Quantifying Transmission Losses in a New Mexico Ephemeral Stream – A Losing Proposition

Gerhard Schoener

Watershed Scientist, Southern Sandoval County Arroyo Flood Control Authority (SSCAFCA)
1041 Commercial Dr. SE, Rio Rancho, NM 87124

Abstract

Under natural conditions, stormwater runoff in much of the semiarid Southwest drains through a network of unlined stream channels called arroyos. Dry during most of the year, arroyos are transformed into raging rivers for short periods of time following intense rain events. As stormwater travels downstream, a portion of the flow infiltrates into the highly permeable arroyo bed. The purpose of this study was to quantify these so called transmission losses for a 13 km reach of one New Mexico arroyo. Infiltration rates were tested in the field using a double ring infiltrometer. Test results varied considerably from 3.0 cm/hr to 19.6 cm/hr, with a median rate of 9.4 cm/hr. Additionally, three stream gauging stations were installed along the arroyo; for two storms in 2015, they measured a dramatic decrease in peak discharge (91% and 84%, respectively) and runoff volume (90% and 80%, respectively). Gauge data was used to successfully simulate transmission losses in HEC-HMS; the average loss rate for the arroyo was found to be 3.8 cm/hr. On average, infiltrometer results overestimated reach-scale loss rates by 60%.

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Introduction

Under natural conditions, stormwater runoff in the greater Albuquerque area and much of New Mexico drains through a network of unlined stream channels called arroyos. Dry during most of the year, arroyos are transformed into raging rivers for short periods of time – often only hours – following intense rain events. Channel bottom sediments are typically composed of coarser grain sizes than the surrounding overland areas, since fine particles are transported downstream with the runoff. Infiltration rates in arroyos are therefore typically much higher than in the overbank areas adjacent to the channel. This is important because, as stormwater flows through an arroyo towards the receiving water body, a portion of the flow infiltrates into the channel bed. Abstractions from the flood hydrograph due to infiltration into the channel bed are called transmission losses.

Transmission losses have been described for ephemeral streams in arid and semiarid regions worldwide (Pilgrim, Chapman and Doran, 1988) using various methods. Belmonte and Beltrán (2001) qualitatively described observations of transmission losses for ephemeral streams in the Valencia region of Spain. Hughes and Sami (1992) estimated transmission losses for two events in a semiarid watershed in South Africa based on moisture measurements of the alluvium. They concluded that during the first event, 75 percent of the flow infiltrated into the channel bed; for the second event, transmission losses were estimated at 22 percent of the total volume.

Multiple studies quantify transmission losses by calculating the water-balance for a reach with at least two stream gauging stations. Greenbaum et al. (2001) studied a 5.5 km reach of the Nahal Zin in Israel's Negev desert; they found that transmission losses reduced the discharge volume between 20 percent for large flow events, and up to 85 percent for small flows. Goodrich et al. (2004) reported losses of 26 percent and 31 percent of the annual discharge volume for the years 1999-2000 and 2000-2001, respectively, over a 6 km reach in the Walnut Gulch watershed in Arizona. McMahon et al. (2008) found that on average, losses equaled 77 percent of the total flood volume for a reach (approximately 250 km) of the Diamantina River in the Lake Eyre Basin, Australia. Lange (2005) studied a 150 km reach of the Kuiseb River in Namibia, and concluded that transmission losses ranged from 29 percent to 94 percent of the upstream inflow volume.

In summary, research shows that transmission losses play an important role in the hydrology of arid and semiarid regions, both at large and small scales, and should therefore be included in hydrologic models that simulate rainfall-runoff processes.

Objectives

The aim of this study was to quantify transmission losses along a 13 km reach of the Montoyas Arroyo in Sandoval County, New Mexico. The study approach was to:

1. Analyze and describe the alluvial sediments along the study reach.
2. Conduct in-situ infiltration tests at numerous locations along the arroyo, and evaluate whether any correlation exists between soil properties and infiltration test results.
3. Measure discharge at three stream gauging stations and quantify transmission losses by calculating a reach water-balance based on hydrographs measured during storm events.
4. Use results from in-situ test and gauging stations to assess whether transmission losses can be successfully incorporated into an existing hydrologic model for the watershed.

