An Analysis of Transmission Losses in Ephemeral Streams

A Case Study in Walnut Gulch Experimental Watershed, Tombstone, AZ

A Report to the
National Center for Housing and the Environment

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Executive Summary

Transmission losses (TL) are complicated phenomena that characterize the processes of evapotranspiration and infiltration as water moves down a channel. Infiltration-based losses may result from runoff overtopping channel banks and storage in depressions. This analysis focuses primarily on aggregate losses that occur within the channel. Expected losses due to evapotranspiration are added at the end to provide a perspective on relative contributions to TL.

The first phase study "Transmission Losses in Ephemeral Streams in the US" describes a large number of models to estimate TL. These models vary from phenomenological models to methods using differential equations and regression analyses. Among the findings are that TL have been shown to be related to: (1) flow duration; (2) channel length and width; (3) antecedent moisture content; (4) peak discharge; (5) flow sequence; (6) volume and characteristics of alluvium; (7) amount of colloidal material in suspension in the runoff; (8) watershed geometry; and (9) location and intensity of the isohyets of the watershed (Renard, 1970; Hedman and Osterkamp 1982).

Often models of TL that show the most promise require comprehensive data on the watershed and the stream to estimate TL (Goodrich, 2002). With the exception of experimental watersheds, these data rarely exist. An alternative approach to estimate TL in ephemeral streams is to develop a simplified procedure. Where data are available on upstream and downstream gages, it is desirable to estimate TL as the difference in flow volume at these tandem gages.

This study focuses on an experimental watershed, Walnut Gulch Experimental Watershed (WGEW), which has been actively studied for more than 50 years. WGEW is located in southeast Arizona and consists of subwatersheds that can be individually studied. The WGEW is a typical watershed in the region where the network of alluvium-filled stream channels represents a range of channel widths and slopes. The site has a network of stream and rain gages to facilitate accurate estimation of TL. In addition, the site is actively studied and accordingly, the data quality is good.

TL was estimated by subtracting outflow volume at a downstream gage from inflow volume at the upstream gage. Only storms that occurred upstream from the upstream gage were selected to prevent the introduction of lateral flows between the tandem gages. To compare estimates of TL between stream reaches, TL data were computed per mile and as a percentage of upstream flow.

Data for estimating TL in this study are obtained for several storms that produce runoff in several stream reaches. This analysis identified 6 storm events from which 12 TL estimates were obtained. These previously unpublished data were augmented with data from published reports of TL in WGEW. Other data used in this study come from a report of TL in Queen Creek, AZ, a creek located east of Phoenix, AZ. TL was estimated between two gages that were 20 miles apart. Data on 15 individual flow events are presented in the report. These data were used to compare findings at WGEW. An additional comparison of TL was conducted by examining data reported in two studies of sites in Midwest U.S.

Estimates of TL at WGEW range from 0.3 to 20 acre-feet/mile (af/m) and the percentage losses (compared to upstream flow) range from 4% to 100%. The losses for a given stream cover a large range. This range is an order of magnitude for WGEW and two orders of magnitude for Queen Creek.

When these transmission losses are modeled against the inflow volume (Vol) and/or peak inflow discharge (Q_p) a consistent pattern emerges. By using inflow Q_p, TL per length of channel appears to be consistently predicted between most gages in WGEW. In addition, volume of the inflow hydrograph can be used to predict TL per length of channel. One-parameter statistical models were developed using data collected in this report and data from previously published reports on WGEW. Estimated parameters in the predictive equations were obtained from a statistical analysis of TL and inflow characteristics.

The parametric models were then used to predict TL in Queen Creek based on upstream flows. Reasonable approximations of the published losses at Queen Creek were obtained from the predictive equations. The TL predictions using a model with inflow Q_p as the independent variable were better than the model using inflow Vol. In addition, a relationship between inflow Vol and Q_p was estimated to allow future assessments in streams that have only one of these data.

While these results are encouraging, caution should be taken when using this method for other watersheds because many factors can lead to site-specific differences. In Walnut Gulch, Queen Creek and several sites in Midwestern streams, the slopes of the lines describing the rates of TL are similar. However, the lower rates of TL reported for Queen Creek when compared to Walnut Gulch, were lower still in the Midwestern sites. A common link to explain these similarities and differences has not been found. Applications of our predictive model to these data would result in an overestimate of transmission losses.

To comply with the Clean Water Act (CWA) policy perspective regarding whether "an ordinary flow reach navigable water," TL rates (in af/m) must be converted to distance. The distance of interest must be the length of the stream measured from the point where flow starts to the point where the flow ceases. However, no relationship has been found between TL and this distance. An estimate of this distance can be obtained by assuming that transmission losses per mile are relatively constant as the flow moves downstream.

It is beyond the scope of this study to examine the hydro-geological and hydraulic theories applicable to fully understanding transmission losses and why there is such a large spread in the data at a given stream for similar inflow conditions as well as the explanation of the physical meaning of the coefficients in the predictive equations. Clearly, the use of one parameter (inflow Q_p or Vol) is a simple approach to defining such a complicated phenomena as transmission losses. While this one parameter has a large influence, it does not provide sufficient information to predict TL on a broad scale. Therefore, the next logical step is to conduct a comprehensive analysis of the data from an experimental station such as Walnut Gulch. This analysis would involve an expanded regression of variables, such as: intake rates of sedimentation, location of rainstorm, antecedent conditions, surface yield, canopy coverage, magnitude and sequence of discharge, and other hydrologic, hydraulic, climatic, and geologic conditions.

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1. Introduction

1.1. Background

The Clean Water Act (CWA) defines "navigable waters" as "the waters of the United States." The Corps of Engineers (COE) uses a number of definitions and policies to define its jurisdictional limits under Section 404 of the CWA. Key to all inland determinations is the term "ordinary high water mark" (OHWM), which is used to define the "limit of jurisdiction," suggesting that if a waterbody having an OHWM is morphologically connected, it is a "tributary" to navigable waters, and therefore, subject to CWA jurisdiction. The COE currently defines the term as:

> ...that line on the shore established by the fluctuations of water and indicated by physical characteristics such as clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas [33 CFR 328.3(e)].

The COE routinely decides the presence of an OHWM with generally no consideration of whether "ordinary" or any other measurable flows actually reach navigable waters, (Pierce 2003). The CWA defines most anthropogenic conveyances as "point sources." Increasingly, the COE 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 "ordinary" flows through them ever reach navigable waters. What constitutes "ordinary" flow, while having a long history, is at the present not quantified.

In considering the longitudinal limit of federal authority, one consideration must be whether ordinary flow reaches navigable waters. A major element of that analysis is transmission losses that occur as water flows from its point of origin to its ultimate surface extent. An earlier literature review examined the state of the science for measuring and predicting the loss of water (i.e., transmission losses) from morphologically-defined channels as it flows downslope towards navigable waters (Cataldo, et al. 2004). This study examines empirically derived data to assess the viability of development of a readily applied method for estimating transmission loss for ephemeral streams in the arid southwest. The ultimate goal is the formulation of a process that would allow an individual to use existing data to estimate whether "ordinary" flow will reach navigable waters.

1.2. Scope of Study

The scope of work for this project involved estimating transmission losses (TL) for six storm events. As part of this effort, sub-tasks included (a) selecting one or two ephemeral streams for analysis from a county in the southwest U.S.; (b) determining the lag time between successive gauges at low, moderate, and high flows for the two streams; (c) determining likely sources and volumes of inputs between gauges using water resources models; and (d) computing transmission losses at low, moderate, and high flows.

Upon exploring the data availability in several areas in Arizona, the experimental watershed at Walnut Gulch, AZ was selected as offering the best representation of TL. This conclusion was

based on the quality of the data available at the site, the length of the data record and the variability in stream characteristics. In addition, modeling complexities of transmission losses could be reduced and would thereby enhance the quality of the results. For example, a water resources model need not be implemented because it was possible to select storms that occurred upstream from the upstream gage. In addition, transmission losses could be computed without having to estimate lag times between gages. Instead, a direct estimation of transmission losses was possible by subtracting downstream volumes from upstream volumes.

Transmission losses could be computed with reasonable accuracy using this simple method. In addition, because estimating TL was straightforward and the watershed offered a variety of sub-watersheds to examine, more TL estimates were obtained than had been originally anticipated. These additional data were added to a dataset of existing TL estimates that were available from published studies. This combined set of data provided a basis for conducting a statistical assessment of TL in that region.

This report summarizes information about the watershed, the data used in this study and the analysis of TL. Several tables and charts present TL estimates and their subsequent analysis as well as more detailed information about the watershed, storms chosen for analysis and the hydrographs of flows in the channels.

1.3. Site Description

1.3.1 Walnut Gulch

Walnut Gulch is located in Cochise County, in southeast Arizona at 31.72 N, 110.68 W (Figure 1). It is an ephemeral tributary to the San Pedro River basin, which originates in Sonora, Mexico. The San Pedro River drains in a northerly direction to its confluence with the Gila River approximately 120 miles distant. From its confluence with the San Pedro River, the Gila River is morphologically connected to the Colorado River (a navigable water) approximately 360 miles west.

The Walnut Gulch Experimental Watershed (WGEW) is a 58 square mile area located in the Southeast AZ, (Figure 2). Altitudes range from 4,000 – 6,200 feet above sea level. This watershed is a transition zone between the Chihuahua and Sonoran Deserts.

WGEW has been actively studied for more than 50 years (Renard and Nichols, 2003). The watershed is typical for the region and consists of a network of alluvium-filled stream channels that include a range of channel widths and slopes. In addition, because the site is actively studied in a research context, it provides a higher level of data quality and assurance.

Figure 1: Map of Arizona

This map shows the locations of Walnut Gulch, the confluence of the San Pedro and Gila Rivers, Queen Creek and the confluence of the Gila and Colorado Rivers. (Delorme, Topo usa 5.0).

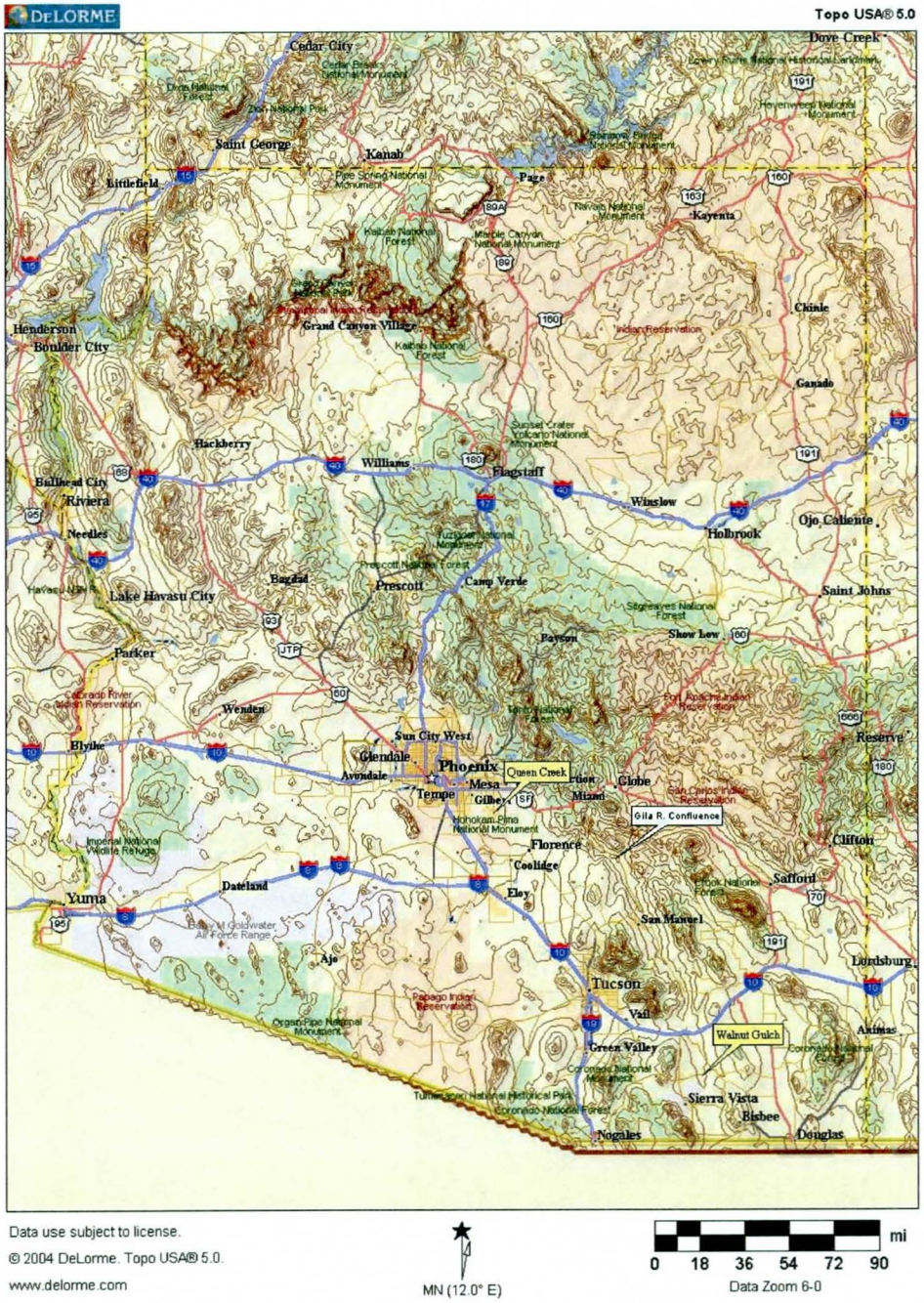
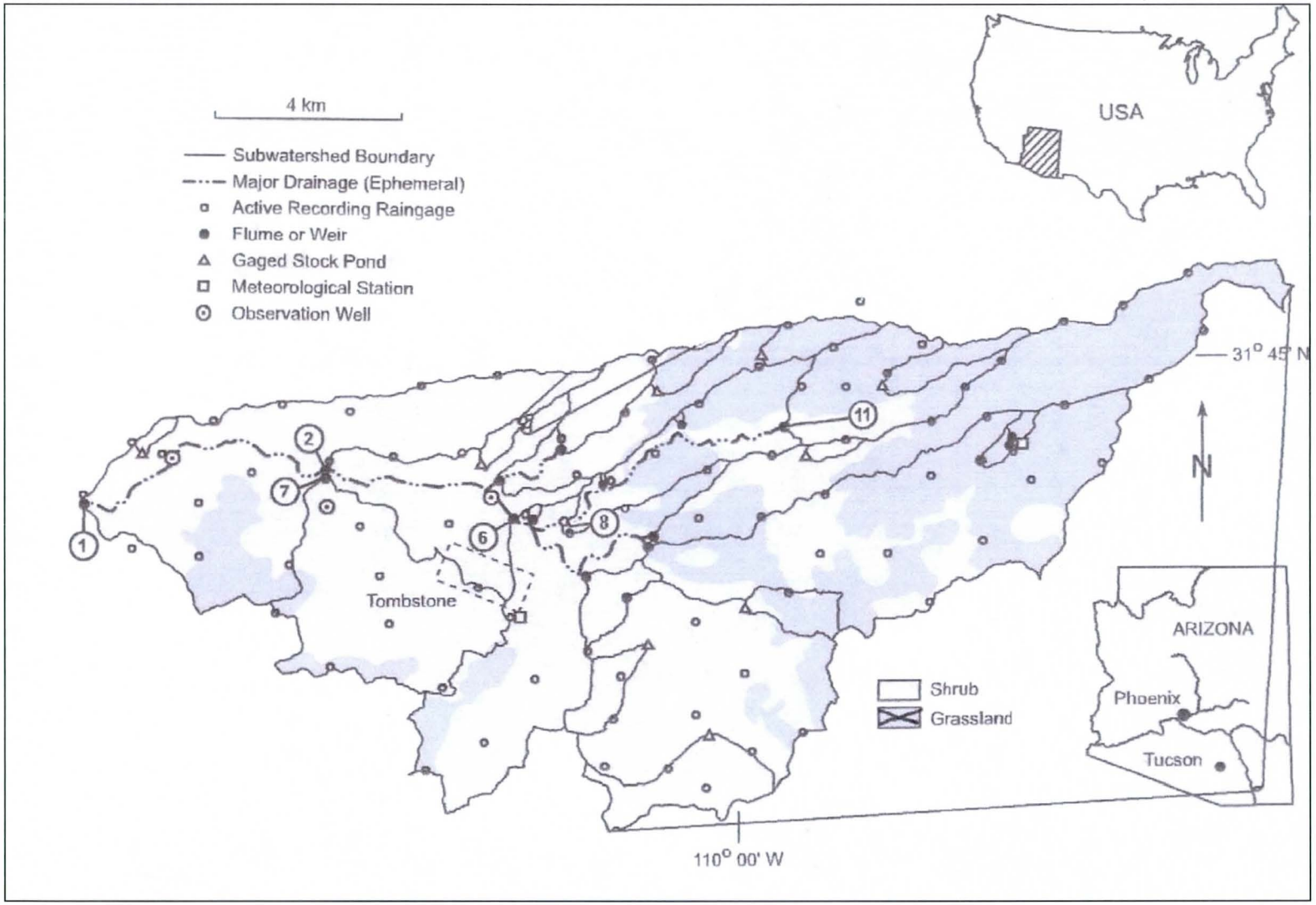


