow hydrographs for a stream reach were used to predict the outflow hydrograph.
- Stepwise linear regression was used to develop a relationship between outflow hydrograph parameters and the parameters of the inflow hydrograph and of the channel.
- This regression approach produced a model with a small set of significant variables.
- Transmission losses could then be predicted for this site based on new data on covariates

Modeling and Data Assumptions

- Rainstorms were selected to exclude cases of tributary inflow

Modeling Results

- Significant relationship was found between transmission losses and the inflow volume.
- Outflow hydrograph could be fairly well represented by a gamma distribution.

Limitations in Model Application

- Method could not be used when hydrographs were double peaked

Estimated Transmission Losses

- Reported 14 rain events between 1963 and 1968.
- Estimates of transmission loss range from 0.3 – 20.0 acre feet/mile

Sharma & Murthy (1994b) "Estimating transmission losses in an arid region – a realistic approach."

Site and Data Information

- Northwest India – arid zones
- 78 hydrographs in 14 channel reaches
- Color-coded landsat data provided information on channel width and wetted area

Method Details

- Developed regression model to assess log-transformed data from all reaches
- Antecedent moisture was calculated with standardized equation based on the days since the last flood

Modeling and Data Assumptions

- Assumed that the 14 different channel reaches were reasonably comparable and could be used in the regression model
- No tributary inflow occurred in channels
- Depth to water table indicated sufficient storage capacity to allow free infiltration of runoff waters into the channel beds
- Only events with flow at both the upstream and downstream gauges were selected for use

Modeling Results

- Results describing the relationship between upstream flow and transmission loss in the first kilometer were consistent with findings from Lane (1971) and Walters (1990)
- Authors suggested that correspondence in findings across sites in India, Saudi Arabia and the U.S. indicated that results could be applied in other sites as well.
- Provided several empirical equations that could be used to predict transmission losses based on the availability of data on characteristics of the channel, flow, etc.
- Provided simplified approach to model application with narrow set of data
- Demonstrated that landsat data can be used for channel characteristics such as length, average width and bed slope

Limitations in Model Application

- Where assumptions were violated, empirical equations (with estimated parameters) could not be used

Estimated Transmission Losses

- Transmission losses in the first kilometer were reported for each of the 14 sites in India
- Losses in the first mile ranged from around 80 to 17,300 acre feet

Walters (1990) "Transmission losses in arid region."

Site and Data Information

- South-western Saudi Arabia
- Data included flow volume, channel antecedent condition, channel slope, channel bed material, duration of flow, and active channel width

Method Details

- Two regression model forms were developed to assess transmission losses; one was normal, the other used log-transformed variables
- Dependent variable was transmission loss in first mile (following Jordan (1977) approach to compute these data)

- Antecedent moisture was computed as a unit-less index based on the days since it has rained to provide a common baseline (on a 0 to 1 scale)

Modeling and Data Assumptions

- Analyses were only valid for range of flows considered

Modeling Results

- Three regression equations were developed to estimate transmission losses
- Best model used only upstream flow as a covariate; other covariates (such as channel width) did not add to explanatory power
- Results for models of both normal and log-transformed data were similar.

Limitations in Model Application

- Only a small dataset was available for analysis – therefore parameter estimates may not be well defined and prediction is limited at different sites

Estimated Transmission Losses

- Transmission losses for the first mile in Saudi Arabia ranged from 1.5 - 150 acre feet

B. Simplified differential equations

Simplified differential equations have been developed to represent transmission losses from single events. Jordan (1977) developed a first order differential equation to describe the losses between gauging stations and transmission losses in the first mile below the upper station were related to the flow at the upper station. Peebles *et al.* (1981) uses differential equations based on the continuity equation (change in storage over time equals the difference between inflow and outflow) and discharge-stage and storage-stage relationships to describe streamflow recession. Simplified differential equations can have limited applicability when used as the sole method for estimating transmission losses.

Jordan (1977) "Streamflow transmission losses in Western Kansas."

Site and Data Information

- Several sites in western Kansas and Nebraska

Method Details

- Developed a first order differential equation to describe the losses.
- Transmission losses in the first mile were computed as a function of flow at the upper and lower station and distance downstream
- Model enabled comparison of transmission losses of different rivers and streams.

Modeling and Data Assumptions

- Ignores lateral and tributary inflows
- At a given point in the stream, the rate of loss between two gauging stations was proportional to the flow at that point
- Channel and valley characteristics were uniform and proportionality was the same between gauging stations.

Modeling Results

- Developed a method to assess loss in the first mile
- Approach allowed for a non-linear decrease of flow and variations in distance between gauging stations
- Estimated transmission losses were lower bounds (because method disregarded lateral and/or tributary inflows)

- Scatter in results was due to factors such as antecedent moisture conditions and differences in alluvial material that were not considered

Limitations in Model Application

- Used transmission losses data for high flow events only; low or medium flows would be affected by factors such as reservoir release after streambank storage volume was filled.
- Transmission losses are only approximate because flow is not linear between gauge stations and distance between stations vary

Estimated Transmission Losses

- Average transmission losses ranged from 4.5 – 1,550 acre feet per mile
- Transmission losses in first mile was proportional to about 2% of upstream flow volume

Peebles, et al. (1981) "A leaky reservoir model for ephemeral flow recession."

Site and Data Information

- Walnut Gulch (AZ)

Method Details

- Leaky reservoir model was developed with continuity equation and dynamic equation to represent streamflow recession (note: "leaky reservoir" describes a modeling approach that assumes a water body looses water as it travels downstream)
- Continuity equation for leaky reservoir was found by integrating model of flow in open channel (with infiltration) over length of the stream
- Infiltration loss was modeled as a function of discharge and time
- Discharge from leaky reservoir was modeled as a differential equation based on continuity equation
- Discharge-stage relationships were combined with continuity equation.
- Peak flow was estimated (as initial storage) to obtain a unique solution using a peak-stage value from an observed recession curve or probability distribution function of peak stage
- Transformed (with log function) flow, storage and reach stage (height) data and applied these data in the continuity equation
- Used point infiltration function (following Smith, 1972)

Modeling and Data Assumptions

- Dynamic equation of flow was simplified by assuming that flow in the reach was uniform during recession
- No lateral inflow occurred
- Shape of the river reach was uniform
- Constant transmission loss rate per unit area in the stream
- High transmission loss was assumed at the onset followed by a decrease to nearly constant rate of loss

Modeling Results

- Calibrated model using two parameters: reservoir leakage rate and initial storage
- Reservoir was considered a reasonable physical representation of the mechanisms operating in the stream during flow recession
- Parameter with largest influence on results was reservoir shape
- Model recession curves did not change with changing loss rate
- Produced fairly simple model to apply with gauged streams

Limitations in Model Application

- Model provided a good fit of the data as it conceptually approximates the physical mechanisms in the stream during recession where wetted area in bottom of channel decreases along length and width of stream
- Parameter for shape of stream bed could not account for large differences along reach length

Estimated Transmission Losses

- At peak discharge (Q_{peak} = 790 cubic feet /second (cfs)) transmission loss was 42 cfs.[2]

C. Combined use of differential equations and regression

Methods that combine differential equations and regression analysis consider physical processes related to transmission losses and use regression or optimization methods to develop site-specific equations. This approach has advantages over simplified differential equations because regression provides estimates of parameters in the differential equations. Authors who applied these approaches have tended to build on the work of Lane et al. (1980) who developed a simplified procedure to estimate the volume of outflow (and from that, transmission losses) given a volume of inflow at a point upstream. The fundamental differential equations build from Jordan (1977) who related inflow volume and the transmission losses over a length of stream. The method produces an estimate for flow volume at any point downstream. Regression is used to estimate parameters from streamflow data in the differential equations. Rao and Maurer (1996) depart somewhat from this model by coupling an infiltration function with a stage-discharge relationship. They then integrate this relationship over the entire reach produced a one-parameter seepage loss model that can be more easily calibrated using stream gauge data. This approach lumps all types of losses into a single term but retains a non-linear relationship between infiltration and flow.

Lane (1982) "Distributed model for small semiarid watersheds"; Lane (1983) "Chpt. 19: Transmission losses"; Lane (1985) "Estimating transmission losses"; Lane (1990) "Transmission losses, flood peaks, and groundwater recharge"; Lane, et al. (1980) "Estimating transmission losses in ephemeral stream channels"

Site and Data Information

- Walnut Gulch (AZ)

Method Details

- Extending Jordan (1977), Lane et al. (1980) developed estimated transmission losses in channels of arbitrary length and width
- Method provides estimate of transmission losses at any distance downstream from a point with known inflow volume
- Estimates parameters in the differential equations using linear regression and stream data
- Differential equations were further developed by Lane (1983) and were included in the channel component of a distributed model
- Lane (1982) added a basin scale simulation model
- Lane (1985) described the distributed model in an application of flood frequency analysis

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[2] Note that in this case, cfs cannot be converted to acre-feet/mile because information is not provided on the duration of flow over a particular distance.

