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Prediction of Transmission Losses in Ephemeral Streams, Western U.S.A.

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Abstract: Transmission losses (TL) are complicated phenomena that characterize the processes of evapotranspiration and infiltration as water moves down a stream. This analysis focuses on transmission losses that occur within the stream and can be computed with data from tandem stream gauges. Data from Walnut Gulch Experimental Watershed (WGEW), in southeast Arizona, are the primary source. The WGEW is a typical watershed in the region where a network of alluvium-filled stream represents a range of widths and slopes. TL results were compared with those from other U.S. streams as reported in several published papers. TL per kilometer (TL/km) were calculated by dividing the difference between flow volumes at the upstream and downstream gages by the distance between gages. Only storms that occurred above the upstream gage were considered. TL/km for several storms and stream reaches were plotted against the inflow volume and peak inflow discharge and a consistent pattern emerged. These plots yielded parameterized equations that were used to compare published TL for Queen Creek, AZ and several Plains States streams. The sediment characteristics of the streams were also incorporated into the model by using their hydraulic conductivity. The objective of this study was to develop a simple, rapid method requiring only a minimum of pre-existing data to determine transmission losses in ephemeral streams in arid climates that can be used easily by regulators and planners. Furthermore, the models can contribute to the determination of "significant nexus" of the US Clean Water Act (CWA), Section 404 jurisdiction.

Keywords: Transmission Losses, runoff, arid zones, ephemeral streams, hydraulic conductivity.

INTRODUCTION

Population growth and urbanization are increasing the global demand for limited natural resources such as land and water. In areas/counties/regions where development pressure is high and natural resources scarce, engineers currently play a key role in the design of sustainable means of meeting human needs while protecting ecosystems and the important services they provide.

This paper presents a new approach to the rapid assessment of stream transmission losses (TL) for planning level analyses. Transmission losses are a key hydrologic process of importance in upstream/downstream water rights negotiations, quantification of environmentally significant flows, municipal water supply system planning and management, as well as, in the United States, in the establishment of spatial limits on urban and suburban development. TL determinations have implications for estimating groundwater recharge and the "significant nexus" test necessary for federal regulation under Section 404 of the CWA as set forth by the U.S. Supreme Court [1]. Recent regulatory guidance [2] requires that hydrologic factors be evaluated in assessing whether a remote waterbody has a significant nexus to traditional navigable waters (TNW), effectively protecting it from development. Because the magnitude of TL occurring along a stream determines the timing, volume, and rate of water that will reach a TNW, there is a need to develop techniques for rapidly estimating TL based upon minimal available site data. As a rapid assessment technique, the approach presented in this paper is not intended to occur in lieu of detailed hydrologic investigations, in instances where very precise estimates of TL are warranted.

Transmission losses are equivalent to the sum of infiltration, evaporation, and evapotranspiration losses over a given stream reach. They may occur in any climate but are most common in arid and semi-arid regions. Infiltration-based losses, the much larger share of TL as compared to evapotranspiration [3], may occur in streambeds as well as along and beyond stream banks if runoff is large enough to exceed the bank-full stage. The magnitude of TL occurring in a given stream is also a function of sediment type and concentration [4], water and air temperature, and antecedent stream flow [5], as well as heterogeneous sediment and stream characteristics [6], spatially variable infiltration rates [7], and climatic variability [8].

Reliable estimation of stream TL is necessary in a wide range of hydrologic planning studies, yet most estimation techniques require either extensive data inputs or extensive

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field work, limiting their usefulness to planners. Estimation techniques that have been employed include field and empirical methods based on physical observations, and statistical and physical modeling approaches. These techniques are generally reviewed below.

Field and Empirical Methods

A wide range of field and empirical methods have been reported. However, the use of regression and empirical equations as a prediction tool is site specific and caution must be exercised when attempting to extrapolate specific findings to multiple sites. Field and experimental studies are valuable in that they supply data for modeling and insight into the TL phenomenon but are generally only applicable to limited geographical areas and may not be useful as a generally applicable estimation tool for regulators and planners.

An approach based on three distinct types of events was developed by Knighton *et al.* [8] for the channel-country rivers in Lake Eyre Basin, Australia. The purpose of the study was to investigate the effects of local hydrologic variability on transmission losses. In the study, single events were defined as having one well defined peak discharge rate, multiple events were defined as having more than one peak, and compound events were defined as having several peaks with non progressive rises and falls. Generally, a progressive increase in magnitude, duration, and time to peak was found from single to compound events. However, uncertainty in the predictions also increased along this gradient.

Sharp *et al.* [9] provided a site-specific prediction of watershed-scale transmission losses using hydrographs from tandem–gauge stations for runoff-producing storms occurring upstream of the upper stream gauge only. Wallace *et al.* [10] used observation wells to determine that TL were a primary source of recharge to underlying aquifers of ephemeral streams in southeast Arizona. The same phenomenon was found in the Eastern Cape Province of the Republic of South Africa, where Hughes *et al.* [11] presented transmission loss estimates based on moisture observations of the alluvium material using neutron probe access tubes. Transmission losses were considered a primary source of recharge in these systems. The estimated losses were only considered accurate to an order of magnitude, because they were based on extrapolation from a limited number of observations.

Dunkerley *et al.* [12] presented TL estimates from study of a single, small flow event. The flow volumes were calculated by measuring (on the day after the flow) the lateral extent of debris and dampness from the thalweg. They found that transmission losses from large events were governed by water infiltrations into the wetted perimeter and settling of fine sediment in the bed and bank. Losses were smallest during bank-full-flow because the ratio of volume to wetted perimeter was maximized.

Greenbaum *et al.* [13] reported event-based recharge from several empirical studies conducted in an intensively instrumented alluvial reach of an alluvial fan of the lower Nahal Zin in hyper-arid Negev Desert. The results indicated that transmission losses and recharge were related to the flood volume by a power decay function, and that flood volume increased exponentially with flood peak. Goodrich *et al.* [14] estimated recharge in the Walnut Gulch Watershed using several methods including a reach water balance; geochemical methods, modeling of groundwater level or microgravity measurements; and vadose zone water temperature transport modeling. Estimates differed by less than a factor of three between these methods.

Statistical and Physical Modeling

Statistical and physical modeling approaches to TL estimation generally make some assumptions about the stream and watershed geomorphology, derive parameterized relationships between TL and certain measurable parameters, and then curve fit the model to a set of observations. The results of these studies help to derive insights into how TL processes occur, but are also difficult to use in planning studies.

Lane *et al.* [15] presented regression equations relating TL and inflow volume, and also between inflow and outflow volume for ephemeral streams in south-eastern Arizona. Their prediction equation for TL was related only to events with the flow contained within the banks of the stream. Walters [16] provided three regression equations for estimating transmission losses in southwest Saudi Arabia. One of the equations was found to be a reliable predictor of losses associated with small upstream volumes. The other two equations can be utilized to make TL predictions for losses associated with large floods. However, the data set studied was relatively small [16], and a number of the variables rejected in this regression analysis may be important (ex: hydraulic conductivity, drainage area, and lateral inflow).

Several regression equations were presented to estimate the transmission losses and recharge from a wadi-bed in Saudi Arabia [6, 17]. These studies indicate that the magnitude of transmission losses and consequent recharge resulting from given upstream runoff hydrographs is a function of stream and sediment characteristics. Greater TL may occur as a result of high initial moisture content and shallow depth to water table. Sediment heterogeneity, especially in the center or near the edge of the wadi channel, influences the movement of the wetting front as well as the recharge amount.

Using an analytical modeling approach, Jordon [18] assumed that the rate of loss at any point between gauging stations was proportional to the flow at that point, and also that the stream and watershed characteristics were uniform. He then developed a first order differential equation to describe TL. Jordon's approach is easy to use and has been tested for a large set of data in the plain states to determine TL for ephemeral and intermittent streams. Among the factors Jordon did not consider were antecedent moisture conditions and differences in alluvial material.

Knighton *et al.* [19] developed a three parameter Muskingum procedure to estimate outflow hydrographs and transmission losses. The estimated parameters behaved well when flow was within the primary channel. Predicted TL were less when clay sealing prevented transmission losses over significant lengths of the river, and evaporation and drainage diffusion were major causes for transmission losses.