Figure 2: Walnut Gulch Experimental Watershed, AZ. (Goodrich, et al., 2004)

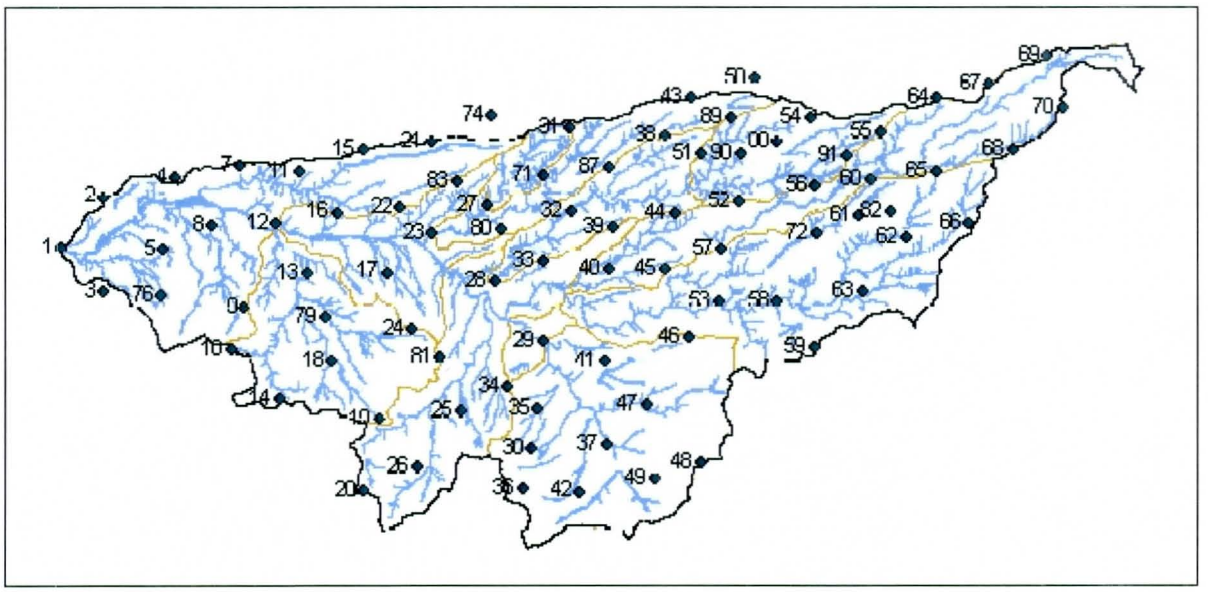


Vegetation in the WGEW consists of a brush and grass-covered rangeland that is found throughout the semi-arid Southwest U.S. Stream channels are generally wide, shallow, flat-bottomed and filled with coarse, clean, sandy gravel that overlie conglomerate bedrock.

The climate is classified as semi-arid with mean annual temperature at 17.7 degrees C and mean annual precipitation of 13.8 inches (Walnut Gulch Brochure, 2003). Virtually all of the runoff occurs from summer thunderstorms (about 90%) during July and August, which tend to fall in intense bursts (Lane, et al. 1971). Rainfall is measured with 88 weighing-type rain gages that are distributed throughout the watershed (Figure 3).

Figure 3: Rain gages Stream Network, and Major Sub-watersheds

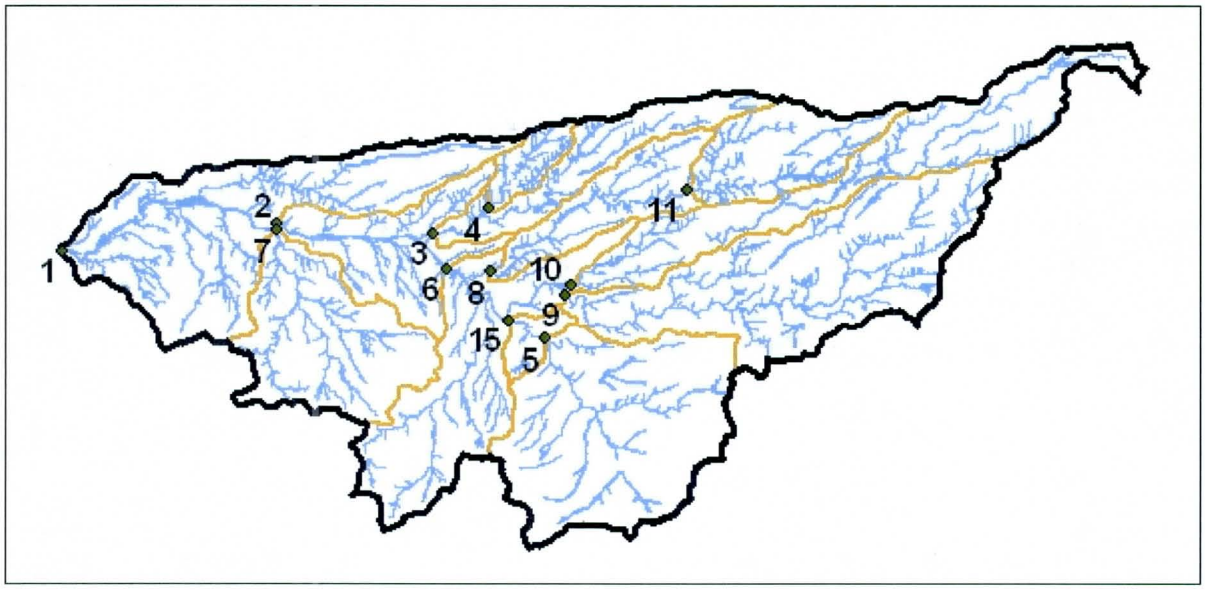
Rain gages are numbered 1-91; the stream network is depicted by blue lines; major sub-watersheds are outlined by yellow lines. Data from WGEW (Walnut Gulch, 2004).



Runoff from the watersheds that are greater than 99 acres is measured using either staff gages located in livestock watering flow-through ponds or large, in-channel, supercritical flow flumes. The watershed is divided into sub-basins by flow-measuring flumes at various locations within the stream network (Figure 3). The runoff-measuring network has over 15 gages; some of these locations are shown in Figure 4.

Figure 4: Stream gages, Stream Network, and Major Sub-watersheds

Stream gages are numbered 1-15; the stream network is depicted by blue lines; major sub-watersheds are outlined by yellow lines. Data from WGEW (Walnut Gulch, 2004).



The largest flume at the outlet of the WGEW has a flow capacity of 23,000 cubic feet per second (cfs). These flumes isolate seven channels segments where TL magnitude can be measured by comparing the hydrographs at the up and downstream stations of a reach for a storm event with all runoff originating above the upper station. All locations are automatically and sequentially queried and data are transmitted to a dedicated computer at the Tombstone field office on a daily basis (Walnut Gulch Brochure, 2003).

This study examines flow in several channel reaches in the watershed (Figures 2, 4). Stream Reach 1 begins at Flume 11 and continues through Flume 8. Stream Reaches 2, 3, and 4 begins at Flume 8 and proceeds through 6, 2 and 1. Stream reach 1 is about a quarter of the width of reach 4 (Table 1). The difference in flows between these reaches can be between 2 to 4 times, with larger flows occurring downstream.

Table 1: Stream reach descriptions

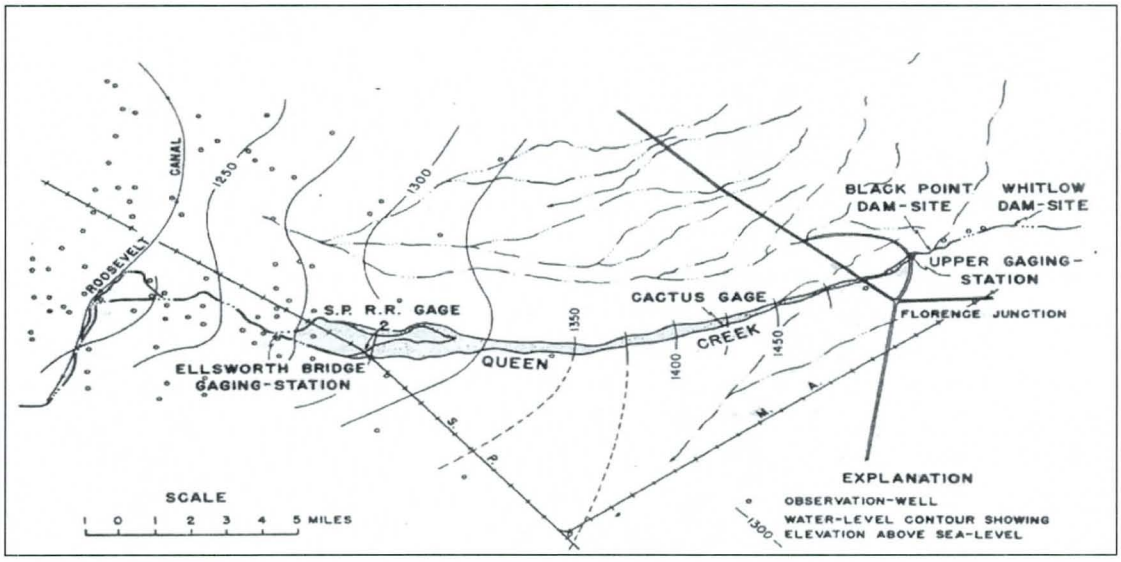
WGEW				
Stream Reach (ID#)	Stream Reach (Upstream – Downstream Flumes)	Reach Length (miles)	Contributing Watershed (miles^2)	Channel width (ft)
1	11 – 8	4.1	5.7	38
2	8 – 6	0.9	36.1	68
3	6 – 2	2.7	43.2	107
4	2 – 1	4.2	57.1	132
Queen Creek				
1	UG – EB	20	Not available	277

Sources: Lane (1983); Renard (1970)

1.3.2 Queen Creek

A second pair of gaging stations, located on Queen Creek (Figure 5), crossing Maricopa and Pinal Counties and located between Phoenix and Superior, AZ was selected to (a) compare TL with WGEW and (b) explore whether a TL model developed from WGEW data could predict TL at Queen Creek. Queen Creek is a large desert wash watershed in the Pinal Mountains. The stream passes over the desert in a southwesterly direction toward Chandler, AZ. The flow of the stream consists almost entirely of quick storm events common to the deserts of that region. For the storm events considered in this study, the stream was deposited with gravel, sand, and silt cover with the sediment becoming finer outward from the mountains. Data on stream flows and transmission losses was derived from Babcock and Cushing, 1941. The upstream gage (UG) is located near the Black Point Dam-Site and the downstream gage is near the Ellsworth Bridge (EB) (Figure 5).

Figure 5: Queen Creek, AZ. Source is Babcock and Cushing (1941)



2. Methods

The TL magnitude was computed by comparing the measured hydrographs at the upstream and downstream stations of the channel reach for storm events with all runoff originating above the upper station. Transmission loss rates per mile were computed by dividing the TL by the length of the reach to facilitate comparison of streams of different lengths.