Modeling and Data Assumptions

- Volume of outflow is proportional to the volume of inflow
- Rate of lateral inflow is constant per unit length of channel
- Volume of losses in the reach is proportional to the volume of upstream inflow with a constant or steady-state loss rate
- Transmission loss rates are proportional to the surface area of the riverbed and bank wetted by the flood wave

Modeling Results

- Model has been tested using hydrologic data from AZ, KS, NE, and TX representing over 260 individual rainfall-runoff events
- Results reproduced trends in runoff rates and amounts
- Model demonstrated a practical application using a minimum number of observed data for calibration
- Model could be used to predict flood frequency distributions by using data from a rainfall frequency atlas

Limitations in Model Application

- Analysis was limited to streamflow in ephemeral stream channels with infiltrating losses.
- Method did not account for sediment concentration in streamflow, temperature effects, seasonal trends and differences between outflow and inflow duration

Estimated Transmission Losses

- Estimated transmission losses were reported in 1980, 1982, 1983 papers.
- Transmission losses were estimated for streams in AZ, TX, KA, NB (these data include those that were originally cited by other authors who are also cited in this report)
- Transmission losses for Walnut Gulch site (AZ) range from 1.9 to 5.9 acre-feet / mile

Rao & Maurer (1996) "A simplified model for predicting daily transmission losses in a stream channel."

Site and Data Information

- Santa Ynez River (CA)

Method Details

- Standard autocorrelation methods were used to assess travel time for the stream reach and to see whether high and low flows should be assessed separately
- Developed a seepage function for a stream reach based on calibration using only stream flow data
- Applied mass balance equation and log-transformation to data on flow and depth of flow
- Regression of stage data yielded a rating curve between flow and depth of flow
- A parameter (associated with hydraulic conductivity) was estimated by calibration
- Inflow and outflow were related by two terms – simplifying calibration
- Individual losses (eg. deep percolation, use by phreatophytes, evaporation) were lumped into a single loss term
- Retained the simulation of the non-linear relationship of seepage to flow
- Method yielded a combined differential equation which, when integrated over the entire reach produced a one-parameter seepage loss model that was calibrated using flow data

Modeling and Data Assumptions

- No tributary inflows

- River state was controlled by upstream dam releases

Modeling Results

- Estimated different relationships between inflow and outflow for rising and falling parts of the hydrograph
- Outflow from falling flow was less than outflow from rising flow
- Difference between outflow estimates was larger for small flows
- Method of combining several parameters into a single one did not appear to effect predictability

Limitations in Model Application

- All lateral inflows, ungauged tributary inflows and water diversions must be accounted for in the inflow or the outflow term
- Model could only be applied to losing streams
- Model is best used where base flow is more dominant than sudden events
- Results depended on assumption of constant (K) over the reach; where K= [geometry · conductivity · length]
- Applied to regulated rivers free of storage and flowing under gravity that convey large amounts of water

Estimated Transmission Losses

- Sample transmission losses (falling hydrograph) were approximately 3cfs at an upstream flow of 10cfs and 10 cfs for upstream flow of 100cfs[3]
- Sample transmission losses (rising hydrograph) were approximately 10cfs at an upstream flow of 20cfs and 20 cfs for upstream flow of 100cfs
- Transmission losses for storm flows > 1000 cfs appear to be less than 4% of inflow

Sharma & Murthy (1994a) "Estimating transmission losses in an arid region."

Site and Data Information

- Arid zones in Northwest India
- 78 hydrographs in 14 channel reaches
- Color-coded landsat data provided information on channel width and wetted area

Method Details

- Developed a simplified regression model to estimate transmission loss from ungauged channels in arid areas
- Simplified model required a minimum of observed data

Modeling and Data Assumptions

- No tributary inflow
- Depth to water table indicated sufficient storage capacity to allow free infiltration of runoff waters into the channel beds
- Only events with flow at both the upstream and downstream gauges were selected for use

Modeling Results

- Transmission loss was proportional to the intercept parameter from the regression equation

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[3] Note that flows in cfs cannot be converted to acre-feet/mile because information is not provided on the duration of flow over a particular distance.

Limitations in Model Application

- Similar to Lane (1980) and others

Estimated Transmission Losses

- Mean inflow minus mean outflow reveals transmission loss estimates between 71 and 8,478 acre-feet / mile

D. Field observations and experimentation

Experimental studies are often carried out at specific locations, requiring special equipment and techniques, and are usually confined to small areas. They tend to have limited applicability to other areas. Their value is in identifying sources of loss that may need more careful modeling depending on the site. In the case of rills, Parsons, *et al.* (1999) found that they should be modeled separately from inter-rill areas. Other studies included in this group did not develop models, per se, but simply subtracted outflow volume from inflow volume to estimate losses.

Babcock & Cushing (1941) "Recharge to groundwater from Floods in a Typical Desert Wash, Pinal County Arizona."

Site and Data Information

- Queen Creek (AZ), a large desert wash
- Two stream gauges about 20 miles apart provided data below Black Point

Method Details

- Research was intended to determine the effect of reservoir controls on normal groundwater recharge

Modeling and Data Assumptions

- Differences in the characteristics of alluvium were noted

Modeling Results

- Reported readings from stream gauges
- Calculated transmission losses as inflow minus outflow volumes
- Assessed rates of infiltration and evapotranspiration

Limitations in Model Application

- Simple calculation was conducted

Estimated Transmission Losses

- Reported transmission losses from 19 rainfall events
- Transmission losses range from 0.7 to 314 acre-feet / mile.

Buono and Lang (1980) "Aquifer Recharge from the 1969 and 1978 Floods in the Mojave River Basin, CA."

Site and Data Information

- Mojave River (CA)
- 5 nearby well gauge stations

Method Details

- Appraised streamflow records and compared with water levels in wells
- Estimated recharge to groundwater basin and compared estimates of recharge resulting from the floods

Modeling and Data Assumptions

- Transmission losses from flow events were a primary source of recharge

Modeling Results

- Factors causing greater recharge included (1) more evenly distributed precipitation translated into more uniform surface runoff, (2) dams regulated flood flow peak and allowed more water to stay in the basin, (3) lower water in the aquifer translated into more space available to store recharge

Limitations in Model Application

- Provided an indirect estimate of transmission losses

Estimated Transmission Losses

- Reported transmission losses from a five month period range from 1,443 to 7,656 acre-feet / mile

Dunkerley & Brown (1999) "Flow behavior, suspended sediment transport and transmission losses in a small (sub-bank-full) flow event in an Australian desert stream."

Site and Data Information

- Western NSW, Australia

Method Details

- Examined results from a single small (sub-bank-full) real flow event

Modeling and Data Assumptions

- Flow volumes could be calculated by measuring (on the day after the flow) the lateral extent of debris and dampness from the thalweg

Modeling Results

- Transmission losses from large events were governed by water infiltration into the wetted perimeter and settling of fine sediment in bed and bank
- Losses were smallest during bank-full-flow because a greater amount of water passes through flat terrain yet is not enough to overtop the bank and become lost in floodplain.
- Implication of relatively lower loss from bank-full flow is that this stage has a greater capacity to transform channel downstream

Limitations in Model Application

- Application of results depends on site-specific data collection and difficulty in measuring variations in bankfull flow over large areas

Estimated Transmission Losses

- Sub-bankfull flow (peak discharge = 318 cfs) had an average transmission loss of about 21% per mile
- Transmission losses for bank-full and shallow overbank flow was estimated to be about half of this rate of loss

Keppel & Renard (1962) "Transmission losses in Ephemeral Stream Beds.", Renard & Keppel (1966) "Hydrographs of Ephemeral Streams in the Southwest.", Renard (1970) "The hydrology of semiarid rangeland watersheds.", Keppel (1960) "Transmission losses on Walnut Gulch Watershed."