A hydrologic-flow-routing technique for arid ephemeral streams was developed by Sharma *et al.* [20] for the Luni River in arid northwest India. The nonlinear volumetric transmission loss rate term, which is empirically estimated

Table 1. Detailed Listing of Stream Characteristics

	Name	Reach km	Contributing Area km^2	D_{10} mm	K value cm/sec x 10^{-4}	Annual Precip.* mm	Annual Runoff* mm
1	Walnut Gulch, AZ (11-8)	6.6	15	0.43	1950	350	11.43
1	Walnut Gulch, AZ (8-6)	1.4	93	0.43	1950	350	11.43
1	Walnut Gulch, AZ (6-2)	4.3	112	0.43	1950	350	11.43
1	Walnut Gulch, AZ (2-1)	6.8	148	0.43	1950	350	11.43
2	Queen Creek, AZ	32.2	866	N/A	N/A	254	6.35
3	Praire Dog Creek KS	41.8	2538	0.055	36	533	10.16
4	Republica Creek, KS	54.7	63564	0.033	23	792	31.75
5	Smokey Hill River, KS	75.8	13520	0.202	630	594	6.35
6	Salina River, KS	48.5	17534	0.165	520	536	35.56
7	Little Blue, NE	48.3	8625	0.109	180	711	55.88
8	Little Missouri, ND	120.7	16032	0.135	400	366	19.05
9	Moreau River, SD	109.4	11189	0.07	38	465	12.7
10	Cheyenne River, SD	48.3	22559	0.102	108	434	19.05
11	Shell Creek, NE	49.9	699	0.029	20	711	44.45
12	Sappa, KS	56.3	2720	0.119	360	508	25.4
13	Cimarron R. OK	252.7	5335	0.089	75	432	44.45
14	Washita River, OK	88.5	5120	0.039	27	749	44.5

*precip and runoff for Walnut Gulch, Az are for the complete watershed.

from the observed inflow-outflow data for a stream reach, is included in the hydrologic-routing equations for the estimate of flood waves. A hydrologic budget approach was used to assess transmission losses and groundwater recharge for a 1400 square kilometer watershed with annual precipitation of 70 millimeters in Negev, Israel [21]. The modeling results indicated that evaporation was substantially smaller than the transmission losses. A loss function was developed that related total inflow (estimated inflow and lateral flow) to transmission losses. This model assumed that transmission losses were estimated by water balance equations that included lateral tributary inflows that could only be estimated indirectly.

Generalized Approaches

Only one attempt [5, 22] to develop a means of estimating TL applicable with or without site specific data was found in the literature. When inflow-outflow data is available, regression equations are used to estimate TL for the gage-bounded stream reach. Detailed procedures are presented enabling the user to determine prediction equations for similar streams with or without lateral inflow, out of bank flow, and streams underlain by nearly impervious material. The approach presented in this study can be extended to consider the effect of hydraulic conductivity on the volume of runoff, peak discharge, and overall TL. Examples are presented that illustrate the wide range of applications of the TL procedures described. The approach is limited only by the fact that hydrographs are not specifically routed along the stream, peak flow equations do not consider storage attenuation, only average conditions are considered, antecedent flow and sediment concentrations in the streamflow are not quantified, and hydraulic conductivity is empirically based.

In this paper, we develop a simplified approach to estimating TL in ephemeral streams for routine policy and planning analyses purposes. An approach that is technically rigorous and requires extensive data collection may be unsuitable for such purposes simply because of time and budgetary constraints to collect field data. Using a regression approach on upstream and downstream gage data, TL/km and the distance streamflow travels can be estimated from the difference in flow volume between gages (Model 1). This initial estimate is also “adjusted” using basic information about stream bed characteristics (Model 2). Models 1 and 2 are compared to a third approach found in the literature (Model 3), and all three estimates of TL for ephemeral streams in the Southwest and Midwest US compared and discussed.

Site Descriptions

The study areas examined in this study include the Walnut Gulch Experimental Watershed (WGEW) in Cochise County (in a transition zone between the Chihuahua and Sonora Deserts), in southeast Arizona; Queen Creek, an ephemeral stream that crosses Maricopa and Pinal Counties and is located between Phoenix and Superior, Arizona; and several streams from the US Midwest. Listing of some key climatic and geomorphological characteristics of these study areas is provided in Table **1**. A map showing the location of all study areas in the US is provided in Fig. (**1**).

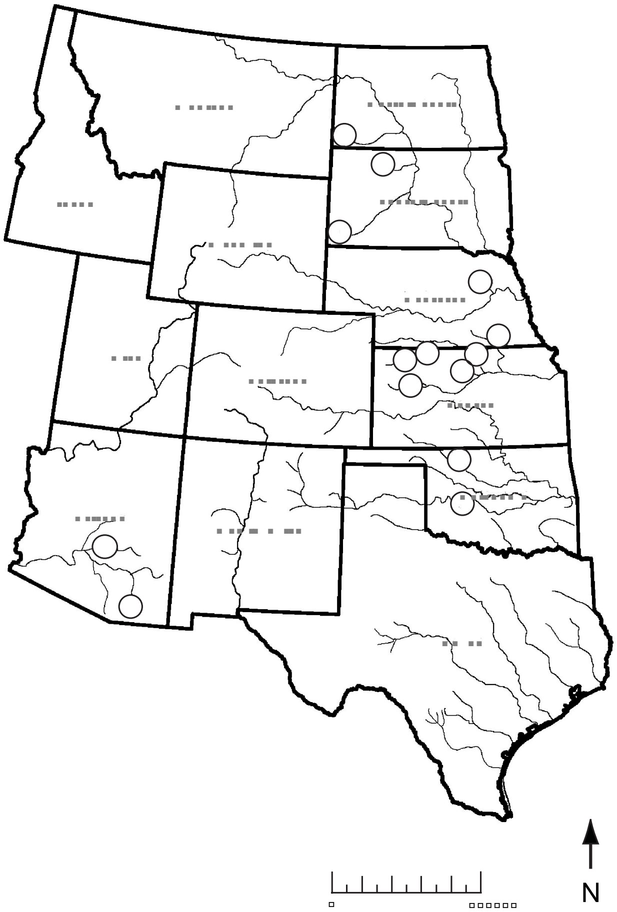

Fig. (1). Location of streams in study sites (numbering corresponds to Table **1**).

Walnut Gulch Experimental Watershed

Walnut Gulch is an ephemeral tributary to the San Pedro River basin, which originates in Sonora, Mexico. The San Pedro River drains in a northerly direction where it joins the Gila River, a tributary of the Colorado River. The confluence of Walnut Gulch and San Pedro is approximately 772 river-km from the Colorado River. The watershed is typical for the region with a network of wide, shallow, flat-bottomed streams that are filled with coarse, clean, sandy gravel that overlie conglomerate bedrock [10]. Streams vary in widths and slopes. Vegetation consists of brush and grass-covered rangelands, also common for that region [23]. The climate is classified as semi-arid with a mean annual temperature at 17.7 °C and a mean annual precipitation of 35 cm [24]. About 90% of all runoff occurs from intense thunderstorms in July and August [15].

Precipitation and runoff data have been collected at WGEW for over 50 years, with gages located throughout the watershed. The initial network of 20 precipitation gages was expanded in the early 1960s to the current network of 88 high resolution gages. Each gage has been laboratory- and field-tested, and consists of a precision, temperature-compensated load cell, that measures the weight of a platform-mounted container that collects water during precipitation events. The events reported here are for flows from zero to peak.

Streamflow in WGEW is measured using supercritical precalibrated flumes constructed and tested at the Agricultural Research Service Outdoor Hydraulic Structures Laboratory in Stillwater, Oklahoma. The watershed is divided into sub-basins by automated, supercritical, precalibrated flow-measuring flumes at various locations within the stream network [25]. Runoff from watersheds greater than 40 hectares is measured using either livestock watering ponds or large supercritical flow flumes. Currently, eight small watersheds, ten stock ponds, and eleven large flume watersheds are being monitored. The largest flume at the outlet of WGEW has a flow capacity of 650 cubic meters per second. There are 10 stock pond watersheds and 11 large flume watersheds currently being monitored.

This study focuses on flow in several connected stream reaches that have different lengths, widths and contributing areas. Each stream reach is between tandem up and downstream streamflow gages. Stream Reach 1 begins at Flume 11 and ends at Flume 8 (Fig. **2**). Stream Reaches 2, 3, and 4 proceed through Flumes 8, 6, 2 and 1, respectively. Stream reach 1 is about a quarter of the width of Reach 4. The average stream length is 4.8 km and the average stream width is 26 m.

Sieve analyses of the stream material in Walnut Gulch [26, 27] indicate sediments that are generally well-drained, calcareous, gravelly loams with large percentages of rock and gravel at the surface. The sieve size through which 10% of the stream material would pass (known as D_{10}) for Walnut Gulch is 0.43 mm [27]. The large volume of coarse-textured, high-permeability alluvium in the stream significantly reduces the volume of discharge through the streams, leading to relatively large values of TL at Walnut Gulch.

Queen Creek

Queen Creek crosses Maricopa and Pinal Counties and is located between Phoenix and Superior, Arizona (Fig. **3**). The stream is a large desert-wash originating in the Pinal Mountains near the Town of Superior. It enters the outwash-plain at Black Point about three miles north of Florance Junction. The flow then passes through the desert in a southwesterly direction towards Chandler, spreads over the lowland. The flow of the stream results almost entirely from brief storm events common to the deserts of that region.