A statistical relationship is found between transmission losses per length of stream and inflow volume and inflow peak discharge, respectively. These one-parameter statistical models used a linear regression on data that was converted by a log-transformation (i.e., the fitted model used the log of the data, not the data itself). This model is in a class of models called "log-log" because both the dependent and independent variables have been log-transformed. In log-log form, the model is essentially a standard linear regression with parameters for the intercept and slope. A reason for taking a log-transformation of the data was that transmission losses did not appear to have a linear variation with inflow volume and inflow peak discharge.

Statistical models can be compared with respect to their goodness-of-fit in several ways. A common measure uses the Pearson correlation coefficient, R^2, which provides an assessment of how well the independent variables in the model explain the values of the dependent variables. R^2 values range from 0 to 1 and higher values normally correspond to better predicting models. Another measure, p-values, can be used in hypothesis testing to assess whether a parameter in the model is statistically significant. In this case, low p-values indicate that the independent variable has a highly significant relationship to the dependent variable. P-values that are sufficiently small may be reported to have a level of significance at a particular level, say 5% or 1%.

3. Results and Discussion

3.1. Data Description

This analysis used several stream discharge events that flowed between two tandem gages, an upstream and a downstream gage. Only stream flows that occurred successively in both gages were selected. In addition, selected storm events were those that generated stream flows above the upstream gage and did not produce additional tributary flow or overland flow between the tandem gages. To ensure that there was no lateral flow entering a stream reach, storm events were excluded if runoff resulted from rainfall within the downstream gage watershed (see isohyets shown in Figures 6-11) Runoff was not produced from areas that received 0.2 inches of rainfall or less (Lane, et al. 1971). Data collected in this analysis includes previously unpublished flows in Reaches 2 – 4 (Table 2).

Table 2: Previously unpublished Data for WGEW

Storm #	TL #	Date	Stream Reach
1	1	8/29/1961	4
2	2	7/18/1965	4
2	3	7/18/1965	3
2	4	7/18/1965	2
3	5	8/5/1968	4
3	6	8/5/1968	3
3	7	8/5/1968	2
4	8	8/9/1970	4
5	9	7/18/1985	4
5	10	7/18/1985	3
6	11	9/25/1994	4
6	12	9/25/1994	3

Figure 6: Isohyets - Storm 1, 8-29-61; Flumes 2,1

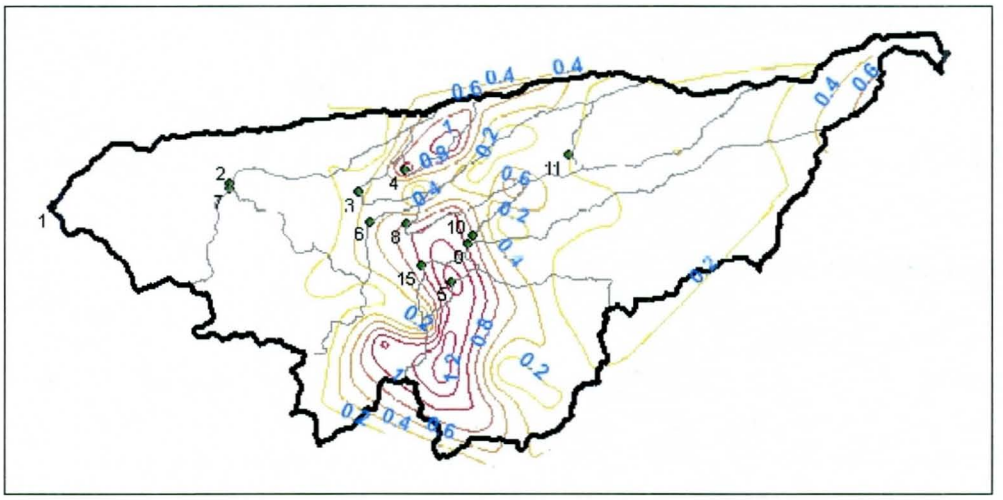
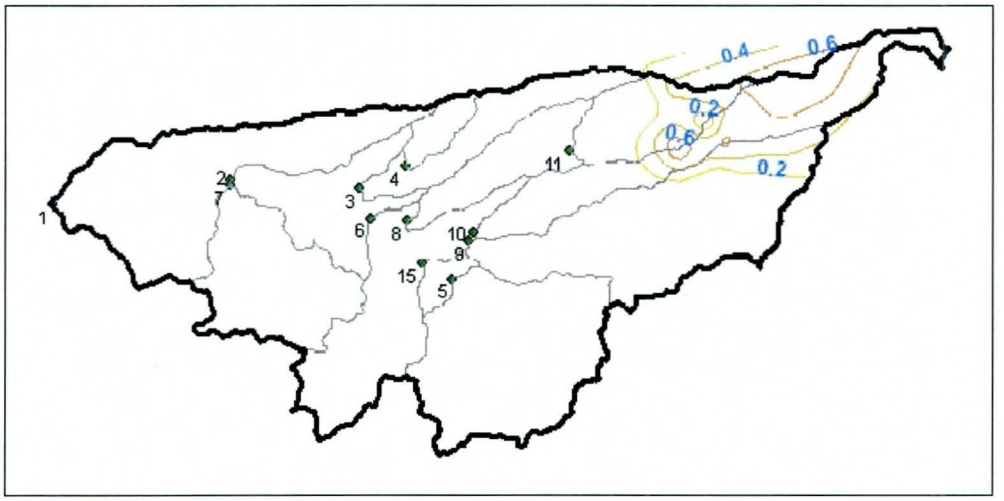


Figure 7: Isohyets - Storm 2, 7-18-65; Flumes 8,6,2,1



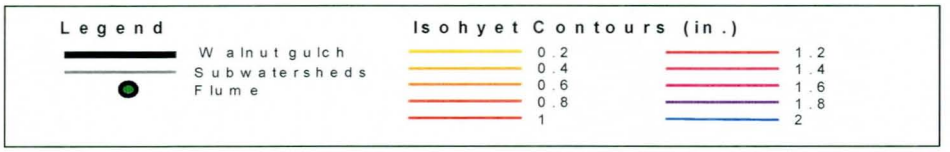


Figure 8: Isohyets - Storm 3; 8-5-68; Flumes 8,6,2,1

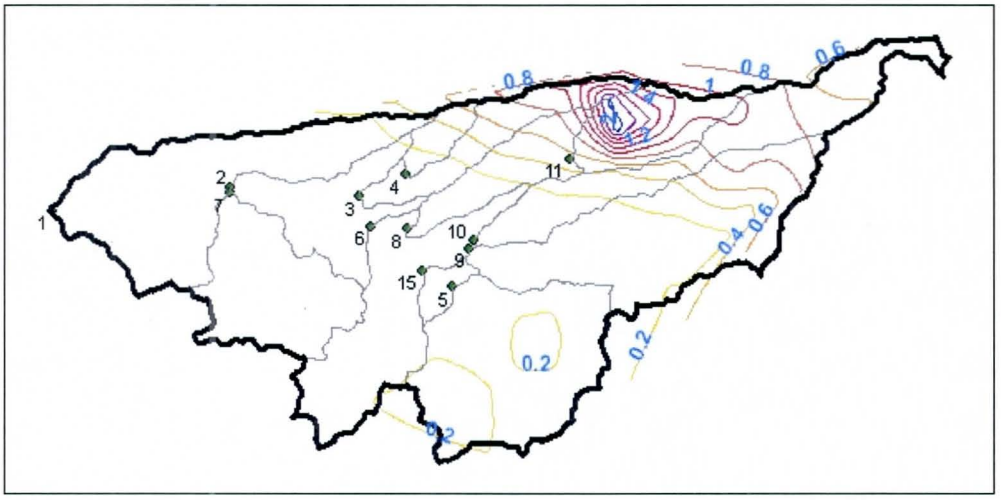


Figure 9: Isohyets - Storm 4; 8-9-70; Flumes 2,1

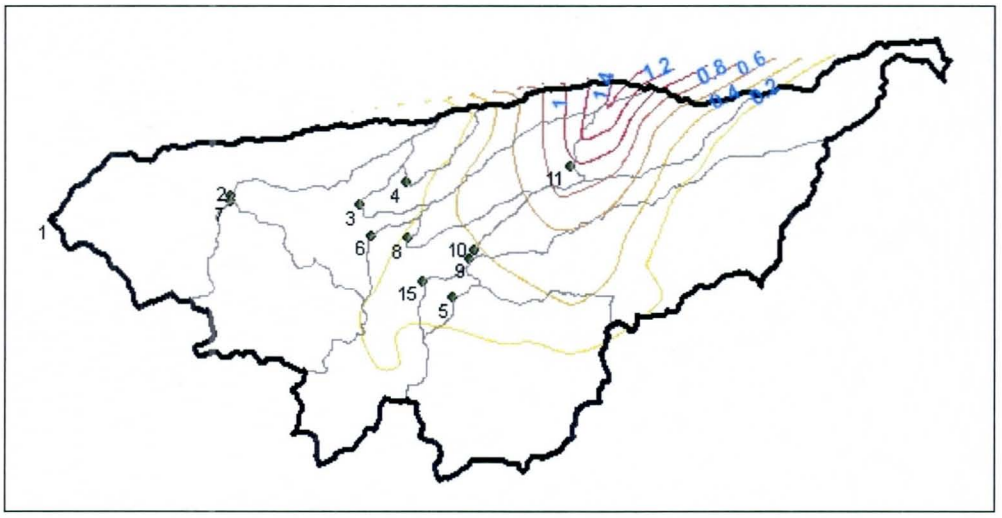


Figure 10: Isohyets - Storm 5; 7-18-85; Flumes 6,2,1

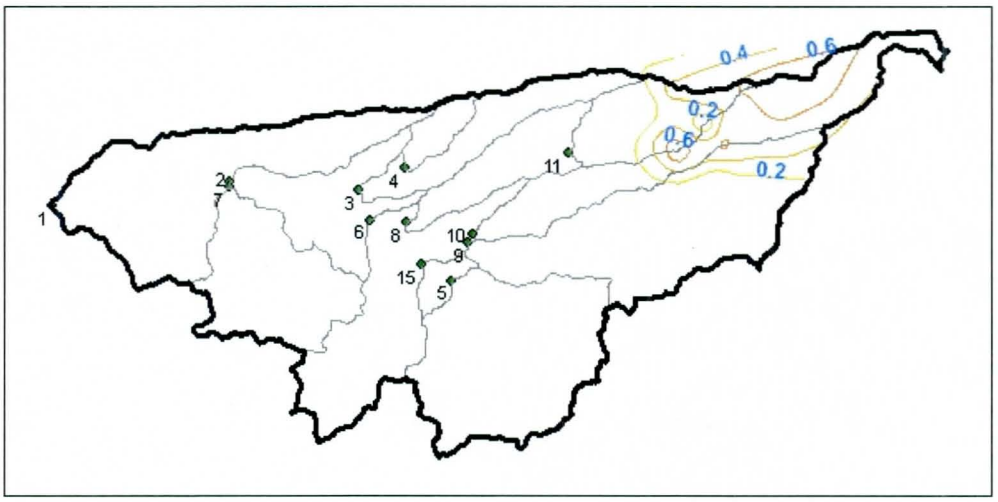
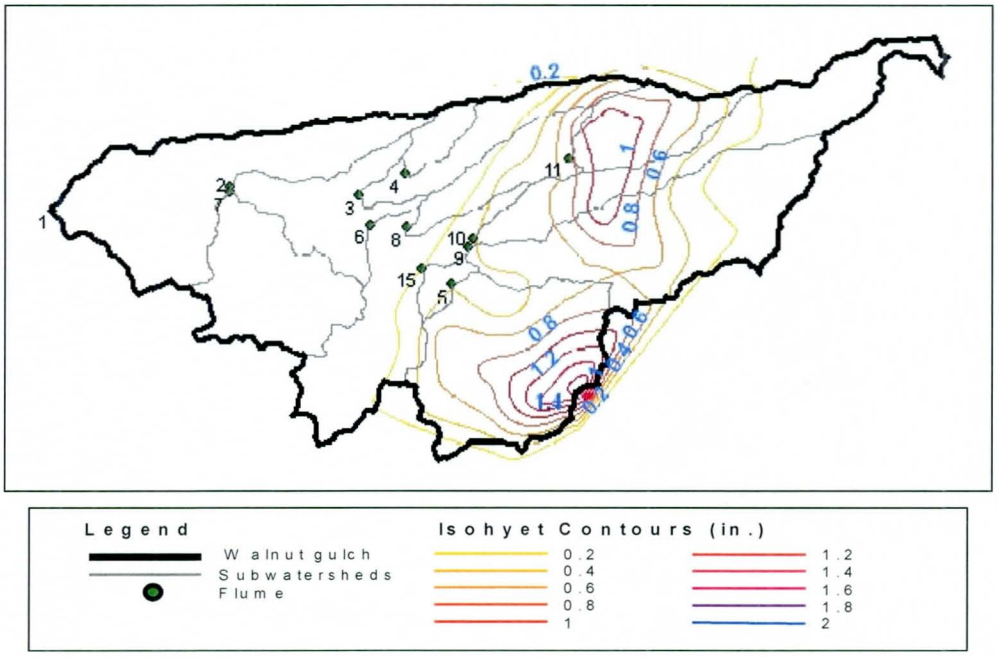


Figure 11: Isohyets - Storm 6; 9-25-94; Flumes 6,2,1



Lateral flows, when they exist between two tandem gages, can be estimated with water resource models (WRM) such as HEC-1 and KINEROS2 (Cataldo, et al. 2004). The difficulty in using these methods is the inherent error in predicting model input parameters. By only considering storms above the upstream gage, this difficulty was eliminated.

The need to apply a WRM was avoided in this analysis by selecting storms by location and range of rainfall depth. For example, extremely large storms could produce runoff that overtops stream banks and spreads runoff overland. Having an unknown volume of water exceeding the channel banks would add another factor of complexity to estimating the infiltration component of TL. Furthermore, from a CWA policy context, such extremely large flows would not be considered "ordinary" and, therefore, should not form the basis for Section 404 jurisdiction. The determination of overland watershed infiltration is difficult and has similar modeling problems as lateral inflow.