Study Area

The Montoyas Arroyo, located in Sandoval County, New Mexico, was selected for this study. The arroyo drains a 150 square kilometer watershed and discharges into the Rio Grande just north of Albuquerque. About 20 percent of the watershed is urbanized. The arroyo remains largely in its natural condition (see Fig. 1), except for the last three kilometers, where storm flows are conveyed in a concrete channel to alleviate flooding in the lower watershed. On average, the watershed receives approximately 250 mm of rainfall per year, with annual values ranging from about 100 mm to 400 mm (NOAA, 2016).

Fig. 1. Image of the Montoyas Arroyo after a storm; at this location, the arroyo is approximately 40 meters wide (image by author).

This study examines the 13 kilometer long main stem of the arroyo upstream of the concrete channel. The arroyo bottom is composed of alluvial sediments dominated by sand. Arroyo cross-sections are characterized by wide, very flat bottoms, and often incised, vertical banks. Arroyo bottom widths range from 25 to 90 meters, with an average width of approximately 45 meters (Fig. 1).

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Soil and Infiltration Testing

Surface sediments within the Montoyas Arroyo are the result of relatively recent transport and deposition within the active stream channel. To characterize the depth and properties of channel sediments, test borings were drilled to a depth of 15.5 meters at four sites along the arroyo using a truck-mounted drilling rig (see Fig. 2). Lithologic logs of the test borings were recorded by a field engineer, and samples of subsurface materials were taken at selected intervals. The multi-colored columns in Fig. 2 represent the soil types and their respective thickness encountered at each site. Boring results show that surface sediments are comprised of sands with trace amounts of fines (Fig. 2, yellow) or sand with silt (orange, 5-12 percent fines). Due to their unconsolidated nature and small amount of fines, these sediments were expected to result in high infiltration rates. The depth of the sandy surface layer ranged from four meters (boring sites 2 and 3) to 13 meters (site 4). At sites 2 through 4, the sandy surface layer was underlain by silty sand (red); due to the higher content of fines (> 12 percent), the silty sand horizons are expected to slow infiltration when reached by the wetting front. At site 1, a layer of silt that would largely impede the vertical movement of water was found at a depth of 7 meters. Depth to groundwater along the study reach decreases from approximately 200 meters at site 1 to 30 meters at site 4 (McAda and Barroll, 2002).

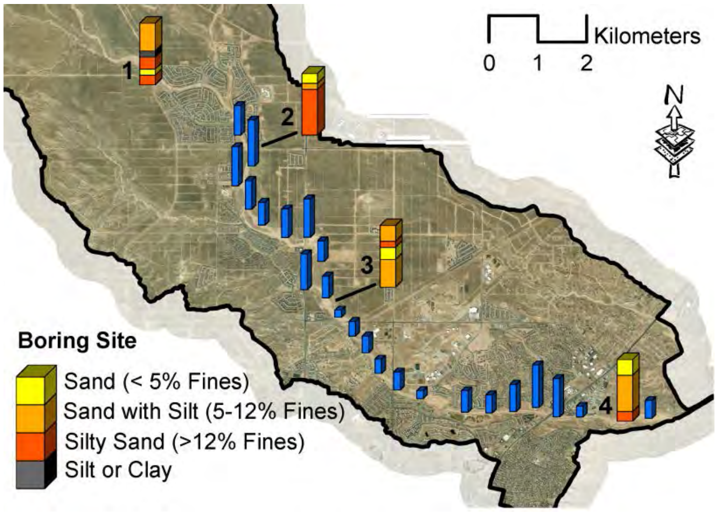

Fig. 2. Map of the lower Montoyas watershed showing boring locations and soil columns as well as infiltration test locations and results (blue bars).