Site and Data Information

- Two reaches in Walnut Gulch (AZ),
- Almogordo (NM)

Method Details

- Hydrograph at upstream and downstream gauging stations were compared and transmission loss were determined per length of channel and per time durations

Modeling and Data Assumptions

- Storms that occurred on upper end of watershed did not have tributary inflow or lateral inflow
- Although abrupt translatory waves[4] of considerable height were measured, the more common case was that of waves a few inches in height
- Most measuring stations in Walnut Gulch were dry more than 99% of the time, with only 5 to 15 runoff events each year

Modeling Results

- Runoff volume and Q_{peak} were proportional
- Hydrograph rise time was inversely proportional to watershed area, transmission loss (most of which probably occurs during the rising hydrograph)
- Magnitude of transmission loss was related to: (1) flow duration, (2) channel length and width, (3) antecedent conditions, (4) Q_{peak}, (5) flow sequences, (6) volume and characteristics of alluvium, (7) amount of clay in suspension in the runoff ephemeral streams
- Transmission losses were smaller in Alamogordo because the site has a greater amount of fine-textured channel alluvium
- Water yield in semi-arid areas was greatly affected by soil deposition in the channels
- Large volume of course textured, high porosity alluvium in the channel significantly reduced the volume of the runoff
- There is a tendency for the transmission losses to flatten out somewhat at discharges starting at 1000 / 1500 cfs and then level off

Limitations in Model Application

- A simple direct method to measure transmission loss by gauging stations and hydrographs
- Limited to storms that occur at upstream gauge stations

Estimated Transmission Losses

- A maximum value of transmission loss was measured as 25 acre-feet/mile; estimated maximum transmission losses were 30 acre-feet/mile
- The loss rate appears constant at 4.3 acre-feet/mile per hour (these units can be obtained from hydrographs)

Parsons, *et al.* (1999) "Transmission losses in rills on dryland hillslopes."

Site and Data Information

- Jornada Ecological Experiment Station (NM); Walnut Gulch (AZ)

Method Details

- Site experiment with rain simulators and water sampling stations along prepared rills in the semi-arid areas

Modeling and Data Assumptions

- Few assumptions were made because the study was primarily based on experimentation

Modeling Results

- Found variation in transmission loss from rills and inter-rill areas

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[4] Translatory waves are a series of shallow waves characterized by later waves overriding earlier ones as flow progresses downstream.

- Found exponential relationship between loss and distance as well as in differences between soil type

Limitations in Model Application

- Field experiments are generally limited to site specific context
- May be difficult to model rill areas separately without site data

Estimated Transmission Losses

- Transmission losses were estimated on a very small scale – over a distance of 6 meters – and accordingly, the units of measurement are not converted to acre-feet / mile
- Gravel bed rills: transmission losses are 9.7- 32.0% in 6 meters; transmission losses do not increase with distance.
- Sand bed rills: transmission losses are 22.5 – 50.7% in 6 meters; transmission losses increase exponentially with distance

Maurer (2002) "Ground-Water Flow and Numerical Simulation of Recharge from Streamflow Infiltration near Pine Nut Creek, Douglas County, Nevada."

Site and Data Information

- Pine Nut Creek (NV)

Method Details

- Study aimed to estimate reasonable limits for the approximate volume of water that may be stored by recharge through infiltration basins and the rate at which recharged water would dissipate or move towards the valley floor
- Indirect measurements of flow were developed using the slope conveyance method (a standard method that relates physical stream properties and evidence of flow to actual flow).
- Water marks indicating flow stage levels included algae deposits on culverts and cobbles in the stream channel

Modeling and Data Assumptions

- Used water marks from flow in 1999

Modeling Results

- Methods for estimating transmission loss were appropriate when data is unavailable

Limitations in Model Application

- Study was not intended to provide accurate transmission loss estimates

Estimated Transmission Losses

- Transmission losses were not estimated in this study.
- Indirect estimates of stream losses were casually reported as 1-2 cfs in the first 2.8 miles and 1 cfs in the next 2.2 miles.

Sharp & Saxton (1962) "Transmission Losses in Natural Stream Valleys."

Site and Data Information

- Many sites in Midwestern States (U.S.)

Method Details

- Computed transmission losses on a watershed scale for hydrographs at tandem–gauge stations which had runoff-producing storms above upper stream gauge with little to no runoff between gauges
- Method involved subtracting outflow from inflow
- Applied approach to a large number of watersheds in 6 different states

Modeling and Data Assumptions

- Storms occurred above the upstream gauge and little or no lateral flow occurred between tandem gauges

Modeling Results

- Provided a description of factors affecting seepage, and therefore transmission losses, in natural streams.
- Averaged 40% in transmission loss of flood flows
- Approximately 75% of flood volume loss

Limitations in Model Application

- Analytical results would be limited to the sites

Estimated Transmission Losses

- Transmission losses were over 200 acre-feet / mile

Wallace & Renard (1967) "Contribution to regional water table from transmission losses of ephemeral streambeds."

Site and Data Information

- Walnut Gulch (AZ) (Flume 2-1)
- Single storm (8/10/63)

Method Details

- Observation wells measured the effect of transmission losses on recharge to underlying aquifers
- Explored the effect of soil profile on recharge rates
- Demonstrated an approach to estimating transmission losses that contribute to groundwater table.

Modeling and Data Assumptions

- Used known relationships between infiltration in the channel for various antecedent moisture conditions and peak discharge at the watershed outlet

Modeling Results

- Transmission losses from flow events were a primary source of recharge

Limitations in Model Application

- Limited analysis and modeling

Estimated Transmission Losses

- 16.5 acre-feet / mile

E. Streamflow routing

Streamflow Routing is a process used to predict the temporal and spatial variations of a flood as it moves through a river reach or reservoir. By examining changes in the shape and timing of the hydrograph at different points downstream, the effects of storage and flow resistance within a river reach are explored. Routing techniques include hydrologic and hydraulic methods. Hydraulic routing techniques solve the partial differential equations describing unsteady open channel flow. In most cases, these equations used are referred to as the St. Venant equations which combine (a) the momentum equation (characterizing the forces acting on the stream) and (b) continuity equations (reflecting the change in storage as the difference between inflow and outflow). By contrast, hydrologic routing employs the continuity equation and an analytical or an empirical relationship between storage within the reach and discharge at the outlet.

Hydraulic routing techniques are based on the solution of the partial differential equations of unsteady open channel flow to reveal a wave-level assessment of hydrograph routing. Hydraulic routing models are useful when downstream controls (e.g. dams or weirs) effect the routing process through an upstream reach because they can incorporate backwater effects as well as internal boundary conditions. El-Hames and Richards (1998) develop a physically-based model that is calibrated in the field with measurements of soil hydrologic properties.

In typical applications of the hydrologic routing approach, the upstream hydrograph is routed through a river reach that predicts changes in the hydrograph shape and timing. Lateral flows are added at the downstream location to obtain the total flow hydrograph. This type of approach is adequate as long as there are no significant backwater effects that raise water levels behind an obstruction in the channel. Knighton & Nanson (1994) develop a three-parameter Muskingham Routing model to estimate outflow hydrographs on a stream with a complex network of channels.

El-Hames & Richards (1998) "An integrated, physically based model for arid region flash flood prediction capable of simulating dynamic transmission loss."

Site and Data Information

- Arid regions in south-western Saudi Arabia

Method Details

- Developed a method that can handle sudden kinematic shocks that describe the rapid time to peak of storms in arid areas
- St Venant equations for channel routing and coupled this with Richards' equation to account for infiltration losses into channel beds
- Model was calibrated using existing information on flood wave propagation and transmission losses
- Analysis does not estimate transmission losses, rather it fits a model to existing transmission losses and indicates how subsequent analyses can be conducted

Modeling and Data Assumptions

- No lateral inflow occurs

Modeling Results

- Simulated the dynamic transmission loss as the hydrograph passed downstream.
- Produced reasonable transmission loss simulation with little calibration.

Limitations in Model Application

- Model could be used for catchment-scale analyses

Estimated Transmission Losses

- Did not estimate transmission losses

Knighton & Nanson (1994) "Flow transmission along an arid zone anastomosing river, Cooper Creek, Australia."

Site and Data Information

- Copper Creek, Australia
- River was an anastomosing river (intersecting network of channels) that contained lesser channels, as well as a primary channel
- Length of reach was 32km (20 miles)

Method Details

- Developed three parameter Muskingham procedure (a method that uses a simplified continuity equation with data from streams that have stage information at multiple downstream points) to estimate outflow hydrographs (and therefore transmission losses)
- Demonstrated statistical tools to assess variability in monthly values, flood magnitudes and how this increases downstream in an anastomosing river
- Estimated threshold flow values for the river lengths studied

Modeling and Data Assumptions

- Method required that hydrographs be comparable and that inflow conditions are known

Modeling Results

- Found that estimated parameters behaved well, including the parameter for lateral inflow.
- When flow was within the primary channel, transmission losses were less
- Found that clay sealing prevented transmission loss over significant lengths of the river
- Evaporation and drainage diffusion (which the authors describe as flow that spreads out across the floodplain) were major reasons for transmission losses

Limitations in Model Application

- Application would be limited to datasets that have sufficient inflow volume

Estimated Transmission Losses

- Losses varied non-linearly with stage and could be more than 75% of the initial flow rate

F. <u>Hydrologic budget</u>

Hydrologic budget approach builds from a basic equation describing the change in storage in a reach as a combination of factors including inflow, outflow, evaporation, lateral inflow, bank storage, etc. Each of these components are estimated. The time scale of the analyses may be event-based, monthly or annual averages. In their crudest form, these models assume that inflow and outflow are the only components that need to be estimated; other losses (or gains) are negligible (Burkham, 1970). Estimates of transmission losses made in this way often appear reasonable given that they have been found to fall within the range of values estimates by other methods (Goodrich et al., 2004). Variations on this model explore the influence of variables such as stage height and duration, maximum flood width and duration, and groundwater recharge (Abdulrazzak and Sorman, 1994). In many cases, the primary purpose of these studies is to estimate groundwater recharge; transmission losses are estimated in the process (Goodrich et al., 2004).