Stream flows that are too low can cause depth-discharge relationships to be inconsistent (Thomas and Benson, 1975). Previous studies have indicated that low discharges have cross-section flows that depend on the configuration of the sand and gravel bars laid down by preceding flows (Keppel, 1960). The acceptable range of peak discharges varied between stream sections and was based on previous studies on the WGEW (Lane, 1971).

Storms chosen in this dataset represent a diversity of intensity, spatial extent, and duration (data on storms are presented as Isohyets in Figures 6 – 11 and as hydrographs in Figures 12-17). For example, while Storms 2 and 3 are centrally located high in the watershed (Figures 7 and 8), Storms 1 and 6 span the North-South range of WGEW (Figures 6 and 11). Storms 1 and 6 experience two distinct peak flows (Figures 12 and 17) whereas Storms 2, 3 and 4 have exaggerated single peaks (Figures 13, 14 and 15). Storms 4 and 5 (Figures 15 and 16) are relatively small whereas Storm 1 (Figure 6) is quite large. An additional feature of these data is that Storms 2 and 3 are large enough to flow from Flumes 8 to 1. Storm 3 is also used by Lane (1971) for Stream Reach 1 (Gages 11-8).

Figure 12: Hydrographs - Storm 1, 8-29-61; Flumes 2,1

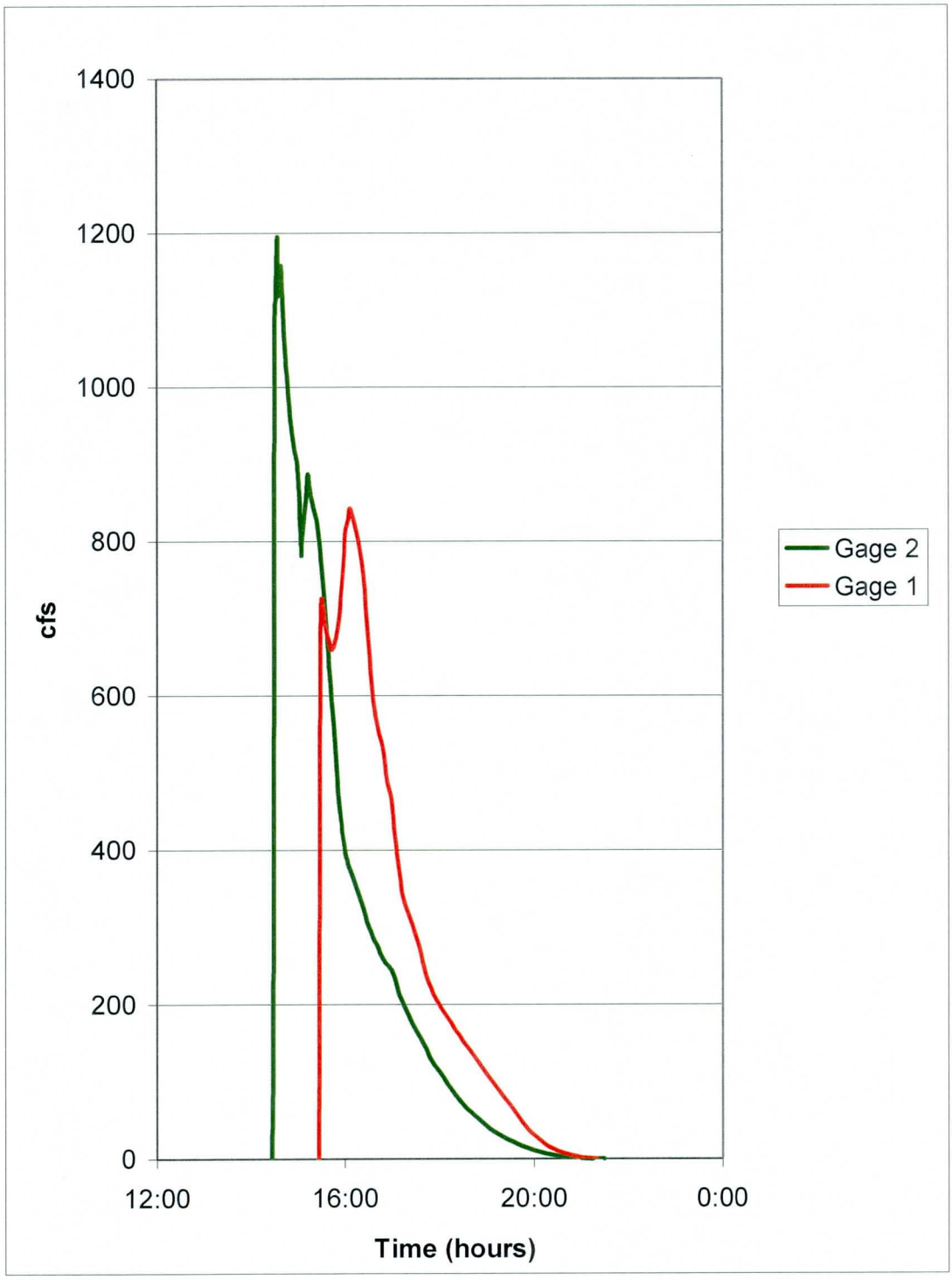


Figure 13: Hydrographs - Storm 2, 7-18-65; Flumes 8,6,2,1

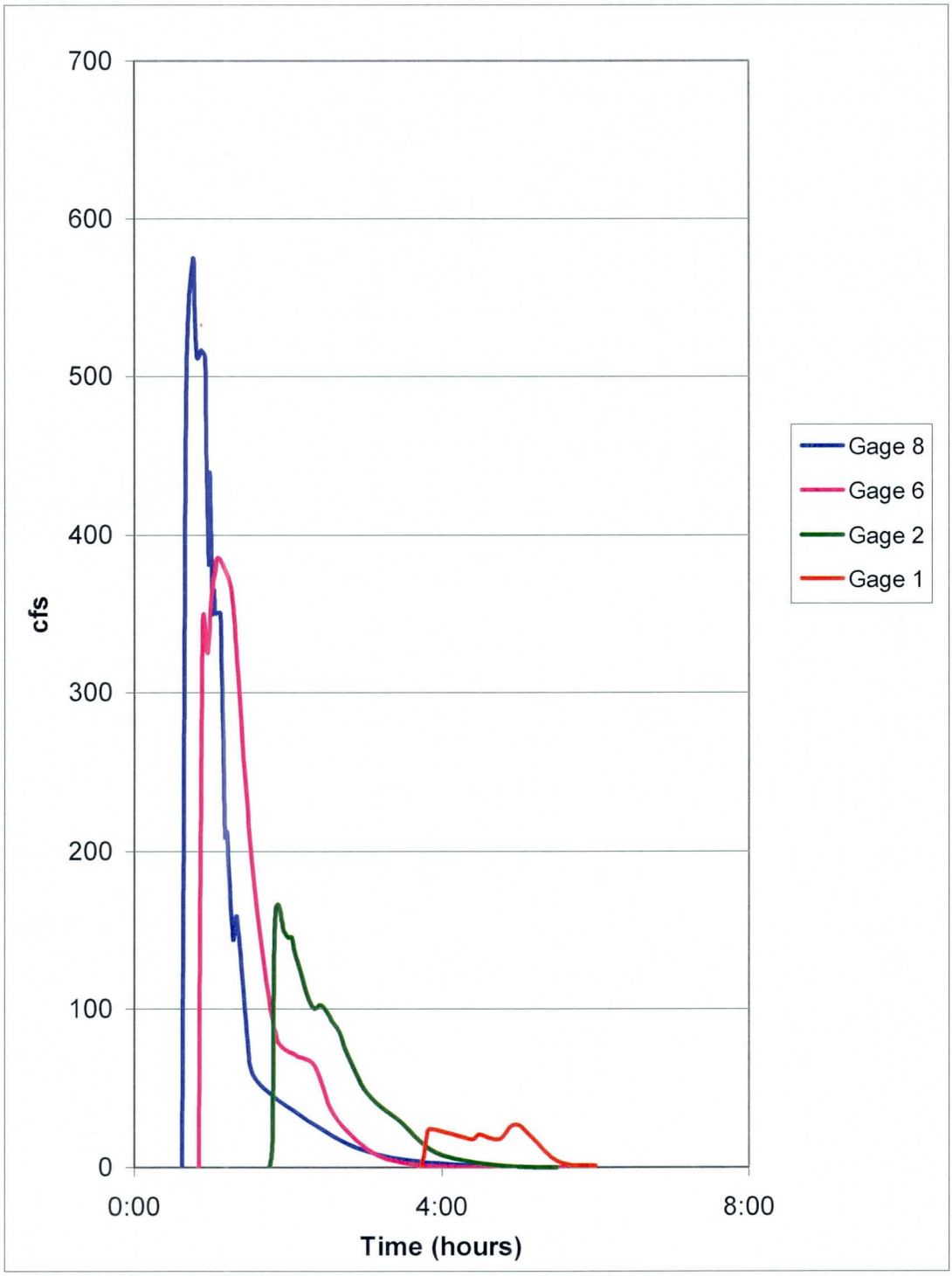


Figure 14: Hydrographs - Storm 3; 8-5-68; Flumes 8,6,2,1

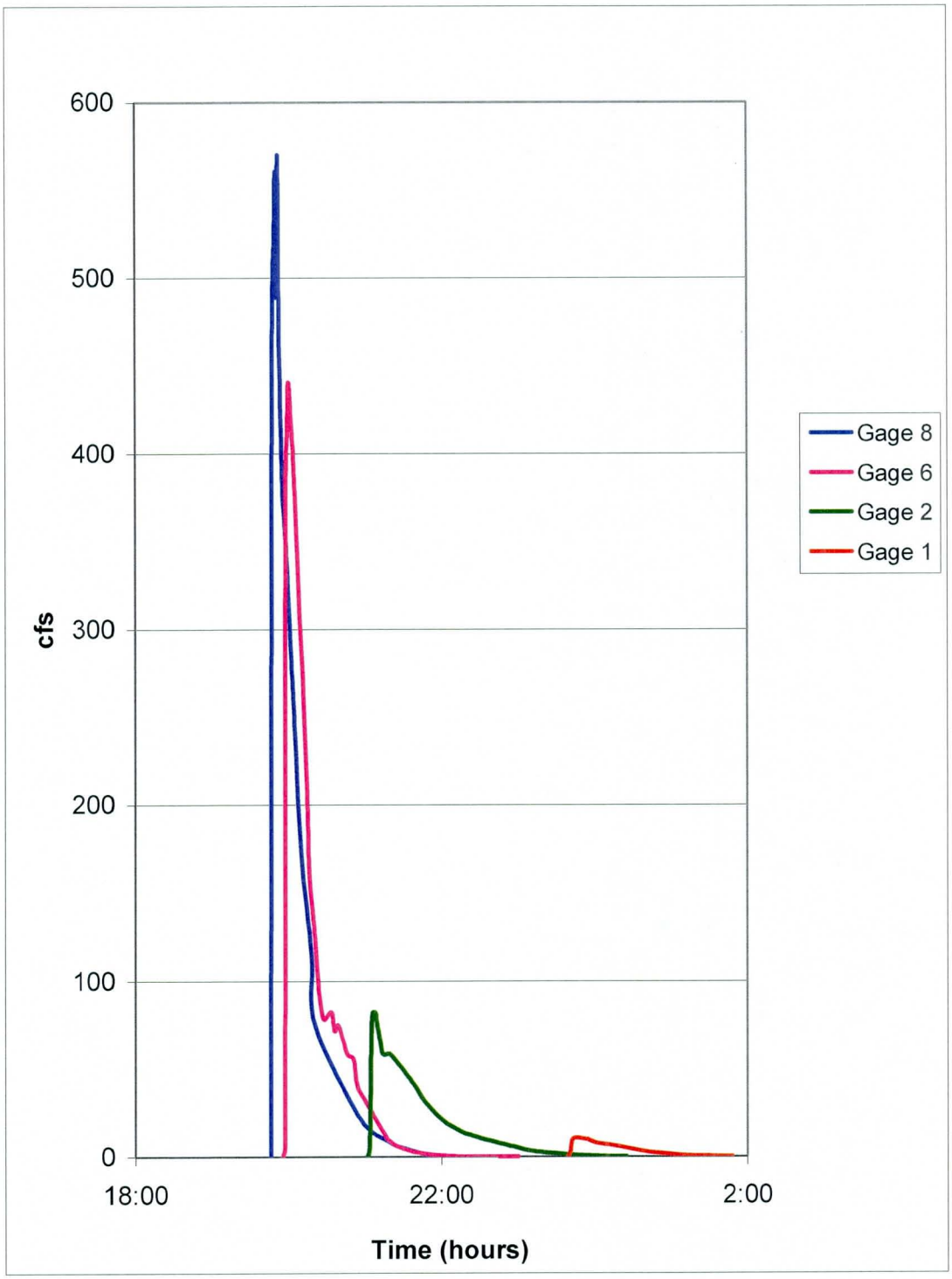


Figure 15: Hydrographs - Storm 4; 8-9-70; Flumes 2,1

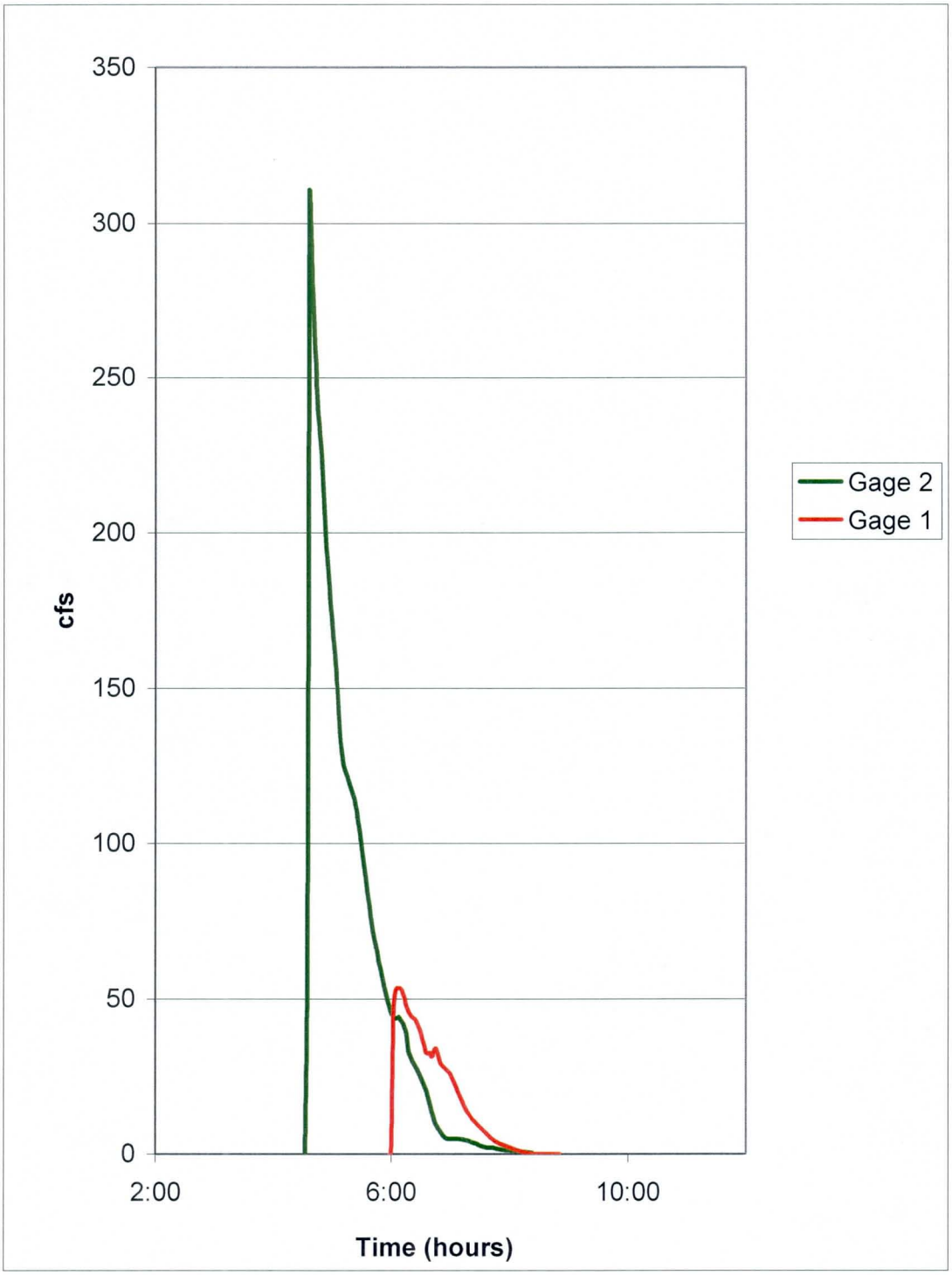


Figure 16: Hydrographs - Storm 5; 7-18-85; Flumes 6,2,1

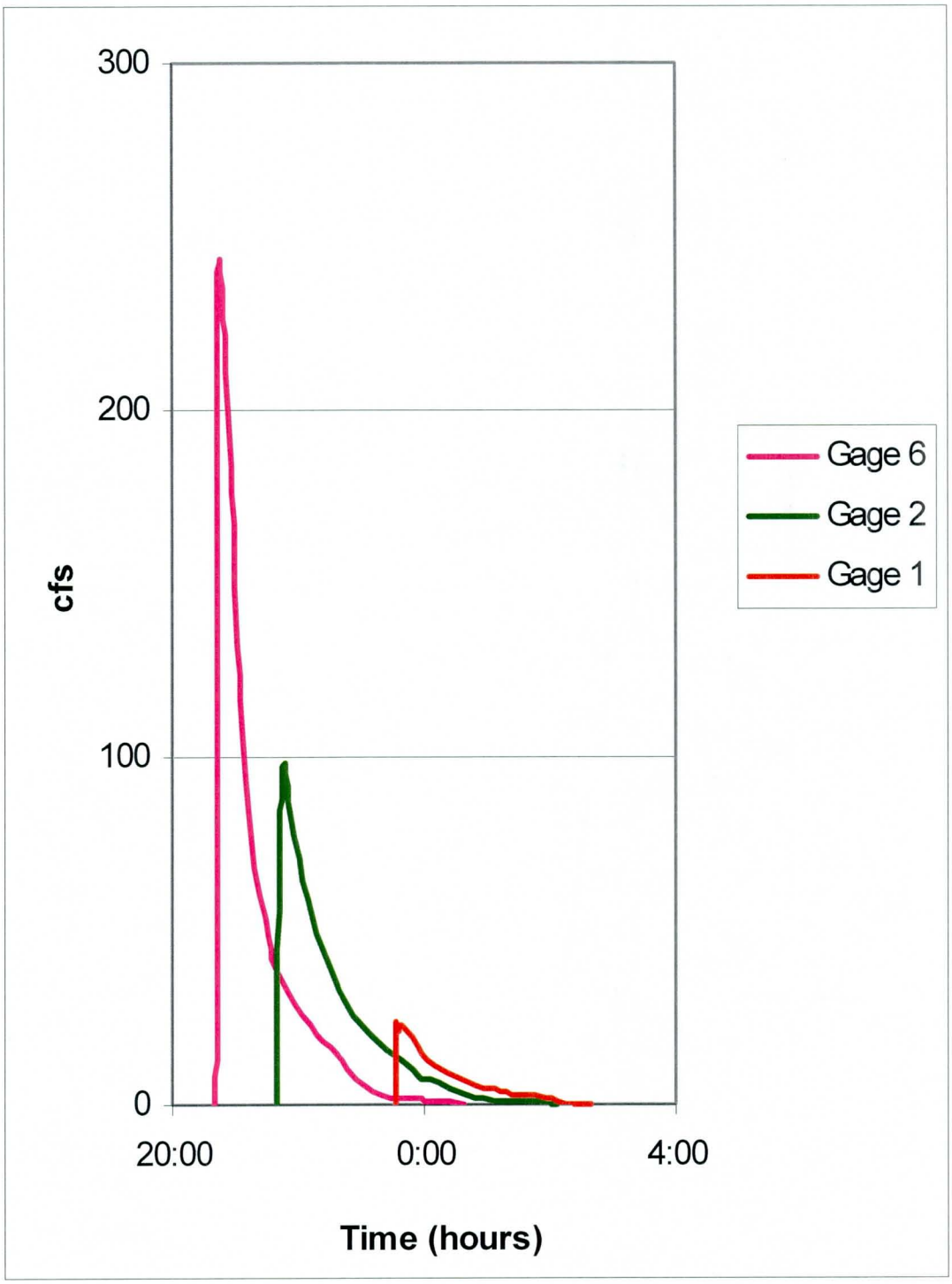
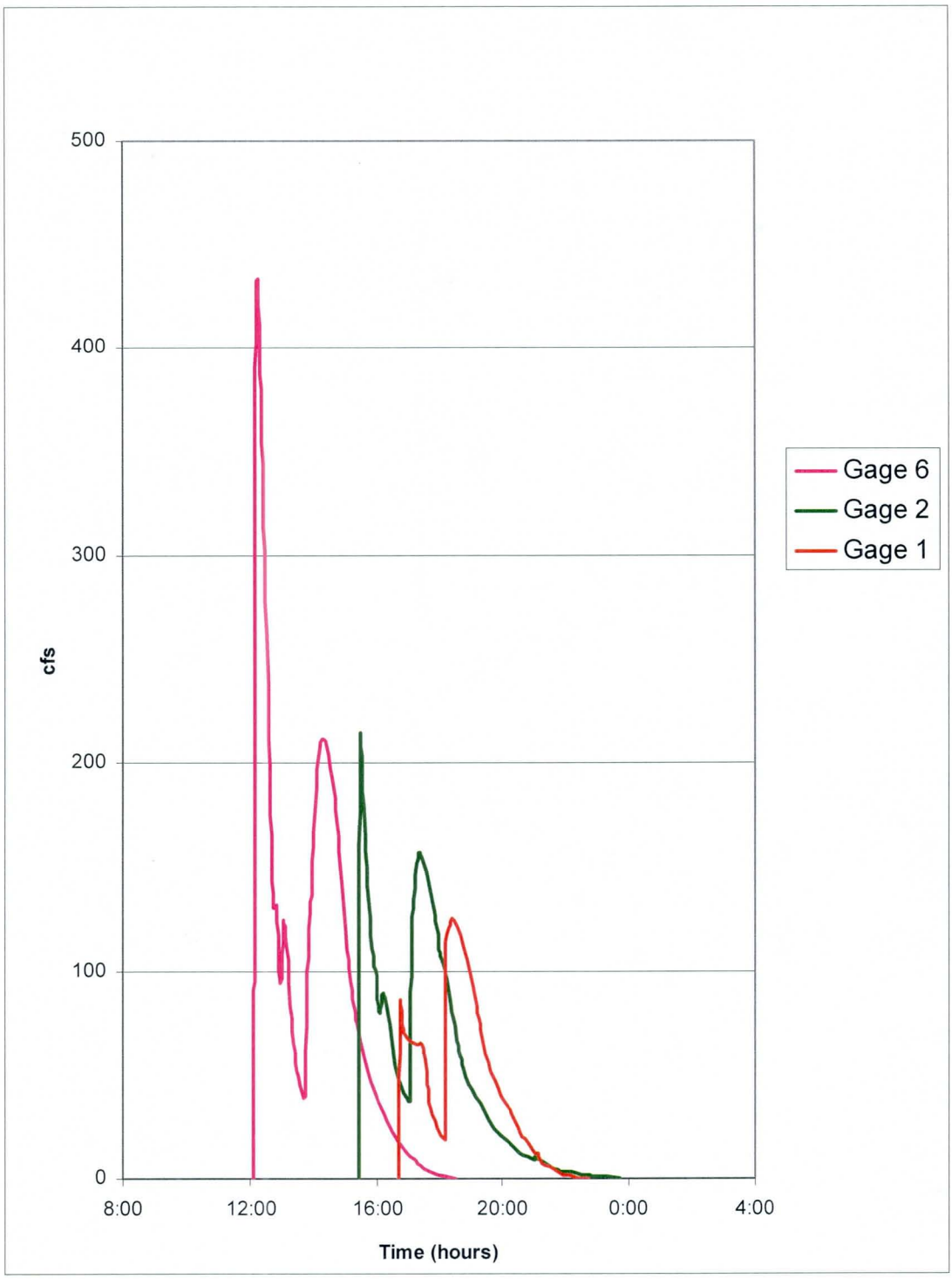


Figure 17: Hydrographs - Storm 6; 9-25-94; Flumes 6,2,1



Existing data on TL in Reaches 1, 3 and 4 were obtained from published sources and have been incorporated into the analysis (Table 3). Data presented by other authors is included in this dataset to provide additional insight on TL. These data come from several sources that were summarized in a previous report (Cataldo, et al. 2004). Common to each of these data sets are that no lateral flows influenced TL estimates. In addition, most of the authors worked in association with WGEW.

Two storms (Storm 18 and Storm 21) have inflow hydrographs that were measured at Flume 11 with no runoff measured at Flume 8. This implies that all of the stormwater entering Flume 11 was lost within this 4.1-mile reach. These two storm events were not included in the study predictive graphs because the stream disappeared into the alluvium before reaching the downstream gage and could not be normalized by the length of the channel.