To quantify surface infiltration rates, infiltration tests were conducted at regular intervals along the arroyo – as indicated by the blue bars in Fig. 2 – using a double ring infiltrometer according to ASTM Standard D3385 (2009). The infiltrometer consists of two steel rings that are driven into the ground to a depth of 15 cm. Both rings are filled with water, and the water level is held constant. Water seeping into the ground from the outer ring is intended to constrain lateral movement of water from the inner ring so as to not overestimate infiltration. The volume of water added to the inner ring was recorded in intervals of three minutes. Initial testing indicated that infiltration rates approached a constant value after approximately 15 minutes. Tests were therefore conducted for a 30 minute period at each site, and results for the last 15 minutes were averaged to estimate the infiltration rate at each test site.

Infiltration test results are displayed as blue bars in Fig. 2. Although arroyo bottom sediments were fairly uniform and consistently low in fines, infiltration rates varied considerably from 3.0 centimeters per hour (cm/hr) up to 19.6 cm/hr, with a median infiltration rate of 9.4 cm/hr. A box and whisker plot of test results can be seen in Fig. 3.

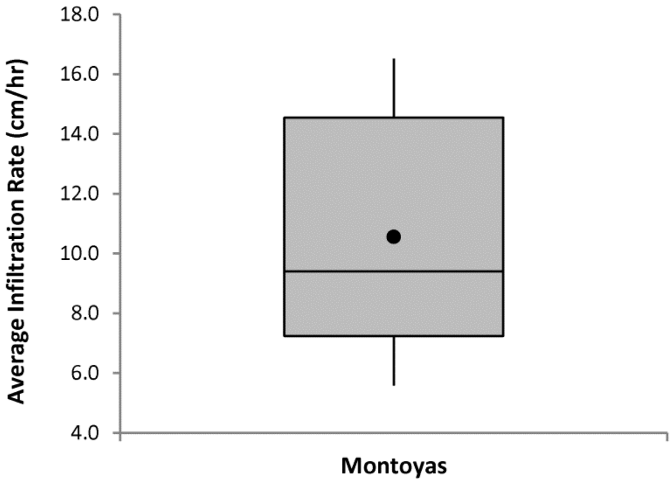

Fig. 3. Box and whisker plot summarizing infiltration test results from 22 test sites along the Montoyas Arroyo.

Grab samples of arroyo bottom sediments at sixteen infiltration test sites were subjected to particle size analysis in accordance with ASTM Standard D422 (2007). Thirteen samples were classified as sands with trace amount of fines (< 5 percent); three samples were found to be sands with silt (5-12 percent fines). No strong correlation between particle size characteristics and measured infiltration rates at the corresponding 16 test sites could be established (see Fig. 4).

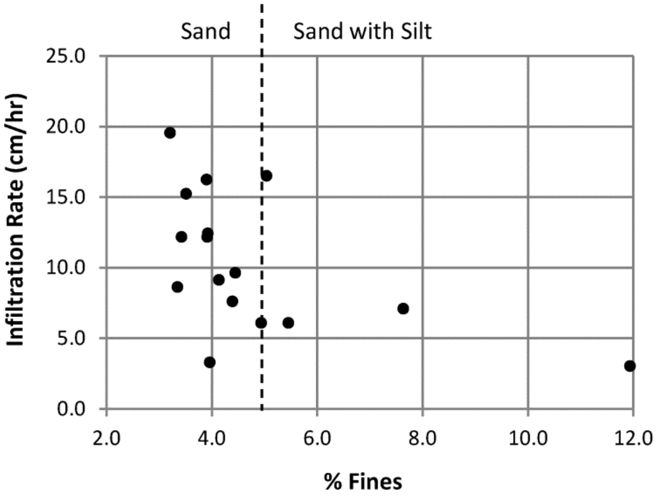

Fig. 4. Scatter plot comparing measured infiltration rates and % fines from soil samples at sixteen sites in the Montoyas Arroyo.

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The three test sites with the highest content of fines consistently resulted in low infiltration rates. Sites with soils low in fines (less than five percent), however, showed no correlation between measured infiltration and percent fine material. Since most of the arroyo bottom sediments fall into the sand category, the percentage of fines in a soil sample is not a good predictor for expected infiltration rates at any given site. Other soil parameters based on the particle size analysis (D_{10}, D_{50}, C_u, C_c) showed no correlation to measured infiltration rates.