Abdulrazzak (1994) "Losses of floodwater from alluvial channels"

Site and Data Information

- Southwestern Saudi Arabia

Method Details

- 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
- 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 used to relate transmission losses to the controlling parameters such as upstream inflow, channel flow width and antecedent soil conditions

Modeling and Data Assumptions

- Data from catchments with similar hydrological and morphological characteristics were combined in the analysis

Modeling Results

- Regression equations indirectly estimated transmission losses

Limitations in Model Application

- Verification of parameter estimates would require more data

Estimated Transmission Losses

- Between 49 - 965 acre-feet per event

Abdulrazzak and Sorman (1994) "Transmission losses from ephemeral stream in arid region."

Site and Data Information

- South-western Saudi Arabia

Method Details

- Relationships between transmission losses and specific influencing parameters were investigated using linear and multi-linear regression techniques.
- Separate regressions were conducted to express transmission loss as a function of (a) (stage height · duration), (b) (maximum flood width · duration), and (c) groundwater recharge.
- Derived regression equations were based on estimates of transmission loss magnitude using the mass water balance approach – this accounts for tributary-runoff contributions and evaporation losses

Modeling and Data Assumptions

- Runoff contributions from tributary basins and evaporation loss were included

Modeling Results

- Results underscored the importance of tributary inflow in these estimations and suggest that ignoring tributary inflow results in lower bound estimation of transmission losses.
- Statistical relationships were not strong
- Initial moisture conditions, the type of bed material, its thickness, and width may have had a bearing on the magnitude of transmission losses.

Limitations in Model Application

- Statistical relationships were not strong and so results were not suitable for prediction

Estimated Transmission Losses

- Transmission losses from 27 rain events were estimated for period (1985 – 1987)
- Transmission losses range from 3.3 – 64.9 acre-feet / mile

Burkham (1970) "Depletion of Streamflow by Infiltration in the Main Channels of the Tucson Basin, SE Arizona."

Site and Data Information

- Santa Cruz River, Tanque Verde Creek, Agua Caliente Wash, Sabino and Runcon Creeks, Pantano Wash, Rillito Creek, Big Wash, and Canada del Oro in the Tucson Basin (AZ)
- Available data for period 1936-63

Method Details

- Research focus was to compute approximate average annual volume of infiltration from unregulated surface flow in ephemeral channels
- Model of infiltration rates (and by extension, transmission losses) involved these steps: (a) Compute average relation between inflow rate and infiltration rate for each source of inflow on the basis of streamflow data; (b) Develop flow-duration curve for streamflow from each flow source; (c) Apply infiltration rates obtained from inflow- to infiltrations-rate relations to the appropriate flow-duration curve to derive infiltration-duration curves; (d) Determine average annual volume of infiltration from the infiltration-duration curve; and (e) Use a budget of water volumes to check analyses.

Modeling and Data Assumptions

- Difference between the precipitation on and the evaporation from the flowing water is negligible, therefore flow is nearly equal to volume of depletion of stream

Modeling Results

- Computed infiltration rates for several channels in cubic feet per second as the difference between surface inflow and outflow
- Empirical equation for average inflow and infiltration rates were obtained
- Annual variation of infiltration mainly resulted from variation in inflow

Limitations in Model Application

- Developed a simple relationship between infiltration and inflow

Estimated Transmission Losses

- Transmission losses were 30-90% of inflow
- Annual inflow to all reaches ~ 66,000 acre feet of which 47,000 (70%) is infiltrated

Gu & Deutschman (2001) "Hydrologic assessment of water losses in river."

Site and Data Information

- Sheyenne River, North Dakota

Method Details

- Adapted work from Rao and Maurer (1996)
- Related seepage from channel by a one parameter relationship
- Autocorrelation was used to estimate the flood wave travel times for the steam reach.
- Flow at the upstream station was compared to the lagged flow at the downstream station.
- Hydrologic budget method was used to estimate transmission losses
- Developed a 1 parameter model to account for lag time between gauging stream stations
- Model is appropriate where data limitations exist for daily rainfall maps and complex stream geometries and flows

Modeling and Data Assumptions

- Evapotranspiration is assumed to be proportional to precipitation and captured by a single parameter

Modeling Results

- Information on long term annual average, temporal and spatial distribution of annual losses, and long-term monthly mean was obtained
- Method appears to also be suitable for short-term events

Limitations in Model Application

- Method is limited to short events (days), losing stream channels, and short reaches without tributaries, water diversions and significant surface runoff

Estimated Transmission Losses

- Maximum annual transmission loss is 248 cfs (1977 storm event)
- Range of losses is from 64 – 277 cfs

Osterkamp, et al. (1994) "Recharge estimates using a geomorphic/distributed-parameter simulation approach, Amargosa river basin."

Site and Data Information

- Amargosa River Basin, (CA)

Method Details

- Estimates were based on a water-balance approach combining field techniques for determining streamflow with distribution-parameter simulation model to calculate transmission loss and upland recharge resulting from high-magnitude, low-frequency precipitation events.
- Builds on work by Lane (1980) and subsequent analyses by introducing channel morphology techniques and data
- Channel network, including tributary inflows, were represented by a variable number of channel reaches (each with an upstream inflow volume) and lateral inflow.
- Inflow from network was computed individually and then summed (as in Lane, 1985)
- Used runoff-simulation model modified for transmission losses
- Water-balance approach yielded annual average data that were used to assess annual flows

Modeling and Data Assumptions

- Requires input of contributing areas of runoff for upland and lateral areas, channel dimensions, hydraulic conductivity of channel alluvium, mean annual precipitation, and magnitudes of storm events and runoff properties for each of the watershed elements
- Runoff and precipitation characteristics for watersheds are uniform over elements
- Streamflow by overland flow and all flow in channel results in transmission loss
- No outflow until threshold volume exceeds inflow volume;
- Channel property uniform with length
- Volume and storage capacity of unsaturated alluvium is large relative to the volume and infiltration rate of recharge water

Modeling Results

- Average annual volume of runoff, evaporation, channel loss, upland (inter-channel) recharge, and total recharge were estimated for watersheds of 53 channels
- ~ 90% of estimated recharge occurs by transmission loss of streamflow
- Annually ~ 1.6% of precipitation becomes recharge

Limitations in Model Application

- Water-balance approach cannot account for transmission losses from high magnitude and low frequency precipitation events

Estimated Transmission Losses

- 20.5 million m^3 (16,619 acre-feet) annually recharges to the groundwater reservoir over a 4.9 million acre watershed (including 53 channels)

Osterkamp, et al. (1995) "Techniques of ground-water recharge estimates in arid/semi-arid areas, with examples from Abu Dhabi."

Site and Data Information

- Oman and Abu Dhabi, United Arab Emirates

Method Details

- Extended work of Lane (1982) to water-balance analyses
- Developed power relations between width and discharge characteristics to estimate streamflow at ungauged streams (using Hedman and Osterkamp, 1982)
- Described an approach for examining flows on a basin scale
- Demonstrated a useful method when data was limited

Modeling and Data Assumptions

- Flow volume (on an index event) was used as a surrogate for mean discharge
- This was presumed to result in transmission losses and recharge equal to the sum of flow losses that typically occur in a year

Modeling Results

- Estimated groundwater recharge for ungauged basins in arid/semi-arid areas
- Relationship between discharge and drainage-basin area are computed and fit by curves for several size storms

Limitations in Model Application

- Scale of analysis is potentially too large to yield reliable results for individual storms

Estimated Transmission Losses

- 17 basins (from mountain slopes to piedmont) were analyzed
- Annual transmission losses ranged from 0.2 – 8.1 million m^3 (162 – 6,566 acre-feet) in the piedmont area
- Transmission losses for individual events were estimated

Shentsis, et al. (1999) "Assessment of transmission losses and groundwater recharge from runoff events in a wadi under shortage of data on lateral inflow, Negev, Israel."