Table 3: Published Data for WGEW

Storm #	TL #	Stream Reach #	Date	Data Source
7	13	4	8/10/1959	Keppel (1960)
8	14	1	8/2/1963	Lane, et al. (1971)
9	15	4	8/10/1963	Wallace and Renard (1967)
10	16	1	7/31/1964	Lane, et al. (1971)
11	17	1	8/2/1964	Lane, et al. (1971)
12	18	1	8/5/1964	Lane, et al. (1971)
13	19	4	9/9/1964	Renard and Keppel (1966)
13	20	3	9/9/1964	Renard and Keppel (1966)
14	21	1	9/11/1964	Lane, et al. (1971)
15	22	1	8/18/1965	Lane, et al. (1971)
16	23	1	9/2/1965	Lane, et al. (1971)
17	24	1	7/30/1966	Lane, et al. (1971)
18	*	1	11/9/1966	Lane, et al. (1971)
19	25	1	8/13/1967	Lane, et al. (1971)
20	26	1	9/25/1967	Lane, et al. (1971)
21	*	1	7/7/1967	Lane, et al. (1971)
22	27	1	8/2/1968	Lane, et al. (1971)
3	28	1	8/5/1968	Lane, et al. (1971)
23	29	4	8/27/1982	Renard, et al. (1993)
23	30	3	8/27/1982	Renard, et al. (1993)

* TL/mile estimates could not be produced because no runoff was produced at the downstream gage.

Storm events from Queen Creek, AZ were used to assess the predictive method presented in this study (Babcock and Cushing, 1941). The tandem inflow and outflow gages were separated by 20 miles (Table 4). The first year of the data presented was considered a dry year, whereas the second year was considered to be more rainy. Two storm events in 1941 were observed when flood storm water was recorded at the upper gage with no flow recorded at the downstream gage. Two other storms produced extremely large flows in the channel and may have overflowed these banks and were excluded.

Table 4: Data from Queen Creek, AZ

Storm #	Date	Storm #	Date
Q1	2/12/1940	Q9	12/24/1940
Q2	7/24/1940	Q10	1/12/1941
Q3	8/3/1940	Q11	1/24/1941
Q4	10/5/1940	Q12	1/28/1941
Q5	10/27/1940	Q13	2/7/1941
Q6	11/181940	Q14	2/24/1941
Q7	12/11/1940	Q15	3/1/1941
Q8	12/12/1940		

3.2. Transmission Losses at WGEW

Transmission losses are a complicated phenomena and may be estimated by considering the following parameters: peak discharge; volume of runoff; flow duration and sequence; channel length and width; depth of flow; antecedent moisture conditions; watershed geometry; isohyets; volume and characteristics of the alluvium; and the amount and type of material suspended in the runoff. From a previous stepwise multiple regression analysis study of most of these parameters, the most significant result obtained in defining parameters to estimate the transmission losses was in flow volume and peak inflow discharge (Murphey, et al. 1977).