During some of the infiltration tests, a blue food-grade dye was added to the water in the inner ring. After completion of the 30 minute test, the steel rings were removed, and a trench was excavated through the center of the test area (see Fig. 5). The depth to which the inner and outer ring penetrated the ground is indicated with black lines in Fig. 5. The dye stained portion of the soil profile reveals that once the wetting front reached the lower end of the inner ring, water started moving laterally. The double ring infiltrometer test therefore likely overestimates actual infiltration rates in the arroyo during flow conditions.

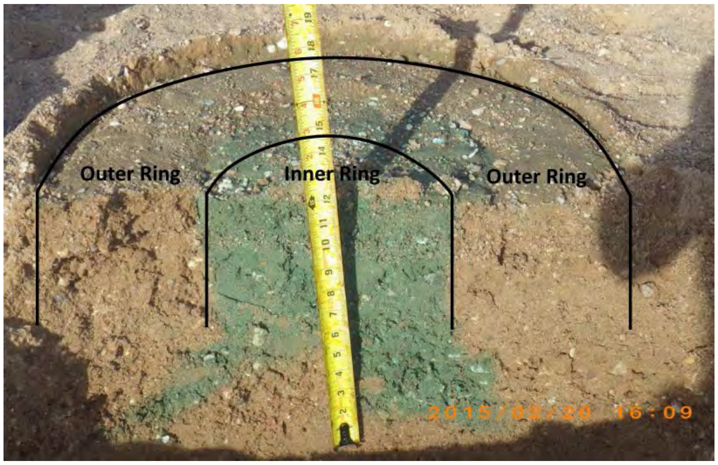

Fig. 5. Dye added to the inner ring of a double ring infiltrometer reveals the extent and direction of flow after steel rings have been removed (scale one the tape measure in inches, 1 inch = 2.54 centimeters) (image by author).

Lain and Ren (2006) studied the effect of inner ring dimension on the variability of double ring infiltrometer test results in heterogeneous soil. They found that variability of measured infiltration rates was greatest for smaller inner rings, particularly rings with a diameter of less than 30 cm. Swartzendruber and Olson (1960) found that for inner rings with a diameter of 40 cm or less, measurements were as much as double the actual infiltration rate. The diameter of the inner ring used in this study was 30 cm.

The high variability of test results and lack of correlation with particle size characteristics indicates that the test is very sensitive to small, local variations in soil composition, layering and/or density, in addition to variability and bias associated with the test methodology itself (Lain and Ren, 2006; Swartzendruber and Olson, 1960). Test results provide some insight into variability of infiltration rates across the study area, but are likely not suitable for characterizing infiltration on a reach scale.

Stream Gauging

In addition to soil and infiltration testing, three stream gauging stations were installed along the Montoyas Arroyo (for station locations please refer to Fig. 6 below). The concept being tested with flow gauging stations was that transmission losses should be reflected in decreasing runoff volume shown in the hydrograph at each gauging station (a hydrograph is a plot of discharge over time) as stormwater travels downstream. For the experiment to work, several conditions had to be met:

1. A storm of sufficient intensity and duration to result in runoff was needed.
2. The storm had to occur high in the watershed and upstream of the upper-most gauging station so that no significant runoff would enter the arroyo between gauging stations (no lateral inflow).
3. Peak discharge had to be small enough so that transmission losses were a significant portion of total flow.

Each gauging station was located at a hardened structure in the arroyo to avoid changes to the channel cross-section due to erosion. Measurement of discharge in the field during a flow event is typically not possible because flow durations are short, and storms often occur at night. Even in cases where storm flows can be observed directly, high velocities and debris in the floodwaters make field measurements difficult and dangerous. At each station, flow depth was therefore recorded automatically in five-minute intervals using a pressure transducer (In-Situ Level TROLL 500). Discharge was estimated by means of a theoretical rating curve developed in HEC-RAS (USACE, 2010) for each station. Two storms that met the criteria listed above occurred in 2015, and are described in detail below.