The Queen Creek data cited in this study is adapted from Babcock *et al.* [28], and references two tandem stream gage stations. The upper station was located about 1.2 km below Black Point. The downstream gage was at the County highway bridge, about 32 km below Black Point. An intermediate staff-gage designated the Cactus gage also was maintained for a period of time. The upper station was established only later. The average stream width was listed as 84 m and the distance between gages was approximately 32 km. During the storm events referenced in Babcock *et al.* [28], the stream was reportedly deposited with gravel, sand, and silt covered with the sediment that became finer with distance from the mountains. No specific grain size distribution data was published.

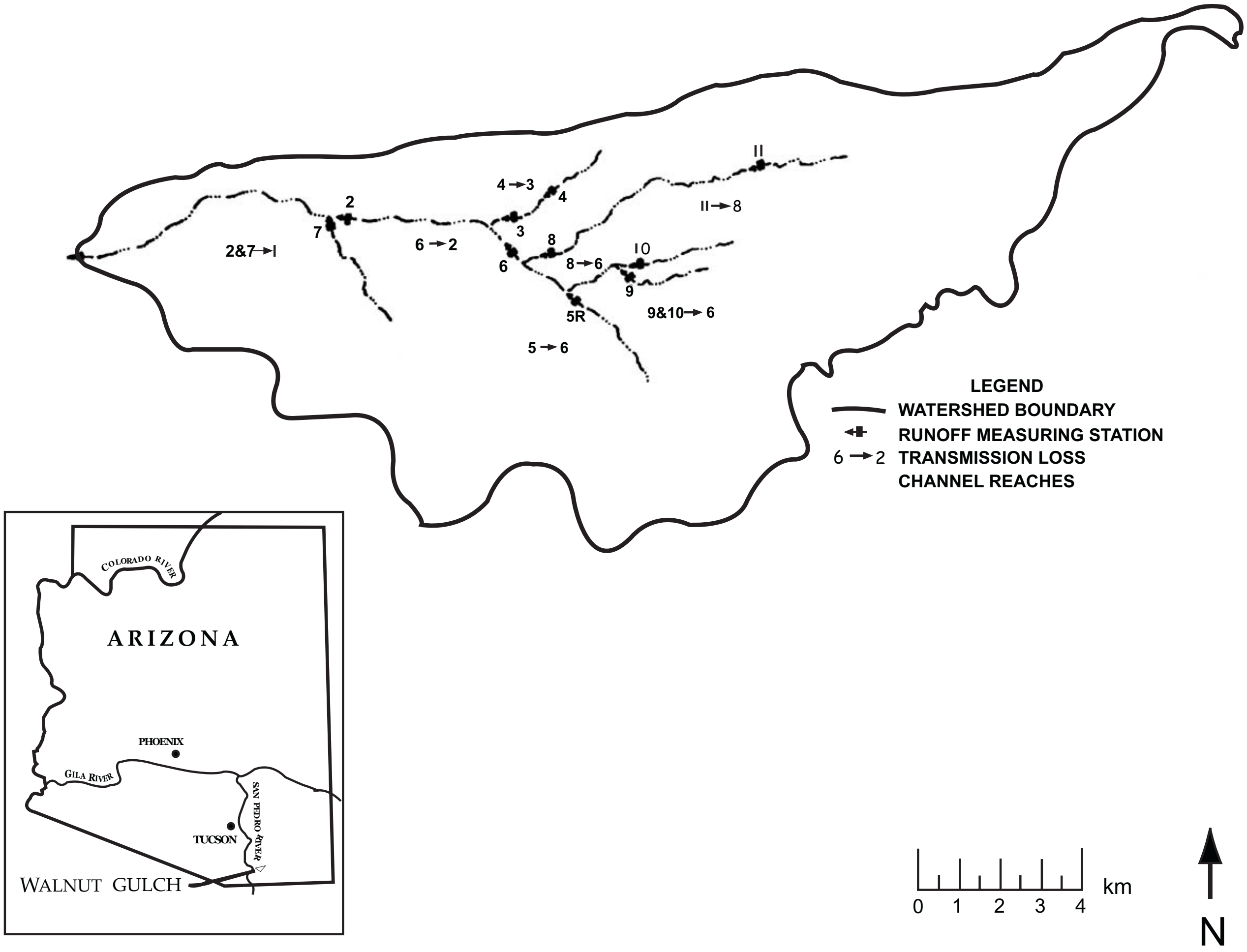

Fig. (2). Walnut Gulch Experimental Watershed, AZ. (Renard, 1970).

Since Babcock *et al.* published their work, there have been a number of substantive changes along Queen Creek. Among these changes is the construction of the Sanogui Flood Retarding Structure (SFRS). The SFRS is in the approximate location of the referenced upstream gauging station, and immediately upstream of the Central Arizona Project Aqueduct which currently diverts a portion of the Queen Creek flow through four 1.8 m diameter culverts. Therefore, sufficient grain size information for the Babcock *et al.* [28] Queen Creek study has not been published and values of D_{10} cannot be determined.

Midwest Streams

The US Midwest stream data referenced in the paper are adapted from Sharp *et al.* [9] and Jordon [18]. These streams have longer lengths and larger watershed areas than those at WGEW, are of varied type (ephemeral, intermittent and perennial) and, due to their US Midwest location, are subject to more temperate climate conditions than the Arizona sites (Table **1**). The studies reference two gage stations operated on the same stream with no large tributaries between them. These gages were operated by the Agricultural Research Service and the US Soil Conservation Service. The locations of these stations are described in the studies referenced above (see Fig. **1**).

3. METHODS

In this paper, regression equations derived from transformations of WGEW data and relating TL to measured streamflow characteristics are used to predict TL/km at WGEW and at other stream locations, using only the measured inflow volume. That is, statistical models calibrated to WGEW data are validated as predictive models of TL at other locations. The validity of these relationships is limited to stream reaches within which: a) no lateral tributary flow occurs, and b) flow is constrained to the channel banks (i.e. no bank overflow). The regression equations generated from the transformed WGEW data are used to make predictions of TL at the Queen Creek and Midwest study sites, both directly (Model 1), and with an adjustment coefficient that considers each site's stream bed characteristics (Model 2). The predictions made with Models 1 and 2 are then compared to TL predictions made using the Lane [5] model. The Lane model is referred to in this paper as Model 3). A validation of all three models is performed by comparing all three sets of predictions to the actual observed TL values using various statistical measures of "goodness of fit."

The first step is to compute WGEW transmission losses as the difference in flow between the upstream and downstream gages. The differences in both the peak flow rates and