Site and Data Information

- Negev, Israel; 1400 sqkm watershed with mean annual precip of 70 mm

Method Details

- Lateral inflow is estimated by subdividing watershed by types of soil and infiltration capability
- Subdivided transmission losses into various components: channel moistening, which subsequently evaporates, and groundwater recharge.

Modeling and Data Assumptions

- Hydrological and meteorological records were incomplete
- Runoff is related to surface lithology,
- Spatial distribution of runoff reflects that of rainfall
- Transmission losses are related to inflow

Modeling Results

- Evaporation is substantially smaller than the transmission losses (approximately 1-2% of the transmission losses)
- Develops a loss function that relates total inflow (estimated inflow and lateral flow) to transmission losses

Limitations in Model Application

- Model would require additional information about geology, soil and lithology

Estimated Transmission Losses

- Predicted relationship through loss functions

Stonestrom, et al. (2002) "Estimates of Deep Percolation beneath Native Vegetation, Irrigated Fields, and the Amargosa-River Channel, Amargosa Desert, Nye County, Nevada."

Site and Data Information

- Amargosa River (CA)
- Flows extended from the headwaters past Amargosa Farms into Death Valley.
- Peak flows were measured between Beatty and Bid Dune (a 21.8 mile stretch of river)

Method Details

- Study was intended to evaluate the amount of water that infiltrates deeply into the long-term storage aquifer

Modeling and Data Assumptions

- Transmission losses were crudely estimated as basic inflow – outflow and assumed a uniform loss rate

Modeling Results

- Transmission losses are not modeled per se

Limitations in Model Application

- Simple estimate was obtained
- Study was not intended to provide accurate transmission loss estimates

Estimated Transmission Losses

- 70 cfs in 21.8 miles; 3.2 cfs per mile

4. Water Resources Models

In the past two decades, governmental agencies have introduced a number of water resource computer programs. These programs have been widely used in engineering practice to determine drainage patterns, flood potential of natural and man-made streams, and a wide variety of watershed and water resource problems for rural and urban sites. The Hydrologic Engineering Center (HEC), Army Corps of Engineers, have developed several programs for simulating flood potential of streams.

Among the most popular programs are HEC-1, HEC-HMS, HEC-2, and HEC-RAS. HEC-1 (Flood Hydrograph Package) and HEC-HMS (Hydrologic Modeling System), which is basically the Windows version of HEC-1, offer many different hydrologic options for each of the main hydrologic processes: precipitation, infiltration/interception, precipitation-excess transformation to streamflow, river-routing, and reservoir routing.

HEC-RAS (River Analysis System) is intended for calculating water surface profiles for gradually varied flow in natural and man-made streams. This water surface engineering software package will replace the HEC-2 backwater program and the HEC-6 erosion and sediment program. The HEC-RAS computer model has a large number of options, such as mixed flow regime analysis, that allow the investigation of both sub- and super-critical flow regimes in a single computer run.

The value of HEC-1 and HEC-2 models is in their ability to compute streamflow characteristics as well as routing potential. For example, there is a subroutine in HEC-1 that allows the user to route flows through a stream with different soil characteristics. The modeler can divide streams into a number of transverse sections with different roughness coefficients. The HEC-2 model can also be used in a similar manner and will also give elevations and flows at pre-determined cross-sections. Another possible value of HEC-1 is to model the flow as it moves out of the main or collector channel. This is important because it has the potential to determine the time a wave moves between upstream and downstream gauging stations as the flow extends its natural banks.

Both HEC-1 and HEC-2 can be used to determine the flooding potential of a stream. The runoff from a watershed may be computed using HEC-1. Flow characteristics in a stream can be determined by HEC-2 where water surface depths and velocities are calculated. Transmission losses in a stream however cannot be determined by these models because there is no way to differentiate between infiltration rates in the watershed and stream. Although these programs do not have subroutines to directly determine transmission losses, they may have value in determining runoff and flood potential as a component of an existing transmission loss model.

Other water resources programs, many of which have been developed by governmental agencies (e.g. Federal Emergency Management Agency (FEMA), U.S. Department of Commerce (DOC), EPA), have useful components for the determination of streamflow (U.S. ACOE, 2004). These models have functions that are similar to HEC-1 and HEC-2 such as stream routing, and determining the hydrograph and water elevations.

One other popular model is the Stormwater Management Model (SWMM), which was developed by EPA in 1972 and has since been improved. The latest version includes a new stormwater storage and treatment package, a sediment scour and deposit routine, and a revised infiltration simulation (U.S. EPA, 1981). Another model, KINEROS2, is a physically-based runoff and erosion model that describes the processes of interception, infiltration, runoff generation, erosion and sediment transport for individual rainfall-runoff events (Smith et al., 1995). This model has been used in arid regions of the U.S. to account for lateral inflows in the estimation of transmission losses from a primary channel (Goodrich et al. 2004).

Application of these models requires a range of characteristics about the site (e.g. soil, watershed, and channel) as well as streamflow. In some cases, ordinary high water marks (OHWM) can be used to calibrate these water resource models to determine parameters such as Manning's roughness coefficient of the channel. Unfortunately, field data with these OHWM and gauge data are generally necessary. These combined sets of data rarely exist particularly for ephemeral streams where a clearly defined channel and overbank are difficult to find.

5. Data on Transmission Losses

Data on transmission losses are presented in several tables below. Data comes from sites located in the plains states and western USA (Arizona, California, Kansas, Nebraska, Texas, Oklahoma, North Dakota, and South Dakota). These sites represent a wide range of watershed areas and channel lengths from less than 10 to greater than 25,000 mi^2 and less than 1 to greater than 100 mi, respectively.

Transmission loss rates from single events cover a range from less than 0.3 to over 1,500 acre-feet/mile (af/mi). As previously discussed, methods for determining these losses varied among subtracting consecutive stream gauges, water-balance, inflow estimates and infiltration rating curves. In addition, data for these sets include single storm events, monthly records and annual records. A summary of data for several papers is provided in Table 1. More detailed information from published sources on specific storm events is reproduced in Table 2. Transmission losses that have been averaged over a longer period are shown in Table 3.

Table 1: Data on Transmission Losses (Low and high data are represented in the tables)

Location / Reference	Reference	Analytical Method	Watershed Drainage Area (mi^2)	Reach Length (mi)	Transmission Loss Volume (af)	Transmission Loss Rate (af/mi)
Walnut Gulch (AZ)	Lane (1971)	Direct measure from gauges	3.18	4.1	1.2 – 81.9	0.3 – 20.0
Queen Creek (AZ)	Babcock & Cushing (1941)	Direct measure from gauges	na	20	13.4 – 6,280	0.7 – 314
Amargosa River (CA)	Osterkamp et al. (1994)	Water Balance (Annual Data)	8.5 – 1,540	1.44 – 59.4	8.1 – 4,165	3.24 – 145
Tucson Basin (AZ)	Burkham (1970)	Inflow – Outflow Rates (Annual Data)	6.2 – 1,662	0.8 – 28.5	10 – 5,360	12.5 – 188
Several Streams in Midwest U.S.	Jordan (1977)	Direct measure from gauges	619 – 25,763	14 – 71	82 – 82,000	4.5 – 1,550
Several Streams in Midwest U.S.	Sharp & Saxton (1962)	Direct measure from gauges	122 – 13,334	24 – 157	176 – 13,711	5.6 – 203.4
Mojave River (CA)	Buono and Lang (1980)	Inflow – Outflow (Monthly Data)	74.6 – 2,120	18.2 – 88.2	45,411 – 282,329	1,443 – 7,656

Data contained in Table 2 comes from streams that can have very different characteristics of flows (e.g. frequency of flow, channel width, and volume of flow). Accordingly, transmission losses in these streams are not strictly comparable. However, to illustrate the range of transmission losses in the Midwest and Western U.S., Figure 1 displays data on the transmission losses from single events as a percentage of upstream flow (Column 10 in Table 2). This chart, a histogram, indicates the number of storm events that produced different levels of transmission losses as a percentage of upstream flow. For example, Figure 1 indicates that in 30 storm events, transmission loss that was between 21-30% of the upstream flow. The chart shows that these relative transmission losses are reasonably well-distributed around 41-50% loss. The computed average (and median) loss over all storm events is 44% (and 42%). Note that these statistics and the chart do not reflect the distribution of events from any one stream or region. In addition, the dataset includes a larger number of storms from some streams which biases the results.