Storm of June 16, 2015

On June 16, 2015, an intense thunderstorm impacted the upper reach of the Montoyas watershed. Rainfall estimates derived from radar data indicated total precipitation depths of between three and five centimeters in little more than one hour at the center of the storm (orange to red shading, Fig. 6).

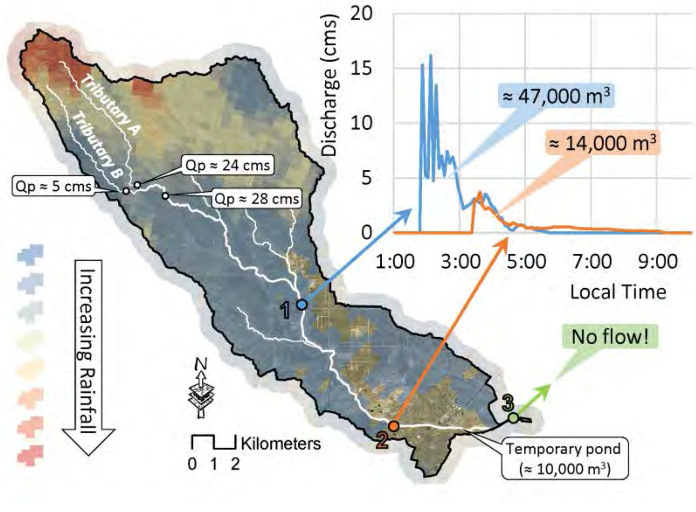

Fig. 6. Map of the Montoyas watershed showing the extent of the June 16, 2015 storm (shaded background), and decreasing storm flows in the arroyo as stormwater moved downstream.

Storm flows had to travel through more than 10 km of arroyo before reaching gauging station 1. Since peak discharges in the arroyo closer to the center of the storm were of interest, three locations with relatively uniform reach geometry were selected in the upper watershed (see Fig. 6, white circles). Debris transported with storm flows (pine needles, branches, etc.) left distinct high water marks along channel banks and vegetation. At each location, high water marks and channel geometry (cross-sections and slope) were surveyed using a TOPCON AT-G series auto level. A theoretical rating curve for each reach was developed in HEC-RAS (USACE, 2010), and peak discharges were estimated based on high water marks. The analysis yielded estimated peak discharge rates of 5 cubic meters per second (cms), and 24 cms in tributaries B and A, respectively, and approximately 28 cms below the confluence of the two tributaries (see Fig. 6).

Fig. 6 illustrates how the runoff hydrograph decreased due to transmission losses as it moved downstream through the arroyo. Peak discharge decreased from an estimated 28 cms just below the tributary confluence to 16 cms at gauging station one (blue circle, Fig. 6). At gauging station 2 (orange circle, Fig. 6) peak flow was less than 4 cms. A temporary pond built in the arroyo just upstream of gauging station three as part of a project under construction at the time of the storm event captured the remainder of the hydrograph, and no flow reached the outlet of the watershed. Runoff volume decreased from approximately 47,000 cubic meters at gauging station one to 14,000 cubic meters at gauging station two. A field survey following the storm event revealed that approximately 10,000 cubic meters of runoff were captured in the temporary pond. No lateral inflow entered the arroyo between gauging stations 1 and 3. Model results (see discussion below) indicate that without the temporary pond, peak discharge at station 3 would have been 1.5 cms – a 91% decrease compared to station 1. Runoff volume at station 3 would have decreased by 90 percent to 4,600 cubic meters compared to station 1.

Storm of July 7, 2015

The storm of July 7, 2015 impacted the majority of the upper Montoyas watershed. Radar data indicates that – at the most intense locations of the storm – between one and three centimeters of rain fell in approximately 30 minutes. The storm resulted in a measured peak discharge of approximately 16 cms at gauging station one (Fig. 7, blue circle), with a total runoff volume of approximately 59,000 cubic meters.