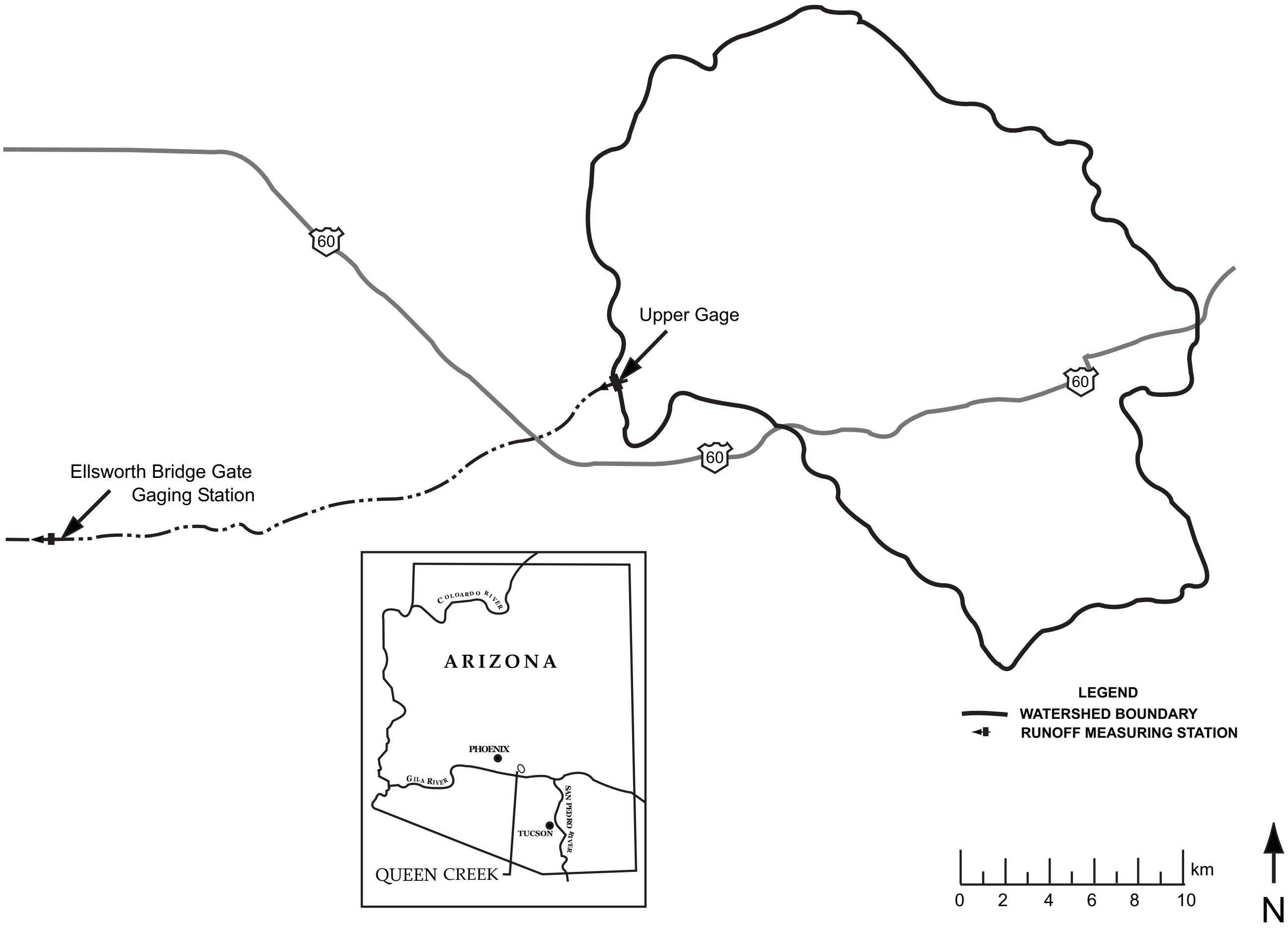

Fig. (3). Queen Creek Watershed (1940).

total flow volumes between the upstream and downstream gages are calculated. Transmission losses per length are then computed by dividing each of these values by the length of each stream reaches.

Linear regression lines are then fit to the data to express mathematically the relationships between TL per stream length (the dependent variable) and the two independent variables: inflow volume and inflow peak discharge. The equations representing the regression lines are then log-transformed in both the dependent and independent variables, such that the fitting parameters become powers on the independent variable after the linear model is back-transformed. Transformations using power functions, exponential, parabolic, hyperbolic or other relationships are commonly used in regression analysis to better represent with assumptions underlying a modeling process, to linearize the relationship between two variables whose relationship may not necessarily be linear, or to modify the variable ranges for more efficient computations [29].

The fitting parameters of the regression lines are estimated from the WGEW data (i.e. the model is calibrated using the WGEW data). These equations are then used to estimate transmission losses per length for Queen Creek and the Midwest streams (i.e the model is validated using the Queen Creek and Midwest streams). This set of predictions is referred to as Model 1. A second set of predictions is made using a simple adjustment to account for differences in stream bed characteristics between the sites. This set of predictions is referred to as Model 2, and is also validated using the Queen Creek and Midwest stream sites. The stream bed characteristics adjustment is described in detail below.

Stream Bed Characteristics Adjustment

Because stream bed infiltration makes up a large percentage of TL, the rate at which water can flow through the bottom and sides of the channel is critical. In Model 2, the predicted TL values derived from the WGEW regression relationships are adjusted by a coefficient equal to the ratio of the hydraulic conductivity of the subject stream (K) to the hydraulic conductivity of the stream bed materials at WGEW (K_{WG}). This coefficient becomes a third independent variable for Model 2 (along with the volume and flowrate). Model 2 transmission loss predictions are computed by multiplying the adjustment coefficient by the original transmission loss prediction equations, derived from the regression of WGEW data.

In planning studies, field measurements of hydraulic conductivity are typically not available. Hydraulic conductivity estimates for different streams can be performed based on assumptions of stream bed material using either a graphical method developed by Burmister [30] or by the Hazen

Equation. The Burmister technique involves the use of empirically derived curves that relate the logarithm of K to the relative density of the sediment. Using this technique, reasonably reliable estimates of K can be obtained from the effective grain size, (D_{10}). The Burmister K_{WG} value for WGEW is estimated at 0.1950 cm/sec. By contrast, using Hazen's equation, the value of K_{WG} is 0.1849 cm/sec (computed as the square of D_{10}) [31]. However, Hazen's equation was developed for uniformly graded sands and thus only provides rough estimates for most soils in the fine sand to gravel range. For this reason, K_{WG} was assumed to be 0.1950 cm/sec, in this analysis.

To compute K for the other streams, data describing the particle size distribution of stream bed material using sieve analyses was obtained from the USGS [32]. This data was used to compute D_{10} values for each location, which could then be converted to K values by the Burmister technique, described above. The USGS conducted sieve analyses for hundreds of US streams during most of the last century, and fortunately most of the streams analyzed by Sharp *et al.* [9] and Jordan [18] were covered in this dataset. This database is accessible to planners and regulators who do not have access to site specific information. For streams with multiple sieve analyses, an average D_{10} was computed. For most streams with multiple data, average D_{10} values were close to the median values and there was little variation around the average. The Jordon data included six streams and 22 flood events; the Sharp *et al.* included six streams and 23 flood events.

An alternative technique was used to calculate the adjustment coefficient to make Model 2 predictions at Queen Creek. This alternative approach was required due to the fact that pre-1941 sieve analyses in Queen Creek were not available from the USGS. Due to the extensive hydrologic modifications of Queen Creek that occurred post-1941, use of later sieve analyses for computing K was deemed inappropriate. As an alternative, the adjustment coefficient for these predictions was set equal to the ratio of the stream bed infiltration rates of the two streams as cited in Lane [5]. These values were 0.000945 cm/s for Walnut Gulch and 0.000381 cm/s for Queen Creek [28].

4. DESCRIPTION OF DATA USED IN THE ANALYSES

Walnut Gulch Experimental Watershed Data

To compute TL at WGEW, both published and unpublished stream gage data were used [33]. Only stream flows that were recorded successively in both the upstream and downstream gages were included in the analysis. Storm events were excluded if a sub-watershed between the tandem gages received 5 mm of rainfall or less [15]. Some storms included in the present analysis that were extracted from previously unpublished data represented a diversity of intensity, spatial extent, and duration. For example, a storm on July 17, 1965 was centrally located high in the watershed, whereas a storm on August 29, 1961 spanned the North-South range of the WGEW. Storms caused two distinct peak flows whereas others had more pronounced single peaks (see Fig. **4**). Some storms were relatively small with upstream flows less than 7,600 m^3 whereas others caused flows of greater than 76,000 m^3. A storm on August 5, 1968 is also noteworthy because flows were measured from Flumes 11 through to 1.

Two storms had inflow hydrographs that were measured at Flume 11 with no runoff measured at Flume 8. This implies that all of the storm flow entering Flume 11 was lost within this 6.6 km reach. These two storm events were not included in the analysis because the stream disappeared into the alluvium before reaching the downstream gage and could not be scaled by the length of the stream.

Several stream discharge events are examined for volume and peak flow (Q_p). The dramatic effect of TL on water flow is demonstrated by the July 18, 1965 storm that flows through three stream reaches (Fig. **4**). In total, peak discharge and volume dropped from 16.3 to 0.8 (cms) and 34,784 to 3,577 (m^3), respectively. This translates to approximately 95 percent loss of initial inflow Q_p. Overall, TL estimates in all reaches ranged from 1,357 to 101,022 m^3 or approximately two orders of magnitude.

Queen Creek Data

Storm events occurred during the period Feb. 1940 through Mar. 1941 for the Queen Creek Watershed. During this period, precipitation at nearby Casa Grande, AZ, was well below the normal range during 1939, normal during 1940 and well above normal in 1941. Two storm events were excluded in which flows did not reach the downstream gage and two other storms that produced extremely large flows that may have overflowed over the banks [28].

Midwest Streams

For additional comparative purposes, the relationship of TL to discharge volume for events reported from several Midwest streams by Sharp *et al.* [9] and Jordan [18] were examined. Volumes - not Q_p values - were provided in Sharp *et al.* [9] and Jordan [18]. Both studies determined TL in the same way as at WGEW and Queen Creek, that is, by subtracting the flow between tandem gages on the same streams with no lateral inflow between the gages.

5. RESULTS

Model validation was performed by estimating the overall "goodness of fit" of the predictions obtained using Model 1, Model 2, and Model 3 [5] to the computed TL per length values (hereafter referred to as the "observations"). This validation also sought to assess whether each model has a tendency to over- or under- predict TL. Three error calculations were computed: the standard error (SE), the mean absolute error (MAE), and the mean cumulative error (MCE). The rationale for computing these three errors is as follows: the standard error and the mean absolute error are both used to assess each model's general goodness of fit. The mean cumulative error allows tracking of the direction in which each model is biased, where a positive value of MCE indicates that the model underestimates the observations. Also computed was the average percent error of each prediction compared to the observations.