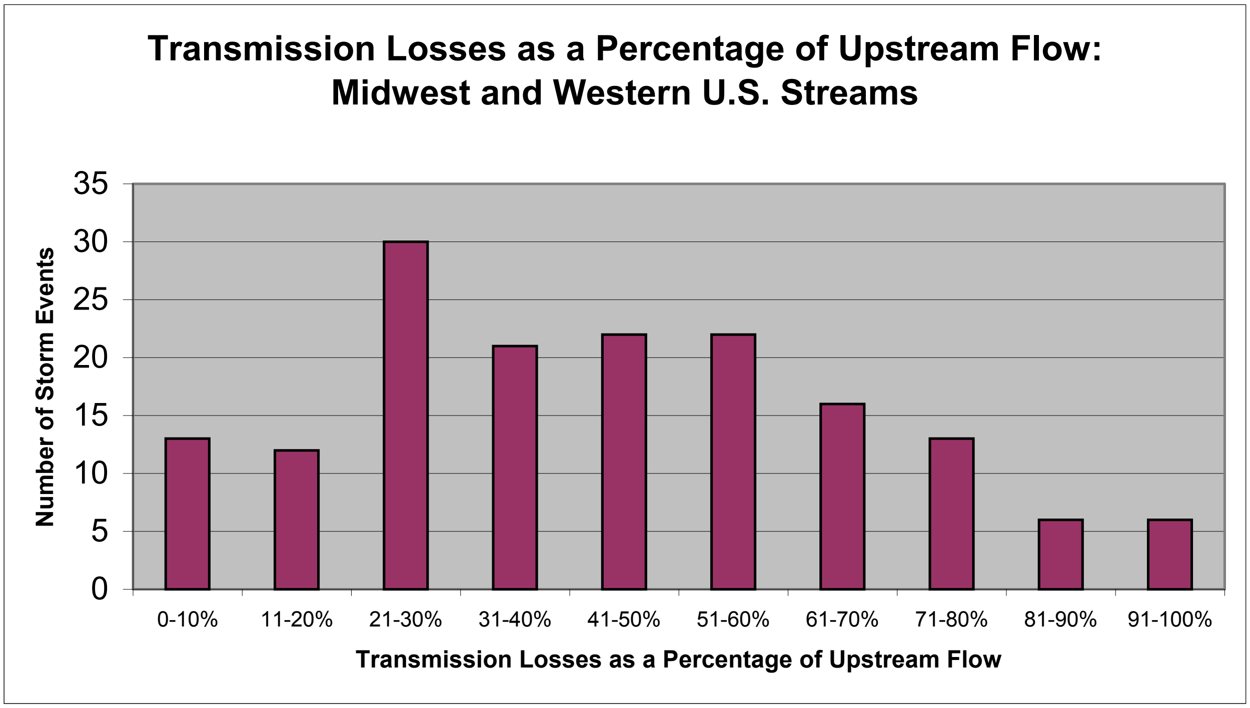

Figure 1: **Transmission Losses as a Percentage of Upstream Flow in Midwest and Western U.S. Streams.**

Table 2: Listing of Published Estimates of Transmission Losses (event based data only)

Ref Code	Reference	Type of Data
1	Sharp and Saxton (1962)	Single Event
2	Babcock and Cushing (1941)	Single Event
3	Walters (1990)	Average of Single Events
4	Lane, et al. (1971)	Single Event
5	Lane (1983)	Average of Single Events
6	Jordan (1977)	Single Event

Ref	Site	State	Reach ID	Reach Length (mi)	Upstream flow (af)	Downstream flow (af)	Transmission Loss (af)	Transmission Loss Rate (af/mi)	Transmission Loss as % of upstream flow	Transmission Loss in first mile (af)
1	Cheyenne River	SD	1	30	26,700	26,287	413	14	1.5%	14
1	Cheyenne River	SD	1	30	1,587	1,164	423	14	26.7%	16
1	Purgatoire River	CO	1	53	3,673	1,495	2,178	41	59.3%	62
1	Purgatoire River	CO	1	53	725	424	301	6	41.5%	7
1	Purgatoire River	CO	2	17	7,156	5,176	1,980	116	27.7%	135
1	Purgatoire River	CO	2	17	424	248	176	10	41.5%	13
1	Little Blue River	NE	1	30	53,914	50,974	2,940	98	5.5%	101
1	Little Blue River	NE	1	30	22,402	16,300	6,102	203	27.2%	236
1	Little Missouri River	ND	1	75	9,430	7,262	2,168	29	23.0%	33
1	Little Missouri River	ND	1	75	14,313	11,401	2,912	39	20.3%	43
1	Moreau River	ND	1	68	10,647	9,072	1,575	23	14.8%	25
1	Moreau River	ND	2	24	9,072	6,849	2,223	93	24.5%	106
1	Cimarron River	OK	1	157	7,333	2,624	4,709	30	64.2%	48
1	Cimarron River	OK	1	157	3,927	2,747	1,180	8	30.0%	9
1	Cimarron River	OK	1	157	5,933	2,967	2,966	19	50.0%	26
1	Cimarron River	OK	1	157	9,112	2,630	6,482	41	71.1%	72
1	Cimarron River	OK	1	157	4,568	2,465	2,103	13	46.0%	18
1	Cimarron River	OK	2	104	2,624	904	1,720	17	65.5%	27
1	Cimarron River	OK	2	104	2,747	2,071	676	7	24.6%	7
1	Cimarron River	OK	2	104	2,967	778	2,189	21	73.8%	38

Ref	Site	State	Reach ID	Reach Length (mi)	Upstream flow (af)	Downstream flow (af)	Transmission Loss (af)	Transmission Loss Rate (af/mi)	Transmission Loss as % of upstream flow	Transmission Loss in first mile (af)
1	Cimarron River	OK	3	102	8,436	7,041	1,395	14	16.5%	15
1	Cimarron River	OK	3	102	904	337	567	6	62.7%	9
1	Washita River	OK	1	55	1,589	1,083	506	9	31.8%	11
1	Washita River	OK	1	55	3,923	3,116	807	15	20.6%	16
1	Washita River	OK	1	55	6,960	5,460	1,500	27	21.6%	31
1	Washita River	OK	1	55	24,778	17,407	7,371	134	29.7%	159
1	Washita River	OK	1	55	25,480	18,401	7,079	129	27.8%	150
2	Queen Creek	AZ	1	20	69	12	57	3	83.3%	6
2	Queen Creek	AZ	1	20	26	5	21	1	80.9%	2
2	Queen Creek	AZ	1	20	58	45	13	1	22.9%	1
2	Queen Creek	AZ	1	20	152	66	86	4	56.8%	6
2	Queen Creek	AZ	1	20	244	149	95	5	38.9%	6
2	Queen Creek	AZ	1	20	1,880	1,260	620	31	33.0%	37
2	Queen Creek	AZ	1	20	309	144	165	8	53.4%	12
2	Queen Creek	AZ	1	20	1,340	1,060	280	14	20.9%	16
2	Queen Creek	AZ	1	20	2,680	1,830	850	43	31.7%	51
2	Queen Creek	AZ	1	20	12,000	8,500	3,500	175	29.2%	205
2	Queen Creek	AZ	1	20	2,700	1,380	1,320	66	48.9%	89
2	Queen Creek	AZ	1	20	569	146	423	21	74.3%	37
2	Queen Creek	AZ	1	20	1,270	321	949	47	74.7%	84
2	Queen Creek	AZ	1	20	1,900	628	1,272	64	66.9%	102
2	Queen Creek	AZ	1	20	3,090	2,360	730	37	23.6%	41
2	Queen Creek	AZ	1	20	1,480	832	648	32	43.8%	42
2	Queen Creek	AZ	1	20	15,600	9,320	6,280	314	40.3%	397
3	Queen Creek	AZ	1	20	4,283	2,658	1,625	81	37.9%	101
4	Walnut Gulch	AZ	11-8	4.1	5	1	4	1	74.1%	2
4	Walnut Gulch	AZ	11-8	4.1	3	0	3	1	97.4%	3
4	Walnut Gulch	AZ	11-8	4.1	40	22	18	4	44.0%	5
4	Walnut Gulch	AZ	11-8	4.1	9	3	6	1	62.7%	2
4	Walnut Gulch	AZ	11-8	4.1	128	46	82	20	63.8%	28
4	Walnut Gulch	AZ	11-8	4.1	2	0	2	0	92.4%	2
4	Walnut Gulch	AZ	11-8	4.1	6	4	2	1	36.2%	1
4	Walnut Gulch	AZ	11-8	4.1	44	28	16	4	36.8%	5