It is not unexpected that the relationship between discharge (Q) and transmission loss is best expressed by a power function. Leopold and Maddock (1953) found that the width, depth, velocity and sediment load of streams were all power functions of the discharge. Hedman (1970) found that peak discharge could best be predicted using a multivariate power equation based upon width and depth of perennial and ephemeral streams. Osterkamp and Hedman (1982) found that discharge for an event of specified recurrence frequency could be estimated as a power function of stream width alone when sorted by bed sediment characteristics. Hedman and Osterkamp (1982) estimated mean annual discharge for perennial, intermittent and ephemeral channels in a variety of climates using a series of power regression equations based upon the width of the active channel of the streams. Thorne (1997) summarizes the literature on the mathematical formulation of channel morphology related to meander patterns, which generally are single or bivariate power functions of Q. There have also been relationships found between the inflow volume and transmission losses by Lane, et al. (1971) and Jordan (1977).

Several channels in WGEW were studied to assess TL in ephemeral streams. The channels studied isolate four different stream reaches between Fumes 11 and 1 (Table 5 and Figure 4) and consist of a number of storm events for each. All of the runoff for the storm events considered in this study originated above Flume 2.

Table 5: Data available for Transmission Loss Estimation (by Stream Reach)

WGEW	
Stream Reach (#)	**Storm Events (#)**
1	12
2	2
3	6
4	10
Queen Creek	
1	15

Table 6 lists all storm events with the inflow and outflow volumes and peak inflow in cubic feet per second (cfs). For each TL measurement, inflow gage is "Up"; the outflow gage is "Down."

Table 6: Computed Transmission Losses from Storm Events in Walnut Gulch, AZ

TL	Date	Reach ID	Volume (Up)	Peak Runoff (Up)	Volume (Down)	Peak Runoff (Down)	Trans. Loss	Trans. Loss / Mile	Trans. Loss (% of Up flow)
#		#	af	cfs	af	cfs	af	af/mile	%
1	8/29/61	4	149.4	1194.6	130.3	842.7	19.1	4.6	12.8%
2	7/18/65	4	12.8	166.2	2.9	26.9	9.9	2.4	77.5%
3	7/18/65	3	27.1	385.3	12.8	166.2	14.2	5.3	52.6%
4	7/18/65	2	28.2	574.7	27.1	385.3	1.1	1.3	4.0%
5	8/5/68	4	4.7	81.8	0.6	9.9	4.1	1.0	86.3%
6	8/5/68	3	13.8	440.7	4.7	81.8	9.1	3.4	65.7%
7	8/5/68	2	16.4	570.0	13.8	440.7	2.6	2.9	16.0%
8	8/9/70	4	18.5	308.0	4.1	52.8	14.4	3.4	78.0%
9	7/18/85	4	7.2	98.1	1.7	23.9	5.6	1.3	77.0%
10	7/18/85	3	11.6	243.3	7.2	98.1	4.4	1.6	37.7%
11	9/25/94	4	32.6	212.4	21.6	124.3	11.0	2.6	33.9%
12	9/25/94	3	47.6	433.7	32.6	212.4	15.0	5.6	31.5%
13	8/10/59	4	56.9	850.0	5.0	95.0	51.9	12.4	91.2%
14	8/2/63	1	5.0	208.0	1.3	14.2	3.7	0.9	74.1%
15	8/10/63	4	73.9	840.0	7.4	240.0	66.5	15.8	90.0%
16	7/31/64	1	3.5	97.2	0.1	1.9	3.4	0.8	97.4%
17	8/2/64	1	39.9	725.0	22.3	463.4	17.6	4.3	44.0%
18	8/5/64	1	9.3	365.0	3.5	142.0	5.8	1.4	62.7%
19	9/9/64	4	64.8	970.0	32.5	570.0	32.3	7.7	49.8%
20	9/9/64	3	74.8	1,481.0	64.8	970.0	10.0	3.7	13.4%
21	9/11/64	1	128.4	1,960.0	46.5	1,914.0	81.9	20.0	63.8%
22	8/18/65	1	2.1	26.3	0.2	7.3	1.9	0.5	92.4%
23	9/2/65	1	6.2	97.2	4.0	75.9	2.2	0.5	36.2%
24	7/30/66	1	43.7	1,074.0	27.6	539.8	16.1	3.9	36.8%
25	8/13/67	1	10.6	260.8	3.1	97.3	7.5	1.8	70.9%
26	9/25/67	1	1.8	69.6	0.6	17.6	1.2	0.3	67.2%
27	8/2/68	1	7.5	331.8	1.9	63.7	5.6	1.4	74.8%
28	8/5/68	1	27.4	1,080.0	12.9	429.5	14.6	3.5	53.1%
29	8/27/82	4	160.0	2,577.6	126.0	1,942.1	34.0	8.1	21.2%
30	8/27/82	3	199.6	3,778.2	160.0	2,577.6	39.6	14.7	19.9%
*	11/9/66	1	3.7	82.9	0.0	0.0	3.7	*	100.0%
*	7/7/67	1	0.1	6.1	0.0	0.0	0.1	*	100.0%

The effect of TL is demonstrated within Storm 2 and Storm 3 corresponding TL numbers are 2 through 4 and 5 through 7 in Table 6. The peak discharge and volume drops from 575 to 27 (cfs) and 28 to 3 (af) for Storm 2 and from 570 to 10 (cfs) and 16 to 0.6 (af) for Storm 3. Clearly, the hydrographs show the TL as the stormwater traverses the 7.8-mile course from gages 8 to 1. This translates to a 95-98% loss of initial inflow Q_p. The spread of the data covers approximately two orders of magnitude (transmission loss range from 1.1 to 81.9 af). Two storms experienced a total loss in runoff between Flume 11 and 8 (Storm 18 and Storm 21 in Table 3 and in Table 6). The TL for Queen Creek is given in Table 7. In addition, the study at Queen Creek indicated that two storms with flow at the upper gage did not reach the downstream gage.

Table 7: Computed Transmission Losses from Storm Events at Queen Creek, AZ

Storm	Volume (Up)	Peak Runoff (Up)	Volume (Down)	Peak Runoff (Down)	Trans. Loss	Trans. Loss / Mile	Trans. Loss (% of Up flow)
#	af	Cfs	af	cfs	af	af/mile	%
Q1	69	170.0	11.5	30.0	57.3	2.9	83.3%
Q2	26	170.0	4.9	28.0	20.7	1.0	80.9%
Q3	58	700.0	45.0	214.0	13.4	0.7	22.9%
Q4	152	650.0	65.7	365.0	86.3	4.3	56.8%
Q5	244	994.0	149.0	395.0	95.0	4.8	38.9%
Q6	1,880	3,730.0	1,260.0	2,500.0	620.0	31.0	33.0%
Q7	309	1,790.0	144.0	795.0	165.0	8.3	53.4%
Q8	1,340	4,710.0	1,060.0	3,250.0	280.0	14.0	20.9%
Q9	2,680	8,020.0	1,830.0	4,340.0	850.0	42.5	31.7%
Q10	2,700	5,990.0	1,380.0	3,300.0	1,320.0	66.0	48.9%
Q11	569	800.0	146.0	535.0	423.0	21.2	74.3%
Q12	1,270	3,340.0	321.0	1,160.0	949.0	47.5	74.7%
Q13	1,900	3,080.0	628.0	1,370.0	1,272.0	63.6	66.9%
Q14	3,090	4,240.0	2,360.0	3,220.0	730.0	36.5	23.6%
Q15	1,480	4,020.0	832.0	2,380.0	648.0	32.4	43.8%

3.3. Models of Transmission Losses at WGEW

A least squares fit to these data and predictive equations for the curves (Figures 18, 19 and 20) are shown in Table 8. Note that storm events in which TL/mile could not be estimated because of a lack of flow in the downstream gage were not included in the study predictive.

Table 8: Predictive equations for WGEW TL data

Transmission loss per mile (TL/Mile) is computed in acre-feet / mile (af/m)
Volume (Vol) is measured in (af)
Peak Flow (Q_p) is measured in cubic feet per second (cfs)

Models	Equation	R^2
1. Transmission Loss and Inflow Volume	TL/Mile = $0.278 \cdot Vol^{(0.750)}$ Vol p-value < 1%	0.825
2. Transmission Loss and Inflow Peak Flow	TL/Mile = $0.026 \cdot Q_p^{(0.775)}$ Q_p p-value < 1%	0.721
3. Inflow Volume and Inflow Peak Flow	Vol = $0.047 \cdot Q_p^{(1.02)}$ Q_p p-value < 1%	0.849

There are convincing trends in the data as suggested by the correlation coefficient of $R^2 = 0.72$ for peak inflow discharge and $R^2 = 0.83$ for volume of inflow. The relationship between the volume of inflow to the peak inflow discharge also has a high correlation coefficient of $R^2 = 0.85$. This curve can be used to estimate the inflow volume from the peak inflow discharge Q_p.

The recommended method to determine the peak discharge for an inflow hydrograph is to use Figure 19 or Model 2 (Table 8) to estimate TL per length of channel. Since it is easy to determine the peak inflow for any gauged channel the TL can be estimated. The inflow volume can also be used to determine TL but a complete, detailed hydrograph is required.

Figure 18: Transmission Loss and Inflow Volume for Walnut Gulch and Queen Creek.

Transmission losses per mile (TL/Mile) is measured in acre-feet / mile (af/m); Volume (Vol) is measured in (af)

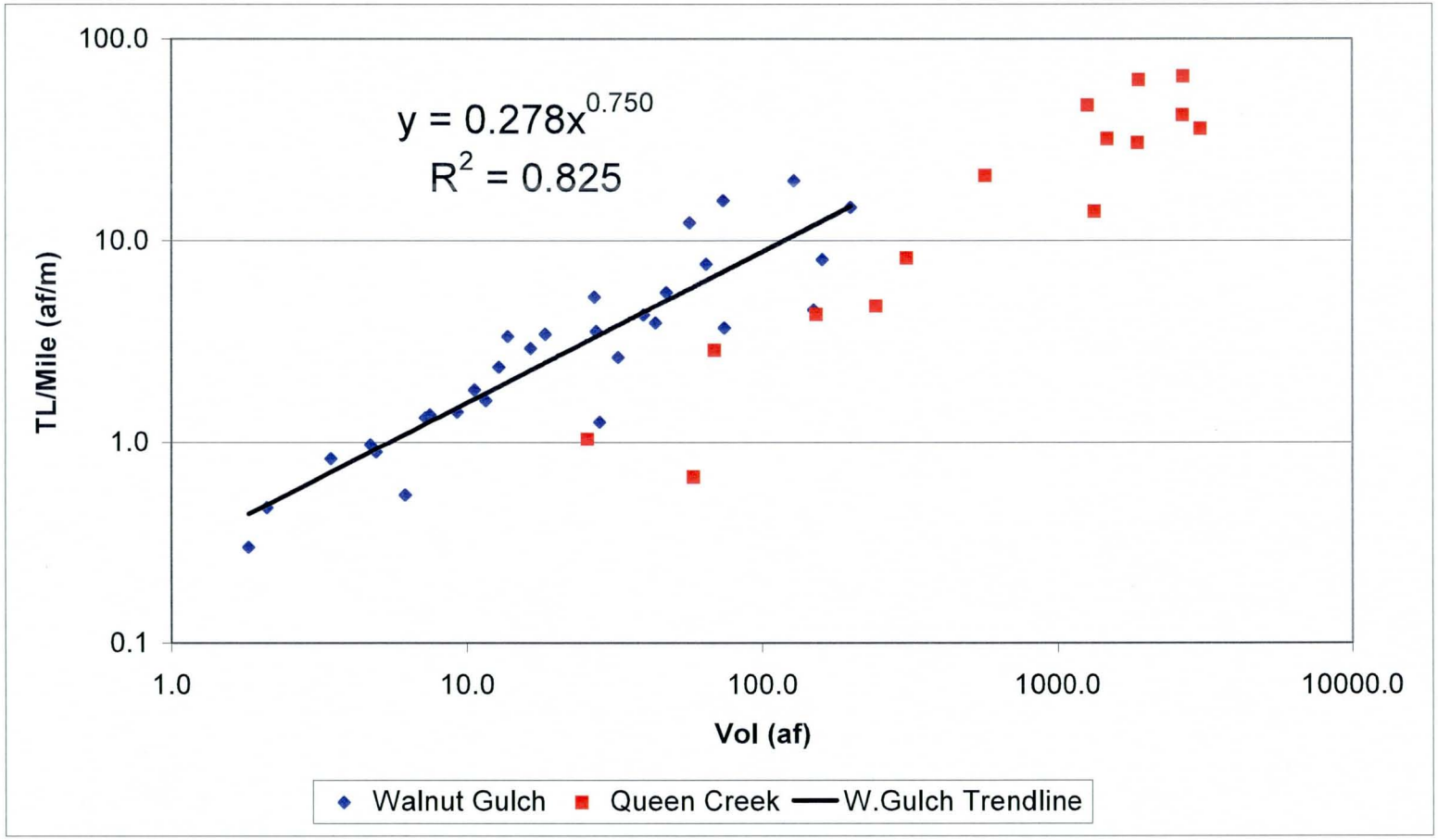
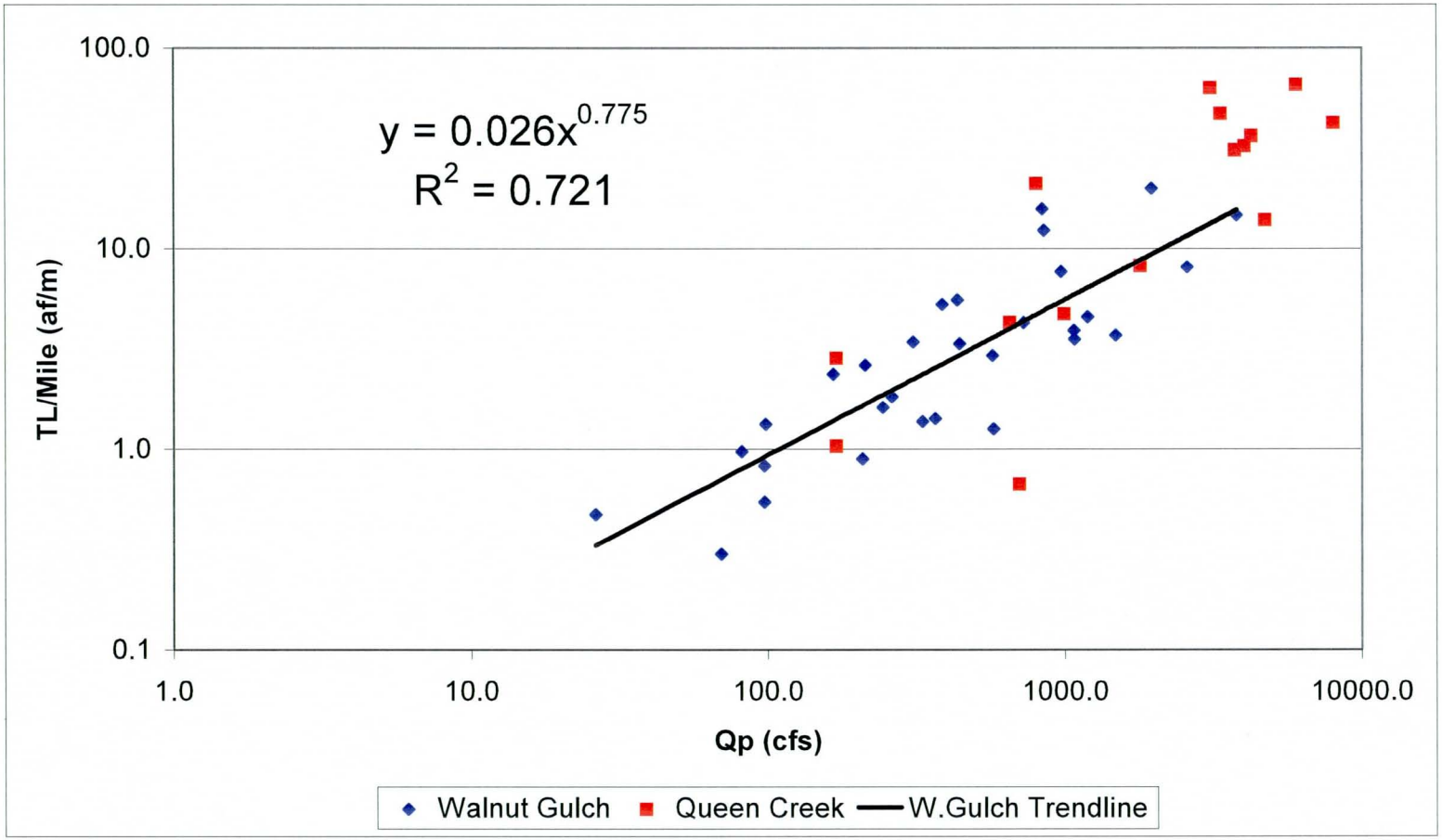