The observed and predicted transmission losses per km of stream versus inflow volume for Walnut Gulch and Queen Creek are shown graphically in Figs. (**5**) and (**6**), and for the Midwest streams in Fig. (**7**). Confidence intervals from Model 1 were not extended for other streams in Fig. (**7**) be-

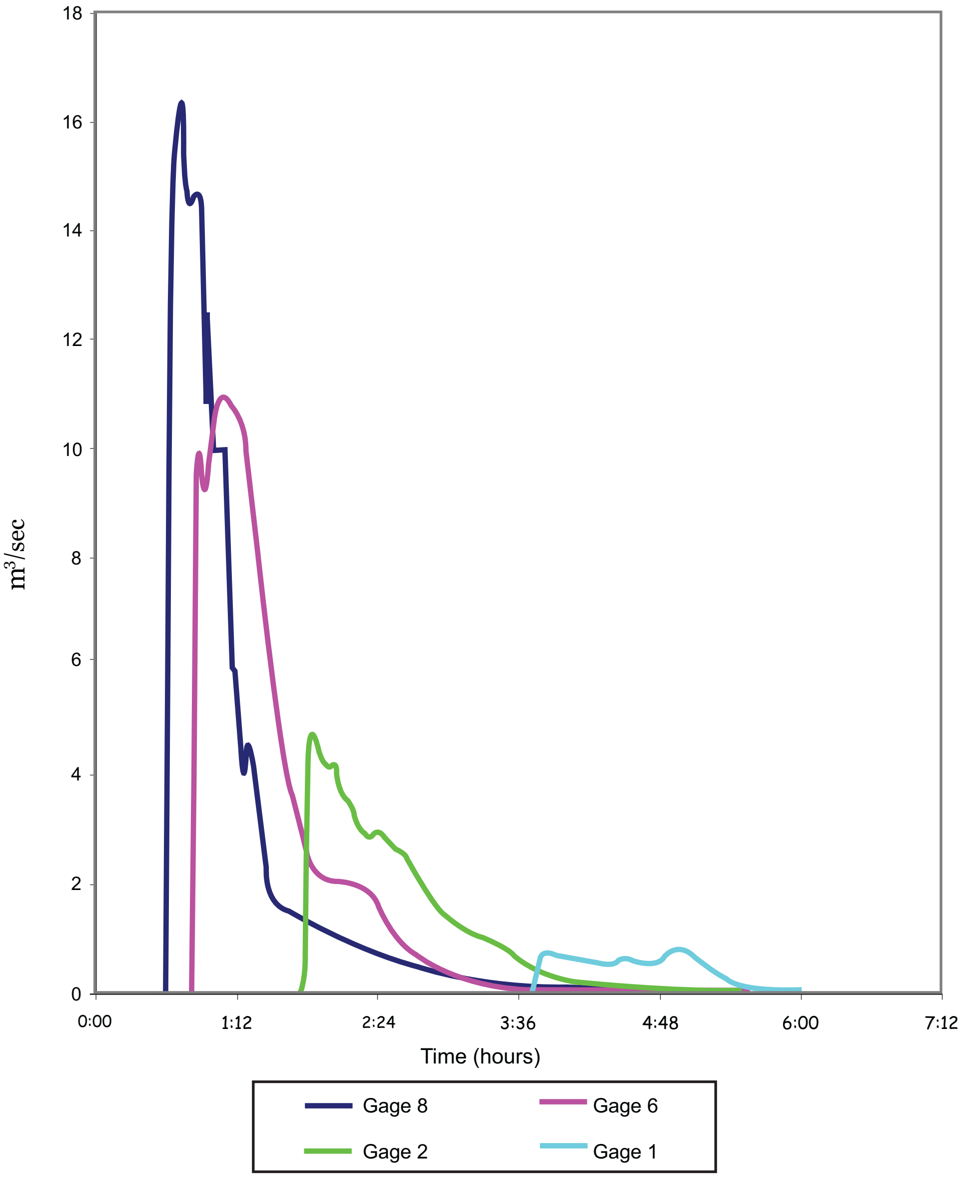

Fig. (4). Hydrographs – 7-18-65; Flumes 8,6,2,1 for Walnut Gulch.

cause the confidence intervals are estimated for only the Walnut Gulch data on the range of stream inflow data found there, which are less than the Midwest streams. Errors associated with all sets of predictions are listed in Tables **2**, **3**, and **4**. Note that storm events for which TL/km could not be estimated because of a lack of flow in the downstream gage were not included in this study.

The regression equations (as power functions) relating WGEW data on TL/km with inflow volume and peak inflow are the following:

Model 1 $TL/km = 1.02(Vol)^{(0.75)}; R^2 = 0.82$ (1)

Vol p-value < 0.01

$TL/km = 317.29(Q_p)^{(0.78)}; R^2 = 0.72$ (2)

Q_p p-value < 0.01

$Vol = 2{,}182.07(Q_p)^{(1.02)}; R^2 = 0.85$ (3)

Q_p p-value < 0.01

Where: TL/km = Transmission loss (m^3/km)

Vol = Inflow volume (m^3), and

Q_p = Peak inflow (m^3/s)

The relationships between these flow characteristics suggest relatively strong trends in the data. The Walnut Gulch data indicate that TL/km is strongly correlated with the inflow volume ($R^2 = 0.82$) and the peak rate inflow ($R^2 = 0.72$). The relationship between the volume of the inflow and

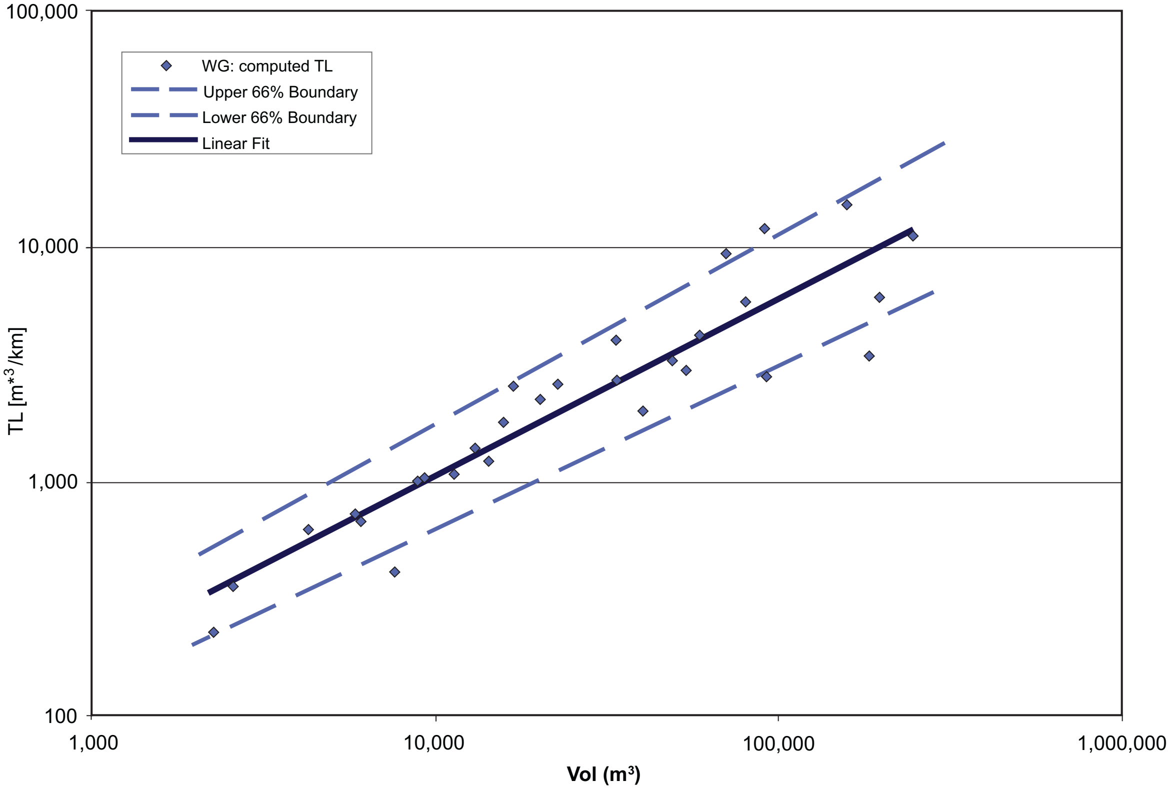

Fig. (5). Transmission Losses versus Inflow Volume for Walnut Gulch with model 1 prediction line and 66 percent boundaries, $R^2 = 0.82$.

peak inflow also has a high correlation coefficient of 0.85 as shown in Equation 3.