Ref	Site	State	Reach ID	Reach Length (mi)	Upstream flow (af)	Downstream flow (af)	Transmission Loss (af)	Transmission Loss Rate (af/mi)	Transmission Loss as % of upstream flow	Transmission Loss in first mile (af)
4	Walnut Gulch	AZ	11-8	4.1	11	3	7	2	70.9%	3
4	Walnut Gulch	AZ	11-8	4.1	2	1	1	0	67.2%	0
4	Walnut Gulch	AZ	11-8	4.1	8	2	6	1	74.8%	2
4	Walnut Gulch	AZ	11-8	4.1	27	13	15	4	53.1%	4
5	Walnut Gulch	AZ	11-8	4.1	17	9	8	2	47.3%	2
5	Walnut Gulch	AZ	8-6	0.9	14	11	2	3	16.8%	3
5	Walnut Gulch	AZ	8-1	7.8	16	2	15	2	90.2%	4
5	Walnut Gulch	AZ	6-2	2.7	75	60	15	6	20.2%	6
5	Walnut Gulch	AZ	6-1	6.9	48	17	31	5	64.6%	7
5	Walnut Gulch	AZ	2-1	4.2	49	24	25	6	50.5%	8
5	Elm Fork	TX	1	9.6	454	441	13	1	2.9%	1
5	Elm Fork	TX	2	21.3	441	424	17	1	3.9%	1
5	Elm Fork	TX	3	30.9	454	424	30	1	6.6%	1
6	Arkansas River	KS	1	53	108,800	77,100	31,700	598	29.1%	653
6	Arkansas River	KS	1	53	26,738	15,278	11,460	216	42.9%	294
6	Arkansas River	KS	1	53	41,800	17,400	24,400	460	58.4%	669
6	Arkansas River	KS	1	53	446,000	364,000	82,000	1,547	18.4%	1784
6	Beaver Creek	NE	1	39	1,083	575	508	13	46.9%	17
6	Beaver Creek	NE	1	39	1,810	725	1,085	28	59.9%	42
6	Beaver Creek	NE	1	39	772	301	471	12	61.0%	19
6	Beaver Creek	NE	1	39	19,787	7,482	12,305	316	62.2%	495
6	Beaver Creek	NE	1	39	6,083	3,693	2,390	61	39.3%	79
6	Beaver Creek	NE	1	39	4,451	2,920	1,531	39	34.4%	49
6	Beaver Creek	NE	1	39	470	272	198	5	42.1%	7
6	Beaver Creek	NE	1	39	741	366	375	10	50.6%	13
6	Prairie Dog Creek	KS	1	26	3,079	1,998	1,081	42	35.1%	49
6	Prairie Dog Creek	KS	1	26	3,457	3,091	366	14	10.6%	14
6	Prairie Dog Creek	KS	1	26	756	270	486	19	64.3%	29
6	Prairie Dog Creek	KS	1	26	555	226	329	13	59.3%	19
6	Prairie Dog Creek	KS	1	26	1,602	1,117	485	19	30.3%	22
6	Saline River	KS	1	71	1,461	885	576	8	39.4%	10
6	Saline River	KS	1	71	400	16	384	5	96.0%	18
6	Saline River	KS	2	24	12,820	10,660	2,160	90	16.8%	103

Ref	Site	State	Reach ID	Reach Length (mi)	Upstream flow (af)	Downstream flow (af)	Transmission Loss (af)	Transmission Loss Rate (af/mi)	Transmission Loss as % of upstream flow	Transmission Loss in first mile (af)
6	Sappa Creek	NE	1	35	24,099	18,416	5,683	162	23.6%	193
6	Sappa Creek	NE	1	35	1,785	825	960	27	53.8%	39
6	Sappa Creek	NE	1	35	978	486	492	14	50.3%	20
6	Sappa Creek	NE	1	35	2,743	698	2,045	58	74.6%	104
6	Sappa Creek	NE	1	35	5,316	1,457	3,859	110	72.6%	191
6	Sappa Creek	NE	1	35	2,212	1,226	986	28	44.6%	37
6	Smokey Hill River	KS	1	47	1,647	1,087	560	12	34.0%	14
6	Smokey Hill River	KS	1	47	1,917	923	994	21	51.9%	29
6	Smokey Hill River	KS	1	47	594	82	512	11	86.2%	24
6	Smokey Hill River	KS	1	47	711	499	212	5	29.8%	6
6	S.Fork Solomon River	KS	1	14	9,379	6,081	3,298	236	35.2%	281
6	Walnut Creek	KS	1	17	4,821	4,279	542	32	11.2%	34
6	Solomon River	KS	1	47	9,724	8,558	1,166	25	12.0%	29
6	Solomon River	KS	1	47	31,240	22,568	8,672	185	27.8%	219
6	Solomon River	KS	1	47	10,516	3,575	6,941	148	66.0%	242

Table 3: Listing of Published Estimates of Transmission Losses (Average, Monthly and Annual Data)

Ref Code	Reference	Type of Data
7	Buono and Lang (1980)	5 months
8	Burkham (1970)	Annual
9	Osterkamp et al (1994)	Annual

Ref	Site	State	Reach ID	Reach Length (mi)	Upstream flow (af)	Downstream flow (af)	Transmission Loss (af)	Transmission Loss Rate (af/mi)	Transmission Loss as % of upstream flow	Transmission Loss in first mile (af)
7	Mojave River Basin	CA	1	18.2			45,411	2,495	14.3%	
7	Mojave River Basin	CA	1	18.2			139,330	7,655	43.5%	
7	Mojave River Basin	CA	2	33.0			126,160	3,823	46.3%	
7	Mojave River Basin	CA	2	33.0			89,612	2,716	49.5%	
7	Mojave River Basin	CA	3	37.0			73,575	1,989	50.4%	
7	Mojave River Basin	CA	3	37.0			53,387	1,443	58.4%	
8	Santa Cruz River at continental, tributary 1	AZ	1	28.5	11,420		5,360	188	46.9%	
8	Santa Cruz River at continental, tributary 2	AZ	1	23.2	1,670		930	40	55.7%	
8	Santa Cruz River at continental, tributary 3	AZ	1	23.0	1,190		680	30	57.1%	
8	Santa Cruz River at continental, tributary 4	AZ	1	17.0	1,780		730	43	41.0%	
8	Santa Cruz River at continental, tributary 5	AZ	1	14.2	1,260		510	36	40.5%	
8	Santa Cruz River at continental, tributary 6	AZ	1	10.2	1,780		430	42	24.2%	
8	Santa Cruz River at continental, tributary 7	AZ	1	8.2	900		220	27	24.4%	
8	Santa Cruz River at continental, tributary 8	AZ	1	3.5	830		100	29	12.0%	
8	Santa Cruz River at continental, tributary 9	AZ	1	3.2	600		60	19	10.0%	
8	Santa Cruz River at continental, tributary 10	AZ	1	0.8	1,020		10	13	1.0%	
8	Tanque Verde creek near Tucson	AZ	2	10.5	4,360		3,390	323	77.8%	
8	Tributary to tanque Verde creek, tributary 1	AZ	2	6.6	430		250	38	58.1%	
8	Tributary to tanque Verde creek, tributary 2	AZ	2	6.6	800		470	71	58.8%	
8	Tributary to tanque Verde creek, tributary 3	AZ	2	3.6	250		90	25	36.0%	
8	Aqua caliente wash at foothills	AZ	2	7.8	820		510	65	62.2%	
8	Tributary to agua caliente wash	AZ	2	6.6	260		90	14	34.6%	
8	Sabino creek and bear creek	AZ	2	4.0	9,150		2,620	655	28.6%	