Figure 19: Transmission Loss and Inflow Peak Flow for Walnut Gulch and Queen Creek.

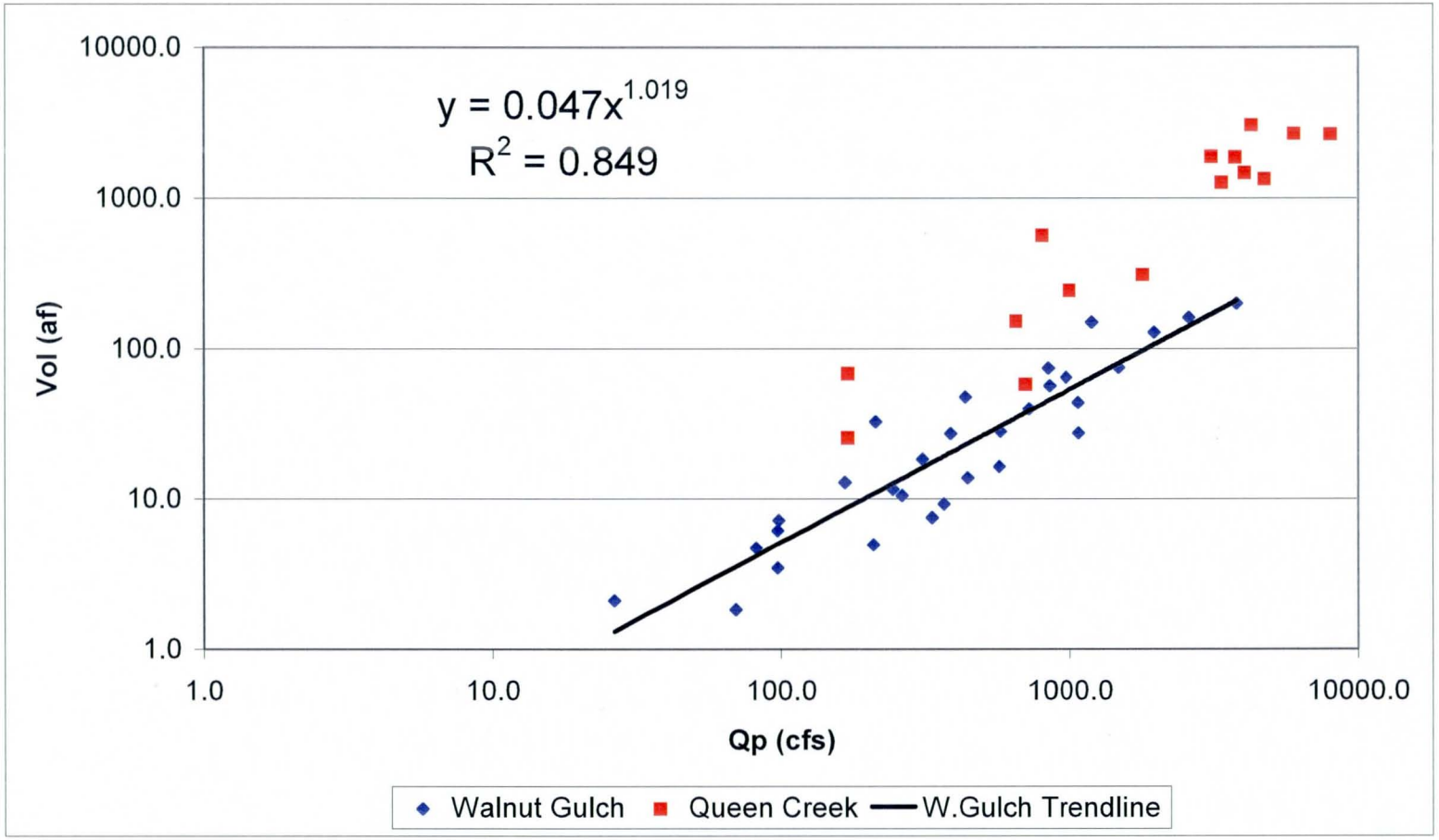
Transmission loss per mile (TL/Mile) is measured in acre-feet/mile (af/m); Peak Flow (Q_p) is measured in cfs.



Note: At gage stations, the peak discharge is generally reported and not the inflow volume. Therefore, Figure 20 depicts the peak discharge for the inflow hydrograph plotted against the inflow volume shown. From this graph, volume can be estimated for any known event peak discharge.

Figure 20: Inflow Volume and Inflow Peak Flow – Walnut Gulch

Volume (Vol) is measured in acre-feet (af); Inflow Peak Flow (Q_p) is measured in (cfs).



3.4. Predictions of Transmission Losses at Queen Creek

At Queen Creek, 15 storm events were used to test the WGEW equations as a predictive method to estimate transmission losses. The Queen Creek data is listed in Table 7 and plotted in Figures 18 to 20. Not only does the Queen Creek data have similar trends to the WGEW but the data are close in magnitude particularly for the peak inflow discharge curve (Figure 19).

When the WGEW equations are used to estimate transmission losses at Queen Creek, the value predicted with the inflow volume is almost twice (189%) the measured value on average (Table 9). A better fit is achieved with the peak inflow discharge where the percentage difference is about 77% (Table 10).

Table 9: Predicted Transmission Losses at Queen Creek, AZ using Walnut Gulch data

Modeled with Inflow Volume: **TL/Mile = $0.278 \cdot Vol^{(0.750)}$**
Transmission losses per mile are computed in acre-feet / mile (af/m)
Volume is measured in af
% Change is computed as an absolute value

Storm #	Computed TL/M	Measured Vol	Predicted TL/M (Vol)	Difference (Computed-Predicted)	% Change (Difference / Computed)
Q1	2.87	69	6.65	+3.78	132%
Q2	1.04	26	3.17	+2.13	206%
Q3	0.67	58	5.88	+5.21	777%
Q4	4.32	152	12.05	+7.73	179%
Q5	4.75	244	17.18	+12.43	262%
Q6	31.00	1,880	79.50	+48.50	156%
Q7	8.25	309	20.51	+12.26	149%
Q8	14.00	1,340	61.66	+47.66	340%
Q9	42.50	2,680	103.72	+61.22	144%
Q10	66.00	2,700	104.30	+38.30	58%
Q11	21.15	569	32.43	+11.28	53%
Q12	47.45	1,270	59.23	+11.78	25%
Q13	63.60	1,900	80.13	+16.53	26%
Q14	36.50	3,090	115.41	+78.91	216%
Q15	32.40	1,480	66.44	+34.04	105%
			Average Totals	26.12	189%

Although the graphs, curves and predictive equations presented here have a good fit with high correlations coefficients, they should be tested on different ephemeral streams. The results from Tables 9 and 10 indicate that the predictive model based upon WGEW volumes (Table 9) will always overestimate TL for Queen Creek while the TL based upon the peak Q model will more frequently underestimate TL (Table 10). From a CWA policy viewpoint and to the extent that any prediction is less than perfectly accurate, it is probably better to underestimate transmission losses to add a measure of environmental caution to the analyses. In both cases, the difference is generally less than one order of magnitude from the computed TL.

Reference to Tables 9 and 10 reveal that the largest deviation between calculated and predicted TL occurs for Storm# Q3. It is unknown at this point why such large differences exist for Q3. If

the values from Q3 are excluded as statistical outliers, the Average Total Change based on Volume (Table 9) is an overestimation of 147% of the calculated TL. The Average Total Change based on peak discharge (Table 10) is 45% of the calculated TL and 71 percent of the time it will be an underestimation.

For additional comparative purposes, the relationship of TL to discharge volume for events reported from midwestern streams by Sharp and Saxton (1962) and Jordan (1977) are examined. The comparison of TL to volume relationships for WGEW, Queen Creek and the Midwestern streams is depicted in Figure 21.

Table 10: Predicted Transmission Losses at Queen Creek, AZ using Walnut Gulch data

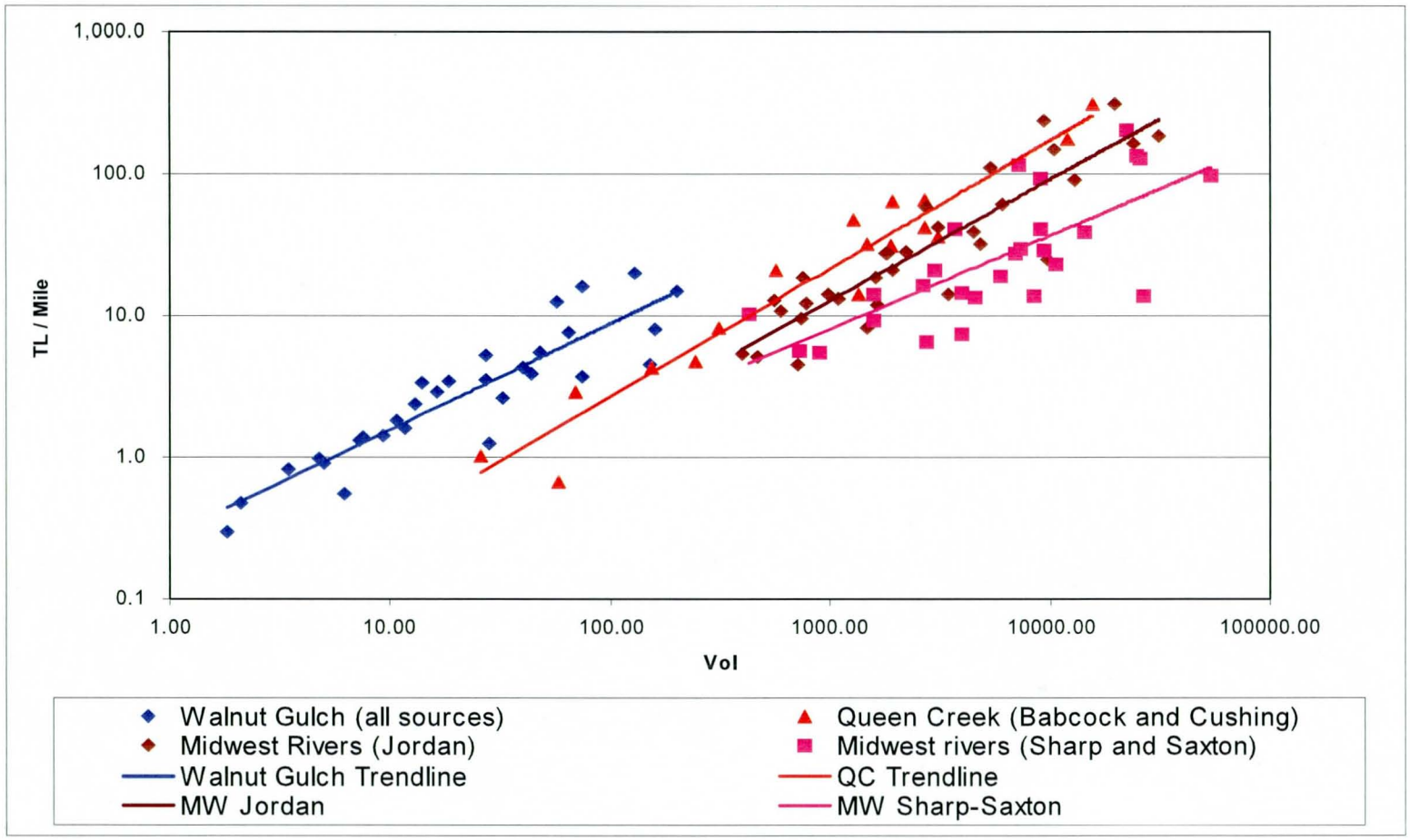
Modeled with Peak Inflow Discharge: **TL/Mile = $0.026 \cdot Q_p^{(0.775)}$**
Transmission losses per mile are computed in acre-feet / mile (af/m)
Q_p is measured in cfs
% Change is computed as an absolute value