When Model 1 is used to predict TL/km at WGEW, the values shown in Table **2** are obtained. These predictions are shown graphically in Fig. (**5**) along confidence intervals for the slope computed at the 66 percent alpha lines or approximately one standard deviation. The standard and mean absolute errors computed were similar. The mean cumulative error was positive indicating an overall underestimation of TL obtained using Model 1.

An adjustment to Model 1 is presented by incorporating the hydraulic conductivity into the predictions, to arrive at Model 2. Guided by Darcy's law [28, 31], the linear rates of the ratio of the hydraulic conductivity, or infiltration rates, for the stream in question and Walnut Gulch were determined and multiplied by the estimated transmission loss outflow volumes in Table **3**. Thus, if the values of K or infiltration rates are available (or can be estimated from stream bed characteristics per the previous discussion), the following equation may be used to adjust Model 1 prediction of the transmission loss:

$$\text{Model 2} \quad TL/km = 1.02(Vol)^{(0.75)}(K/K_{WG}) \qquad (4)$$

Where:

K = hydraulic conductivity or infiltration rate of the stream in question, and

K_{WG} = hydraulic conductivity or infiltration rate of Walnut Gulch

Table **3** displays the TL predictions for Queen Creek made using Model 1, Model 2, and Model 3. These three sets of predictions along with the computed TL values are shown graphically in Fig. (**6**).

Table **4** displays the TL predictions obtained using Model 1 and Model 2 for the Midwest Streams. There is a significant improvement in the Midwest transmission loss prediction when computed with Model 2. The SE, MAE, MCE, and the average percent error were all reduced by an order of magnitude. This was similar to the findings shown in Table **3** for Queen Creek, where sediment properties are included. The negative MCE values in Tables **3** and **4** indicate a tendency of the models to overestimate the true values.

6. COMPARISON OF MODEL 2 TO MODEL 3 ADAPTED FROM LANE (1983)

Equation 19.1 in [5] was used to predict the outflow volume for Queen Creek, without lateral inflow (Model 3). This equation is transcribed below:

$$TL = \begin{cases} 0 & \text{if } Vol \leq Volo \\ a + b*Vol & \text{if } Vol > Volo \end{cases} \qquad (5)$$

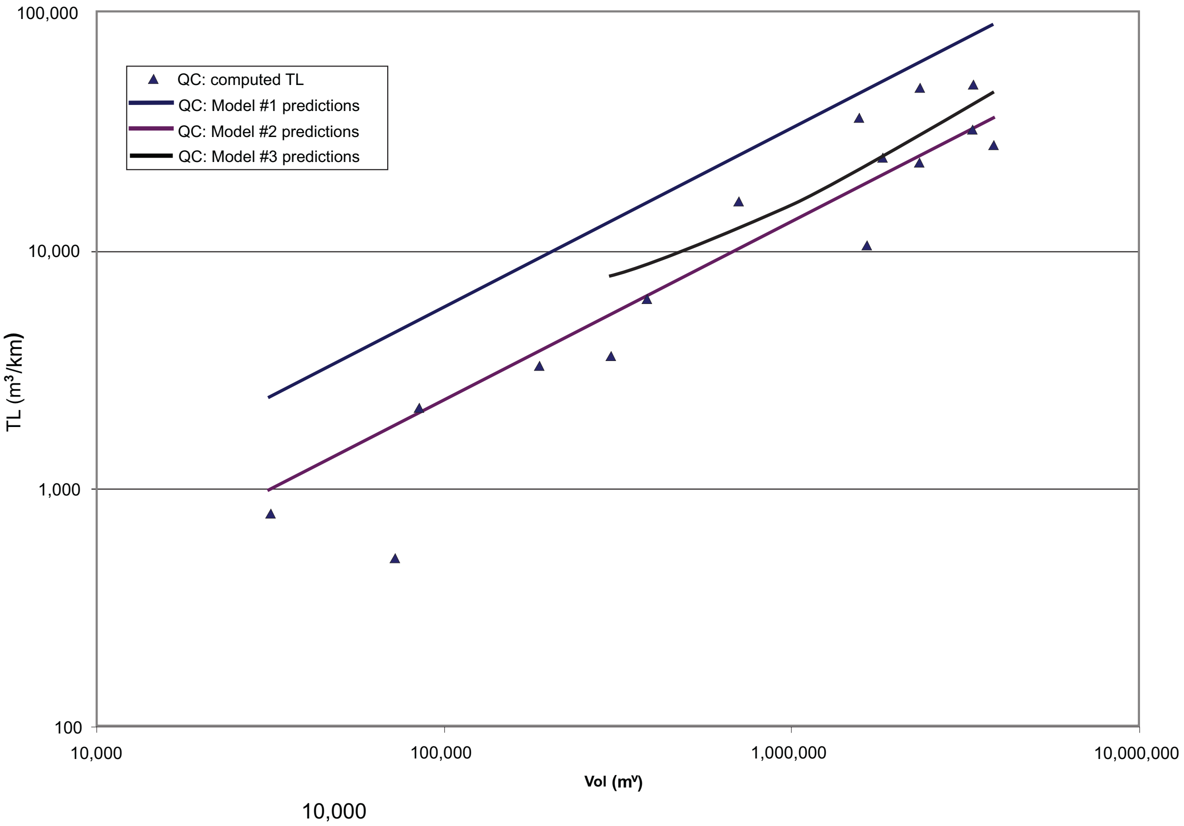

Fig. (6). Transmission Losses versus Inflow Volume for Queen Creek with prediction Models.

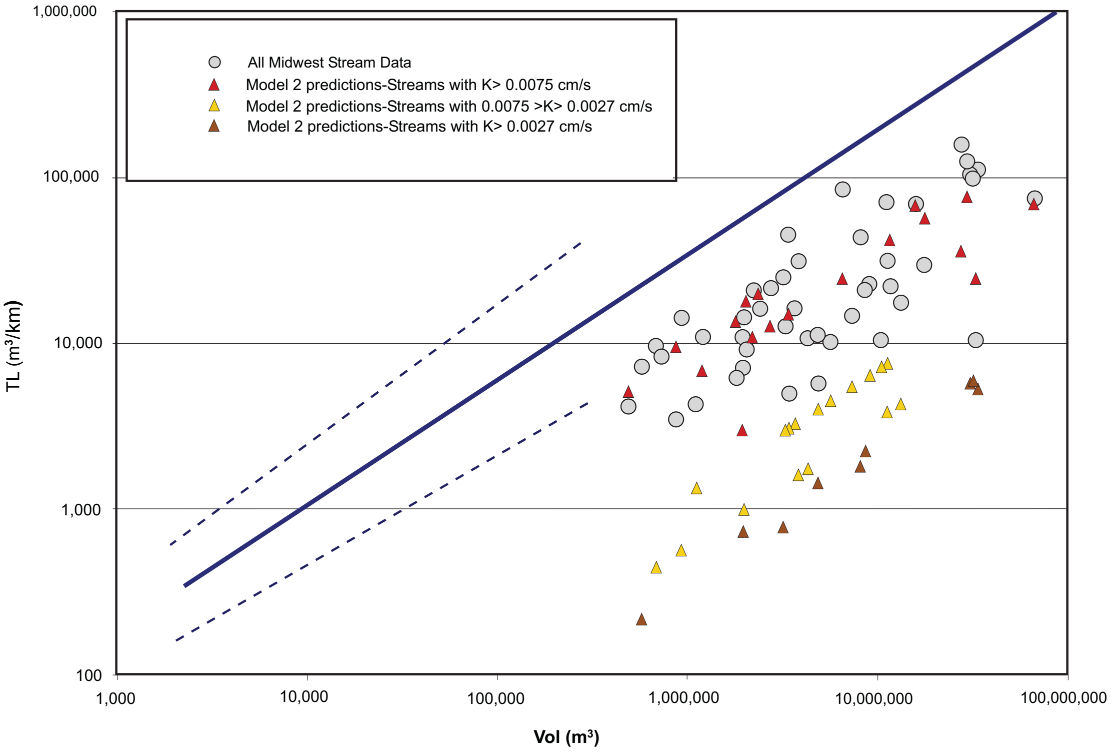

Fig. (7). Transmission Losses versus Inflow Volume for Midwest Streams with Model 1 Prediction line and 66 percent boundaries.