Ref	Site	State	Reach ID	Reach Length (mi)	Upstream flow (af)	Downstream flow (af)	Transmission Loss (af)	Transmission Loss Rate (af/mi)	Transmission Loss as % of upstream flow	Transmission Loss in first mile (af)
8	Tributary to sabino creek	AZ	2	2.8	280		120	43	42.9%	
8	Rincon creek near Tucson	AZ	3	7.8	2,610		2,600	333	99.6%	
8	Tributary to Rincon creek, tributary 1	AZ	3	4.2	590		450	107	76.3%	
8	Tributary to Rincon creek, tributary 2	AZ	3	4.2	590		450	107	76.3%	
8	Pantano wash near vail	AZ	4	21.5	5,050		4,180	194	82.8%	
8	Rincon creek at mouth,	AZ	4	12.0	290		270	23	93.1%	
8	Tributary to patano wash, tributary 1	AZ	4	9.8	840		480	49	57.1%	
8	Tributary to patano wash, tributary 2	AZ	4	5.4	740		230	43	31.1%	
8	Tanque Verde creek at sabino canyon road	AZ	5	9.5	9,150		5,500	579	60.1%	
8	Ventana canyon at mouth	AZ	5	9.0	480		420	47	87.5%	
8	Pantano wash at mouth	AZ	5	7.5	1,990		1,140	152	57.3%	
8	Tributary to rillito creek, tributary 1	AZ	5	6.4	460		290	45	63.0%	
8	Tributary to rillito creek, tributary 2	AZ	5	4.8	620		290	60	46.8%	
8	Tributary to rillito creek, tributary 3	AZ	5	2.6	520		140	54	26.9%	
8	Canada del oro at base	AZ	6	24.1	5,020		4,400	183	87.6%	
8	Sutherland wash,	AZ	6	11.2	840		240	21	28.6%	
8	Tributary to Canada del oro	AZ	6	9.9	750		190	19	25.3%	
8	Tributary to big wash, tributary 1	AZ	6	21.9	820		490	22	59.8%	
8	Tributary to big wash, tributary 2	AZ	6	16.8	890		410	24	46.1%	
8	Tributary to big wash, tributary 3	AZ	6	9.9	820		210	21	25.6%	
8	Santa Cruz River at Tucson, tributary 1	AZ	7	12.3	13,310		4,680	382	35.2%	
8	Tributary to Santa Cruz River 1	AZ	7	11.2	170		120	11	70.6%	
8	Tributary to Santa Cruz River 2	AZ	7	11.2	440		300	27	68.2%	
8	Tributary to Santa Cruz River 3	AZ	7	9.0	350		200	22	57.1%	
8	Tributary to Santa Cruz River 4	AZ	7	6.5	480		150	23	31.3%	
8	Tributary to Santa Cruz River 5	AZ	7	5.7	360		100	18	27.8%	
8	Tributary to Santa Cruz River 6	AZ	7	4.8	350		90	19	25.7%	
8	Rillito creek near Tucson	AZ	7	8.5	6,080		1,730	204	28.5%	
8	Tributary to Santa Cruz River, tributary 1	AZ	7	5.7	490		160	28	32.7%	
8	Tributary to Santa Cruz River, tributary 2	AZ	7	3.2	220		40	13	18.2%	
8	Canada del oro at mouth	AZ	7	2.6	4,000		420	162	10.5%	
8	Tributary to Santa Cruz River 2	AZ	7	1.4	200		10	7	5.0%	

Ref	Site	State	Reach ID	Reach Length (mi)	Upstream flow (af)	Downstream flow (af)	Transmission Loss (af)	Transmission Loss Rate (af/mi)	Transmission Loss as % of upstream flow	Transmission Loss in first mile (af)
8	Tributary to Santa Cruz River 3	AZ	7	1.4	400		30	21	7.5%	
9	Amargosa river, Beatty wash	CA	1	28.3			2,252	80		
9	Beatty Wash, mouth	CA	2	28.7			186	6		
9	Amargosa river, Beatty wash 2	CA	3	28.9			4,164	144		
9	Amargosa river, Amargosa NS	CA	4	33.8			2,990	88		
9	Amargosa river, Beatty	CA	5	1.5			24	17		
9	Amargosa river, Gold Center	CA	6	5.6			49	9		
9	Amargosa river, Carrara	CA	7	9.0			154	17		
9	Amargosa river, Ashton	CA	8	14.5			162	11		
9	Amargosa river, Ashton 2	CA	9	17.1			178	10		
9	Amargosa river, Big Dune	CA	10	21.4			227	11		
9	Amargosa river, Big Dune 2	CA	11	24.4			251	10		
9	Fortymile Wash, LB Trib	CA	12	32.9			2,398	73		
9	Fortymile Wash, LB trib2	CA	13	33.0			2,398	73		
9	Fortymile Wash, Narrows	CA	14	34.2			2,439	71		
9	Fortymile Wash, Yucca Wash	CA	15	35.7			2,568	72		
9	Yucca Wash, Black Glass Cyn	CA	16	5.6			105	19		
9	Yucca Wash, mouth	CA	17	8.6			211	24		
9	Yucca Wash, mouth 2	CA	18	8.9			219	25		
9	Fortymile Wash, Yucca Wash 2	CA	19	36.2			2,828	78		
9	Fortymile Wash, Drillhole W	CA	20	39.5			2,844	72		
9	Drillhole Wash, Fran Ridge	CA	21	7.0			41	6		
9	Drillhole Wash, Mouth	CA	22	7.4			41	5		
9	Drillhole Wash, Mouth 2	CA	23	7.6			49	6		
9	Fortymile Wash, J-13	CA	24	40.5			2,852	70		
9	Fortymile Wash, J-12	CA	25	46.3			2,860	62		
9	Fortymile Wash, road	CA	26	49.0			2,860	58		
9	Fortymile Wash, Lathrop	CA	27	51.0			2,860	56		
9	Fortymile Wash, 1.6 bl 27	CA	28	52.0			2,868	55		
9	Fortymile Wash, 3.2 bl 27	CA	29	53.0			2,868	54		
9	Fortymile Wash, 4.8 bl 27	CA	30	54.0			2,868	53		
9	Fortymile Wash, 6.4 bl 27	CA	31	55.0			2,868	52		

Ref	Site	State	Reach ID	Reach Length (mi)	Upstream flow (af)	Downstream flow (af)	Transmission Loss (af)	Transmission Loss Rate (af/mi)	Transmission Loss as % of upstream flow	Transmission Loss in first mile (af)
9	Fortymile Wash, 8.0 bl 27	CA	32	56.0			2,876	51		
9	Fortymile Wash, 9.7 bl 27	CA	33	57.1			2,876	50		
9	Fortymile Wash, 11.3 bl 27	CA	34	580.6			2,876	5		
9	Fortymile Wash, 12.9 bl 27	CA	35	59.1			2,876	49		
9	Fortymile Wash, 13.9 bl 27	CA	36	59.7			2,876	48		
9	Topopah Wash, shoshone mt	CA	37	5.9			130	22		
9	Topopah Wash, calico hills	CA	38	8.1			130	16		
9	Topopah Wash, test cell c	CA	39	9.3			130	14		
9	Topopah Wash, test cell c 2	CA	40	11.2			138	12		
9	Topopah Wash, e-mad	CA	41	13.4			138	10		
9	Topopah Wash, skull Mt	CA	42	15.5			138	9		
9	Topopah Wash, Stripped hills	CA	43	23.1			178	8		
9	Topopah Wash, US 95	CA	44	25.8			178	7		
9	Topopah Wash, Lathrop Wells	CA	45	26.9			178	7		
9	Rock Valley, US 95	CA	46	2.5			8	3		
9	Amargosa trib, Mercury	CA	47	3.5			16	5		
9	Amargosa trib, US 95	CA	48	3.8			24	6		
9	Amargosa river, CA 127	CA	49	16.6			300	18		
9	Amargosa river, Eagle MT	CA	50	29.6			567	19		
9	Amargosa river, Eagle Mt 2	CA	51	32.7			648	20		
9	Amargosa river, Baxter Mine	CA	52	41.6			834	20		
9	Amargosa river, Red Wg Mine	CA	53	45.0			1,215	27		

6. Conclusions

In this report, a number of approaches and models for predicting transmission losses have been critiqued. These models fall into six categories:

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

The most appropriate approach to use often depends on the site-specific conditions and data availability. The models summarized here do not include possible site-specific parameters such as channel morphology and evapotranspiration. It may be necessary to consider these and other parameters when modeling transmission losses at a specific site.

Among the models that have a potentially greater applicability for site-specific transmission loss predictions include: Jordan (1977), Lane(1982, 1983, 1985), Rao and Maurer (1996), and Sharp and Saxton (1962). Jordan (1977) is easy to use and has been tested for a large set of data. The papers by Lane extended Jordan to include streams of arbitrary length and width. Rao and Maruer (1996) develops models further by using standard autocorrelation methods to assess travel time for a stream reach and yields a combined differential equation (when integrating over an entire reach) that is essentially a one-parameter seepage loss model which may be calibrated from flow data. Sharp and Saxton (1962) provide a site-specific prediction of transmission losses on a watershed scale for hydrographs at tandem–gauge stations which had runoff-producing storms above upper stream gauge with little to no runoff between gauges.

The modeling approach that may have the most promise is combining differential equations with regression analysis. This approach is more realistic because it considers physical processes related to transmission losses. In addition, the use of statistical methods can provide reliable parameter estimates based on available data. This approach lends itself to developing site-specific prediction equations.

When a comprehensive set of site-specific data exists, such as characteristics of flows at tandem gauges in a stream without tributary flows between gauges, the estimate of transmission loses have a reasonable potential for success. Where sites do not have such datasets, there appears to be a potential to estimate storm losses by coupling water resources and transmission loss models. In such cases, possible estimates of watershed runoff and streamflow may be used as inputs to a transmission loss model.

7. References

Codes A-F indicate the type of model or analysis that was conducted in the paper. Codes translate to (A) simple regression equations; (B) simplified differential equations; (C) Combined use of differential equations and regression; (D) Field observations and experimentation; (E) Streamflow routing; and (F) Hydrologic budget. Papers without codes are general papers or have otherwise generated results that are useful in conducting research on transmission losses.

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