Storm #	Computed TL/M	Measured Q_P	Predicted TL/M (Q_P)	Difference (Computed-Predicted)	% Change (Difference / Computed)
Q1	2.87	170	1.40	-1.46	51%
Q2	1.04	170	1.40	+0.37	36%
Q3	0.67	700	4.21	+3.54	528%
Q4	4.32	650	3.97	-0.34	8%
Q5	4.75	994	5.52	+0.77	16%
Q6	31.00	3,730	15.40	-15.60	50%
Q7	8.25	1,790	8.72	+0.47	6%
Q8	14.00	4,710	18.45	+4.45	32%
Q9	42.50	8,020	27.88	-14.62	34%
Q10	66.00	5,990	22.24	-43.76	66%
Q11	21.15	800	4.67	-16.48	78%
Q12	47.45	3,340	14.14	-33.31	70%
Q13	63.60	3,080	13.28	-50.32	79%
Q14	36.50	4,240	17.01	-19.49	53%
Q15	32.40	4,020	16.32	-16.08	50%
			Average Totals	13.46	77%

Both the Sharp and Saxton (1962) and Jordan (1977) studies determine TL in the same way as WGEW and Queen Creek, that is, by subtracting the flow between tandem gages on the same streams with no lateral inflow between the gages. Because the streams in these two sets of data are large (lengths and watershed areas), of varied type (ephemeral, intermittent and perennial) and are in Plains States with different climatic conditions, the equations developed from WGEW should not be comparable. Using the WGEW equations to predict transmission losses in these Midwestern streams could generate overestimates that are larger by several orders of magnitude. Despite these differences, there is a substantial uniformity in the slopes of the trendlines, Figure 21. Transmission loss per mile has almost the same variation with inflow volume. Although these streams show similar trends, we have not found a common link to explain this similarity or the difference in the average transmission losses.

Figure 21: Transmission Loss (TL/Mile) and Inflow Volume (Vol) – Several Sources

Transmission losses per mile are computed in acre-feet / mile (af/m)
Volume is measured in af



Therefore, the analyses presented here are only valid for the range of data in WGEW and Queen Creek and should be used with caution for different watersheds particularly for datasets outside the geographic range of southern Arizona. This procedure should be tested on other ephemeral streams in the arid and semi-arid southwest as well as for other regions of the United States. The following assumptions are made for the predictive curves given in Table 8 and in Figures 18 through 20:

- no lateral flow downstream of the inflow gauge
- the flow is constrained to the channel banks, i.e. no overflow over the banks
- the method has only been tested on the WGEW and Queen Creek data
- only inflow Q_p and Vol were considered in the prediction of TL

To estimate the peak inflow for ungaged streams an additional modeling step must be used. In the simplest form, the rational equation can be used. Hedman (1970), Osterkamp and Hedman (1982), Hedman and Osterkamp (1982) and others have predicted discharge with power equations derived from regression analyses of one or more field-measured parameters of channel width, depth, substrate and slope.

More sophisticated approaches utilize one of the water resources computer models such as HEC-1 or HEC-HMS. The important parameters for these models are precipitation, watershed area, hydrological soil properties, and time of concentration. These parameters may be determined by using AGWA, a GIS-based model (AGWA, 2002). Other models may be used to determine Q_p such as KINEROS2 (Goodrich, 2002). All of these would require a more extensive dataset and/or field data.

3.5. Converting TL Rates to Distance

The data expressed above have been in terms of TL rates (i.e., acre-feet per mile) of flow. Ultimately, from the CWA policy perspective of "will an ordinary flow reach navigable water," rates must be converted to distance. This distance is measured from the point on the stream where flow starts to the point on the stream where flow ceases. In many cases, flows cease in ephemeral streams if the streams are long enough and there is no lateral inflow. However, in this dataset, no relationship was found between the rate of TL and the distance downstream from the point of origin that the stream ceased to flow.

Until sufficient field data is obtained to determine the location in a stream where the flow ceases in a channel, an arithmetic conversion of the rate of TL to distance traveled is proposed. For example, if a flow of 100 af has a TL of 10 af/mi, we can assume that at 10 miles from the point of origin, water will cease to flow. While the predictive models derived in this study may not be directly applicable to flows lower than the range analyzed, it is safe to say that lower flows are unlikely to travel any further downstream from their point of origin than the higher flows analyzed herein.

3.6. Evapotranspiration

It is important that evapotranspiration (ET) be put into context when examining total transmission losses. Small precipitation events that do not deliver sufficient water to initiate flow, but only enough to wet surfaces will be lost as ET. As the rate of water delivered as

precipitation increases, infiltration will begin and eventually overland flow will be initiated. As long as flow continues, both ET and infiltration will contribute to losses.

In general, ET losses tend to be minor when compared with infiltration losses in flowing streams. Intuitively, the larger the volume of flow in a channel of any specified width, the deeper the water and the less surface area will be presented to the atmosphere. Thus, it can be expected that ET as a percentage of total volume will be inversely related to the discharge.

Estimates of ET are often available from climatological institutions, especially where irrigation is a normal practice for agricultural production. Reference crop evapotranspiration (ETo) data were obtained from the Arizona Meteorological Network (AZMET) for Tuscon (the nearest station to Walnut Gulch) and for Queen Creek. AZMET calculates ETo values using a modification of the Penman Equation developed for the California Irrigation Management Information System by Snyder and Pruitt (1985) and are based upon values for air temperature, vapor pressure deficit, wind speed and net radiation (Brown). While ETo values are representative of evaporation from large bodies of water and from vegetated landscapes, they must be adjusted for smaller, shallower bodies of water, which may be more closely represented by Pan Evaporation values. ETo values can be converted to Pan Evaporation values by dividing the ETo values by a conversion constant for winter of 0.7 and for summer 0.6.

The Walnut Gulch area generally has a more severe winter than the Queen Creek area. December, January and February were considered "winter" for Walnut Gulch while only January was considered "winter" for Queen Creek. Values of ETo and the converted pan evaporation estimates are presented in Table 11.

The storms that originated runoff in the stream segments evaluated in this study generally occurred in July, August or September of specified years, i.e., during the summer months (see Table 6). They all lasted for less than one day (Figures 12 to 17). Thus, an estimate of event ET during the period of flow for each event is computed as (hours of flow/24)(daily Pan Equiv).

An estimation of the evaporation loss (in acre-feet) that occurred during each discharge event for each of the stream segments can be computed by multiplying the surface area of the channel in each reach (from Table 12) by the estimated event ET (from Table 11, in feet) for the time period during which water flowed in the reach.

Table 11: Computed ETo and converted value for pan evaporation equivalent for Tuscan, Arizona and Queen Creek, Arizona. All values are in inches. (Source: AZMET)

	Walnut Gulch (Tuscan) (inches)			Queen Creek (inches)		
Month	Total ETo	Ave. Daily ETo	Pan Equiv (inches/ft/day)	Total ETo	Ave. Daily ETo	Pan Equiv (inches/ft/day)
Jan	2.97	0.10	0.14/0.012	2.54	0.08	0.11/0.009
Feb	3.34	0.13	0.19/0.016	3.34	0.12	0.20/0.017
Mar	5.57	0.19	0.32/0.027	5.57	0.18	0.30/0.025
Apr	7.33	0.27	0.45/0.038	7.33	0.24	0.40/0.033
May	9.90	0.32	0.53/0.044	9.39	0.30	0.50/0.042
Jun	10.54	0.34	0.57/0.048	9.66	0.32	0.53/0.044
Jul	9.13	0.29	0.48/0.040	8.72	0.28	0.47/0.039
Aug	7.99	0.26	0.43/0.036	7.96	0.26	0.43/0.036
Sep	7.26	0.24	0.40/0.033	6.62	0.22	0.37/0.031
Oct	5.77	0.19	0.32/0.027	5.11	0.16	0.27/0.022
Nov	3.60	0.12	0.20/0.017	3.13	0.10	0.17/0.14
Dec	2.60	0.08	0.11/0.0092	2.36	0.08	0.11/0.0092

Table 12: Surface area for studied stream reaches at WGEW based upon Table 1.

Reach (ID#)	Reach Length (miles)	Channel width (ft)	Channel Surface Area (acres)
1	4.1	38	18.9
2	0.9	68	7.4
3	2.7	107	35.0
4	4.2	132	67.2

Table 13 provides an evaluation of evaporative losses that could be expected for each TL # event analyzed in this study. Most revealing are ET losses when compared to total TL and to the upstream volume of water entering the reach. The total TL averages 47.8 percent for the 12 events analyzed. The average ET for those same events is estimated at 2.9 percent – more than an order of magnitude less. Thus, it is clear that in channels carrying flowing water, the primary component of TL will be infiltration into the bed and banks.

Table 13: Computed ET for each event from Table 2 in comparison to total TL and the upstream volume.

TL	Date	Reach ID	Volume (Up)	Volume (Down)	Trans. Loss	Trans. Loss (% of Up Flow)	ET During Flow Event	ET (% of Up Flow)
#		#	af	af	af	%	af	%
1	8/29/61	4	149.4	130.3	19.1	12.8	67.2 x 0.036 x 0.29 days=0.70	0.5
2	7/18/65	4	12.8	2.9	9.9	77.5	67.2 x 0.04 x 0.22 days= 0.59	4.6
3	7/18/65	3	27.1	12.8	14.2	52.6	35.0 x 0.04 x 0.19 days=0.27	1.0
4	7/18/65	2	28.2	27.1	1.1	4.0	7.4 x 0.04 x 0.21 days=0.06	0.2
5	8/5/68	4	4.7	0.6	4.1	86.3	67.2 x 0.036 x 0.20 days=0.48	10.2
6	8/5/68	3	13.8	4.7	9.1	65.7	35.0 x 0.036 x 0.19 days=0.24	1.7
7	8/5/68	2	16.4	13.8	2.6	16.0	7.4 x 0.036 x 0.14 days=0.04	0.2
8	8/9/70	4	18.5	4.1	14.4	78.0	67.2 x 0.036 x 0.18 days=0.44	2.4
9	7/18/85	4	7.2	1.7	5.6	77.0	67.2 x 0.04 x 0.21 days=0.56	7.8
10	7/18/85	3	11.6	7.2	4.4	37.7	35.0 x 0.04 x 0.26 days=0.36	3.1
11	9/25/94	4	32.6	21.6	11.0	33.9	67.2 x 0.033 x 0.30 days=0.66	2.0
12	9/25/94	3	47.6	32.6	15.0	31.5	35.0 x 0.033 x 0.54 days=0.62	1.3
Mean						47.8		2.9

4. Conclusions

It is beyond the scope of this study to examine the hydro-geological and hydraulic theories applicable to fully understand transmission losses and why there is such a large spread in the data at a given stream for similar inflow conditions as well as the explanation of the physical meaning of the coefficients in the predictive equations. Clearly, the use of one parameter (inflow Q_p or Vol) is a simple approach to defining such a complicated phenomena as transmission losses. While this one parameter has a large influence, it does not provide sufficient information to predict TL on a broad scale.

It is encouraging that our results suggest that discharge (either as total event volume or peak flow) appears to be the primary factor affecting TL, not only in the arid west but also in at least some Midwestern streams. Simplified power equation(s), with further refinement and qualification (e.g., adjustment for stream flow regime, climate and/or sediment composition), ultimately may be an administratively realistic approach that could be applied on a routine basis. It is clear, however, that we have not reached that point yet. 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. The following observations and physical explanations for WGEW and Queen Creek have been reported and may prove useful in further defining the factors controlling TL:

- A gravelly, sandy channel may have intake rates in tons of feet per day, finer soils such as silts and loams, may have intake rates of only a few feet per day, clays have a intake rate of inches per day.
- In areas in which most flood events results from intensive convectional storms, the position of the storms over the watershed will affect transmission losses.
- The flash floods carry more silt and the TL decreases with the application of dirty or silt-laden water.

- TL progressively decreased downstream as the material in the channel bottom became progressively finer. After floods continuous flows of clear water TL increased, i.e. clear water had sufficient velocity to transport the fine material, leaving the coarser and more permeable material.
- Infiltration in a streambed decreased with time owing to sealing effects of fine sediment suspended in the flow.
- Antecedent precipitation and floods may wet the valley and channel and reduce storage capacity,
- The surface water yield per unit area decreases with increasing drainage area
- Channel antecedent conditions affect infiltration rates particularly at the beginning of flooding events
- Infiltration is associated with canopy plot cover (shrubs, grasses, litter, etc.)
- During the lower discharges, channel resistance effects appear to dominate the flow regime
- At the higher discharges, it appears that translatory waves (bores) control the flow regime. Waves override the flow and result in an extremely rapid rise in the modified hydrograph at the downstream station.

References for the above points include: Babcock and Cushing (1941), Keppel (1960), Sharp and Saxton (1962), Wallace and Renard (1967), Renard (1970), Lane et al. (1971), Jordan (1977), Walters (1990).

Some of the above observations may be addressed by studying antecedent storms and conditions for all of the data presented here for WGEW. These data exist on file and can be the basis for a larger study to better understand the behavior of transmission losses. By better understanding these observations, predictions at new sites would be more reliable. Therefore, the next logical step is to conduct a comprehensive analysis of the data from an experimental station such as Walnut Gulch. This analysis would involve an expanded regression of variables, such as: intake rates of sedimentation, location of rainstorm, antecedent conditions, surface yield, canopy coverage, magnitude and sequence of discharge, and other hydrologic, hydraulic, climatic, and geologic conditions.

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