where Vol^o = -a/b. The coefficients for Equation 19.1 were given in Lane's Table 19.6 (a = -144,543 m^3 and b = 0.648). The inflow volume from Queen Creek [28] was used to determine the outflow volumes and the transmission losses per length of stream for the fifteen stream flows estimated. A statistical comparison of Lane's predictions and our Model 1 and Model 2 for the TL for Queen Creek is presented in Table **3**. Lane [5] incorporated the stream material in his method by using effective hydraulic conductivity (an infiltration rate *i*) of ephemeral streams in a decay factor. Our decision to include, *i* as an independent variable in Model 2 was based on Lane's initial efforts. Of the three sets of predictions, the Model 2 predictions result in the lowest overall SE, MAE, and average percent error. The MCE indicates that while Model 1 and Model 3 overestimate the transmission losses, Model 2 tends to result in underestimates. The average percent error of Model 2 (27.8%) is significantly lower than that of Model 1 (146.6%) and Model 3 (45.9%). Also evident in Fig. (**6**) is the limited range over which meaningful predictions can be made with Model 3. Because Lane's method produced negative, and therefore meaningless, TL/km values for the first four events listed in Table **3**, these were not used to determine errors. All fifteen values of inflow were used to determine the error for Model 2 predictions. A second set of error computations is also provided in Table 3 with the third TL for Queen Creek eliminated as a statistical outlier (this value was significantly lower than the mean observed TL). Even with this exclusion, Model 2 predictions result in the lowest overall SE, MAE, and average percent error. The trend in model bias is also similar. A comparison of TL/km predicted using Model 3 and Model 2 are shown in Fig. (**6**). For larger values of inflow volumes, Model 3 provides a reasonable approximation of the computed TL/km and a better estimate than Model 1. However, at lower ranges of the inflow volume (less than about 100,000 cubic meters), Model 3 yields negative values of TL/km (Table **3**). When Model 2 for the regression model (with K values included in this Equation) is used to estimate Queen Creek TL, shown in Fig. (**6**), the predicted values of TL/km appears to improve the predictions for the complete range of the inflows. Although Model 3 is more comprehensive than our regression Model 2, it yields predictions only over certain ranges of inflow values. It also requires more field data and time to estimate TL. Model 2 can be used to predict TL over the complete range of inflows measured at Queen Creek.

7. DISCUSSION

These findings suggest that over a wide range of flow, TL may be predicted with data on inflow volume or peak flow, consistent with the findings of other researchers [34]. To obtain the distance that water travels downstream from a point, inflow volume and TL/km are required. If inflow volume is unavailable at a site, then Equation 2 may be used to estimate it with data on peak inflow discharges. This is useful because peak inflow is a value that is often measured at gage stations, and therefore may be an easier parameter to obtain than the inflow volume.

The observed and predicted losses at Queen Creek data are plotted in Fig. (**6**). These data suggest similar trends to the WGEW, where the data are close in magnitude particularly for the peak inflow discharge curve. Model 1 over predicts TL when it is used to estimate transmission losses at Queen Creek. The TL value predicted using Equation 1 is almost one and a half times the computed value, as indicated

Table 2. Computed and Predicted Transmission Losses at Walnut Gulch

	Walnut Gulch	
Computed	**Model #1**	
TL	**TL**	**% Error (Difference/ Computed)**
m^3/km	**m^3/km**	
9,471.10	4,417.90	53.4
3,488.60	9,114.60	161.3
686.1	712.7	3.9
12,135.40	5,375.20	55.7
631.9	545.4	13.7
3,280.80	3,385.20	3.2
1,086.10	1,135.20	4.5
2,838.70	5,424.20	91.1
5,894.30	4,870.60	17.4
15,312.10	8,135.50	46.9
976.7	2,609.20	169.6
1,814.80	2,532.50	39.5
4,037.40	1,442.60	64.3
362.7	371.7	2.5
418.7	837.5	100
3,002.20	3,624.30	20.7
1,400.20	1,252.30	10.6
229.9	331.1	44
1,050.60	966	8
744.9	2,553.50	242.8
2,243.40	1,737.40	22.6
2,596.70	1,526.40	40.6
2,720.00	680.3	75
2,628.30	1,901.80	27.6
6,198.80	11,327.20	82.7
11,253.50	9,595.60	14.7
1,014.90	1,339.90	32
1,238.50	936.9	24.3
2,016.30	3,864.30	91.7
4,260.10	2,909.90	31.7
STANDARD ERROR		2,780.50
MEAN ABOLUTE ERROR		1718.9
MEAN CUMULATIVE ERROR		318.1
AVERAGE PERCENT ERROR		53.2

Table 3. Computed and Predicted Transmission Losses at Queen Creek

Events	Queen Creek Transmission Loss Predictions						
	Observations	**Model #1**		**Model #2**		**Model #3**	
	TL	**TL**	**% Error**	**TL**	**% Error**	**TL**	**% Error**
	m^3/km	**m^3/km**	**(Difference/ Computed)**	**m^3/km**	**(Difference/ Computed)**	**m^3/km**	**(Difference/ Computed)**
Q1	2,195.90	5,094.40	132	2,053.90	6.50	N/A	N/A
Q2	793.3	2,426.60	205.9	978.3	23.3	N/A	N/A
Q3	513.6	4,505.00	777.1	1,816.30	253.6	N/A	N/A
Q4	3,307.20	9,233.30	179.2	3,722.60	12.60	N/A	N/A
Q5	3,640.60	13,169.30	261.7	5,309.50	45.80	7,836.00	115.20
Q6	23,759.90	60,929.30	156.4	24,565.20	3.40	30,055.50	26.50
Q7	6,323.20	15,722.10	148.6	6,338.70	0.20	8,718.80	37.90
Q8	10,730.30	47,261.30	340.4	19,054.50	77.60	22,721.50	111.80
Q9	32,574.00	79,495.40	144	32,050.50	1.60	40,920.80	25.60
Q10	50,585.50	79,940.00	58	32,229.80	36.30	41,192.50	18.60
Q11	16,210.40	24,856.00	53.3	10,021.30	38.20	12,250.00	24.40
Q12	36,367.90	45,396.70	24.8	18,302.80	49.70	21,770.70	40.10
Q13	48,746.00	61,415.00	26	24,761.00	49.20	30,327.20	37.80
Q14	27,975.30	88,455.10	216.2	35,662.80	27.50	46,489.30	66.20
Q15	24,832.90	50,919.30	105	20,529.40	17.30	24,622.90	0.80
STANDARD ERROR	All Events		28,656.70		10,485.90		11,904.70
MEAN ABOLUTE ERROR			20,017.50		6,131.20		8,938.00
MEAN CUMULATIVE ERROR			(20,017.5)*		3,410.60		(469.0)*
AVERAGE PERCENT ERROR			188.6		42.90		45.9
STANDARD ERROR	All Events Except Q3		29,804.60		10,907.60		11904.7
MEAN ABOLUTE ERROR			21,162.20		6,476.10		8938
MEAN CUMULATIVE ERROR			(21,162.2)*		3,747.30		(469.0)*
AVERAGE PERCENT ERROR			146.6		27.80		45.9

*Negative values (in parenthesis) indicate overestimates of the mean cumulative error.

by the calculated average percent error. A better fit is achieved using the peak inflow discharge equation (Eq. 2), but in this case the percentage difference is about 77 percent (not shown in Table **3**).

When Model 3 is used for the Queen Creek data to estimate the transmission losses, the percent error obtained for the last eleven storms is approximately 46 percent (Model 3 gave percent error of less than 28 percent). Furthermore, Model 3 is only valid at high inflow volumes and therefore a less valuable planning tool than our Model 2.

Additional analyses were conducted to assess whether predictions improve for a particular set of streams. Because the streams with different bed characteristics may have different transmission losses, three different sets of error statistics were developed in Table **4**. The first set of error statistics includes all predictions. The second considers only streams with K greater than 0.0027 cm/sec. The third includes streams with K greater than 0.0075 cm/sec. The results indicate that TL predictions in streams with K values above 0.0075 cm/s improve in terms of bias (mean cumulative error) and overall performance (average percent error). As such

Table 4. Computed and Predicted Transmission Losses for Midwest Streams

Source	Name	State	Midwest Transmission Loss Predictions				
			Computed	Model #1		Model #2	
			TL m^3/km	TL m^3/km	% Error (Difference/ Computed)	TL m^3/km	% Error (Difference/ Computed)
< Jordan (1977) >	Prairie Dog Creek	KS	31,866.50	88,218.70	176.8	1,628.70	94.9
	Prairie Dog Creek	KS	10,789.20	96,225.20	791.9	1,776.50	83.5
	Prairie Dog Creek	KS	14,328.70	30,762.10	114.7	567.9	96
	Prairie Dog Creek	KS	9,698.50	24,395.80	151.5	450.4	95.4
	Prairie Dog Creek	KS	14,297.20	54,036.90	278	997.6	93
	Republic Creek	KS	43,574.80	155,205.40	256.2	1,830.60	95.8
	Republic Creek	KS	111,315.20	452,913.80	306.9	5,342.10	95.2
	Saline River	KS	6,217.90	50,428.10	711	13,447.50	116.3
	Saline River	KS	4,145.30	19,081.40	360.3	5,088.40	22.8
	Saline River	KS	68,980.30	257,217.90	272.9	68,591.40	0.6
	Smokey Hill River	KS	9,132.10	55,171.70	504.1	17,824.70	95.2
	Smokey Hill River	KS	16,209.50	61,826.70	281.4	19,974.80	23.2
	Smokey Hill River	KS	8,349.40	25,670.90	207.5	8,293.70	0.7
	Smokey Hill River	KS	3,457.20	29,377.90	749.8	9,491.30	174.5
	Sappa Creek	NE	124,449.10	412,993.00	231.9	76,244.90	38.7
	Sappa Creek	NE	21,022.60	58,604.60	178.8	10,819.30	48.5
	Sappa Creek	NE	10,774.10	37,316.60	246.4	6,889.20	36.1
	Sappa Creek	NE	44,782.40	80,893.20	80.6	14,934.10	66.7
	Sappa Creek	NE	84,506.30	132,890.10	57.3	24,533.60	71
	Sappa Creek	NE	21,591.90	68,835.40	218.8	12,708.10	41.1
< Sharp & Saxton (1962) >	Little Missouri River	ND	22,155.40	204,286.90	822.1	41,905.00	89.1
	Little Missouri River	ND	29,758.60	279,378.70	838.8	57,308.50	92.6
	Moreau River	ND	17,752.30	223,763.10	1,160.50	4,360.50	75.4
	Moreau River	ND	70,922.20	198,440.60	179.5	3,867.00	94.6
	Cimarron River	OK	22,988.50	169,158.90	635.8	6,506.10	71.7
	Cimarron River	OK	5,760.60	105,881.90	1,738.00	4,072.40	29.3
	Cimarron River	OK	14,479.50	144,301.20	896.6	5,550.00	61.7
	Cimarron River	OK	31,644.00	199,098.70	529.2	7,657.60	75.8
	Cimarron River	OK	10,266.50	118,600.00	1,055.20	4,561.50	55.6
	Cimarron River	OK	12,675.90	78,245.90	517.3	3,009.50	76.3
	Cimarron River	OK	4,981.90	80,981.70	1,525.50	3,114.70	37.5
	Cimarron River	OK	16,132.20	85,800.20	431.9	3,300.00	79.5
	Cimarron River	OK	10,482.30	187,909.60	1,692.60	7,227.30	31.1
	Cimarron River	OK	4,260.50	35,177.60	725.5	1,353.00	68.2
	Washita River	OK	7,051.30	53,707.60	661.70	743.6	89.5
	Washita River	OK	11,245.90	105,801.00	840.8	1,464.90	87
	Washita River	OK	20,903.10	162,661.90	678.20	2,252.20	89.2
	Washita River	OK	102,717.90	421,692.30	310.5	5,838.80	94.3
	Washita River	OK	98,648.70	430,623.90	336.50	5,962.50	94
	Shell Creek	NE	24,698.40	77,079.70	212.1	790.6	96.8
	Shell Creek	NE	7,293.60	21,397.80	193.40	219.5	97
	Little Blue River	NE	75,111.80	755,603.40	906	69,748.00	7.1
	Little Blue River	NE	155,895.40	390,977.50	150.80	36,090.20	76.8
	Cheyenne River	SD	10,551.40	448,001.50	4,126.90	24,701.60	134.1
	Cheyenne River	SD	10,806.90	53,656.80	396.5	2,971.80	72.5

Table 4. contd….

Source	Name	State	Midwest Transmission Loss Predictions				
			Computed	Model #1		Model #2	
			TL	TL	% Error (Difference/ Computed)	TL	% Error (Difference/ Computed)
			m^3/km	m^3/km		m^3/km	
STANDARD ERROR	Statistics considering predictions for all Midwest streams listed above				188,085		38,097.50
MEAN ABOLUTE ERROR					128,078.90		22,865.80
MEAN CUMULATIVE ERROR					(128,078.9)*		18,949.60
AVERAGE PERCENT ERROR					616.4		72.6
STANDARD ERROR					183,584.50		29,880.50
MEAN ABOLUTE ERROR	Statistics considering predictions for all Midwest streams listed above except for Republic Creek, Washita River, Shell Creek (with k>27*10^-4)				119,719.9		17,387.60
MEAN CUMULATIVE ERROR					(119,719.9)*		12,492.40
AVERAGE PERCENT ERROR					665.1		67.4
STANDARD ERROR					235,059.70		36,767.60
MEAN ABOLUTE ERROR	Statistics considering predictions for all Midwest streams listed above except Praire Dog Creek, Moreau River, Cimarron River, Republic Creek, Shell Creek, and Washita River (with k>75*10^-4)				141,700.80		20,134.70
MEAN CUMULATIVE ERROR					(141,700.8)*		10,859.60
AVERAGE PERCENT ERROR					596.9		63.6

*Negative values (in parenthesis) indicate overestames of the mean cumulative error.

predictions of streams with K greater than 0.0075 cm/s are more balanced with respect to over and under estimates than in streams with smaller K values. Standard error does not decline because one prediction (Little Blue River) is particularly poor and has a greater influence on the standard error statistic when the smaller K value streams are excluded.

Fig. (**7**) presents the data and modeling results from Table **4**. The volume and computed TL/km for all events in the Midwest streams are shown as gray symbols. The blue line represents the TL prediction that results when Model 1 is applied to this inflow volume range. The Model 2 prediction does not fall on a line because the Midwest data include multiple streams with different K values. Model 3 could not be applied to the 12 Midwest streams because Lane [5] did not provide parameters for all of these streams. Predictions of TL/km with Model 1 are greater than the values for the computed TL/km events. The Model 2 predictions are shown for three different sets of data: red symbols have K values greater than 0.0075 cm/sec; the yellow symbols have K values between 0.0027 cm/sec to 0.0075 cm/sec and the brown symbols with K values less than 0.0027 cm/sec. Comparing the Model 2 results it is apparent that predictions in streams with lower values of K have a tendency to be underestimated by the K-value adjustment. The permeability varies with the grain size and is sensitive to the quantity, character, and distribution of the finest fraction [35]. Therefore, Model 2 is also sensitive to these variables and does not predict TL values for streams when K approaches the fine silt and clay range.

Furthermore, the percent error improves from 72.6 percent when all of the streams are included in Table **4** to 67.4 percent when K values less than 0.0027 cm/sec (1.38 percent of K_{WG}) are excluded and 63.6 percent for K values less than 0.0075 cm/sec (3.85 percent of K_{WG}) are excluded.

8. CONCLUSIONS

It is beyond the scope of this study to examine all of the hydro-geological and hydraulic theories applicable to fully understand and accurately predict transmission losses. In addition, this study did not explore the reasons for such a large spread in TL at a given stream for similar inflow conditions. The approach has instead examined one- or two-parameter models of inflow Q_p, Vol, and hydraulic conductivity as a simplified method for estimating TL. While these parameters have a large influence, they may not provide sufficient information to predict TL on a broad scale.

The analyses presented here are valid only for the range of data in WGEW and Queen Creek and should be used with caution in other watersheds particularly for catchments with physical characteristics present elsewhere in the U.S. This procedure should be tested on other ephemeral streams in arid and semi-arid regions as well as for streams in other climatic regions.

The data presented here indicate that the larger values of the TL for the Arizona streams may in part be due to the physical characteristics of the stream bed as measured by the hydraulic conductivity. That is, larger TL corresponds with a larger percentage of gravel and sands in the beds and banks. When the sediment characteristics of the streams, defined by their hydraulic conductivity (K) or infiltration rate, are used to adjust the transmission losses (multiplying by the ratio of K values) the TL appear to follow the Walnut Gulch transmission losses curve and the prediction of TL/km are improved. Again, caution should be applied when using this approach, particularly for streams that do not share the same climate and bed material as Walnut Gulch, but the results appear to be promising.

The results indicate that discharge (either as total event volume or peak flow) and hydraulic conductivity are important factors affecting TL not only in the arid west but also in at least some Midwestern streams. Statistical models of simplified power equation(s), with further refinement and qualification (e.g., adjustment for stream flow regime, roughness, climate and/or sediment composition), ultimately may be an appropriate rapid assessment approach that could be applied on a routine basis. It is clear, however, that this analysis has not reached that point. Still to be determined are those other factors which are most important in predicting the rate of TL from readily measurable features in a local environment.

For purposes of Section 404 of the CWA, it is necessary that federal regulators determine that there is a “significant nexus” between an ephemeral stream and navigable waters of the United States [1]. Currently, the definition of “significant nexus” is still being disputed in the courts. However, to the extent that the magnitude of transmission losses in an ephemeral stream need to be estimated, the predictive equations developed here may be useful to regulators seeking to ensure compliance with Section 404 of the CWA.

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