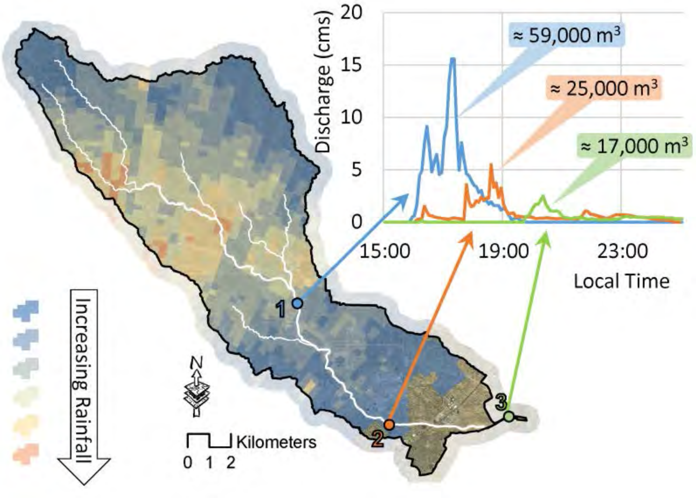

Fig. 7. Map of the Montoyas watershed showing the extent of the July 7, 2015 storm (shaded background), and decreasing flows in the arroyo as stormwater moved downstream.

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It is noteworthy that peak discharge at station 1 was identical to the June 16 storm, even though storm intensity and total rainfall depth for the July 7 storm was lower. This apparent discrepancy can be explained by the fact that the June 16 storm occurred much higher in the watershed, and peak flows estimated at 28 cms (see above) were reduced by transmission losses as they traveled through more than 10 km of arroyo to gauging station 1.

Fig. 7 illustrates the effect of transmission losses on the flood hydrograph below gauging station 1. At station two (orange circle), peak discharge was reduced to about 6 cms, and at station three (green circle) to only 3 cms (84 percent reduction from station 1). The total runoff volume also decreased in the downstream direction from approximately 59,000 cubic meters at station 1 (blue) to 25,000 cubic meters at station 2 (orange), and finally 17,000 cubic meters at the outlet of the watershed (station three, green).

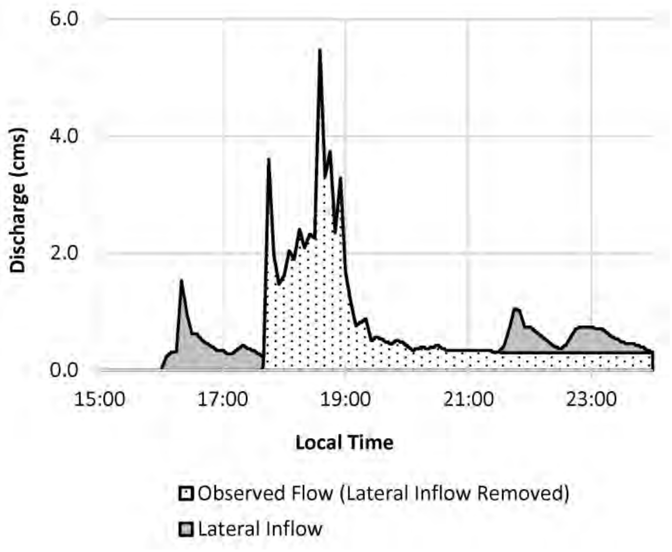

Fig. 8. Measured hydrograph at gauging station 2 for the storm of July 7, 2015; the portion of the hydrograph caused by lateral inflow is indicated in gray.

Most of the runoff from the July 7 storm originated upstream of gauging station one. However, some lateral inflow caused by precipitation lower in the watershed entered the arroyo between gauging stations one and two. Lateral inflow was simulated in HEC-HMS (USACE, 2015) based on rainfall measurements from ten tipping-bucket recording rain gauges (SSCAFCA, unpublished data). Lateral inflow was subsequently removed from the measured flow hydrograph at gauging station 2 (see Fig. 8). The total volume of lateral inflow between stations 1 and 2 was estimated at 6,000 cubic meters, with a peak discharge of 1.5 cms. Lateral inflow (see Fig. 8, gray area) did not coincide with the main portion of the hydrograph for gauging station 1 (Fig. 8, dotted area). Not accounting for lateral inflow, runoff volume between stations 1 and 3 decreased by approximately 80 percent.

Modeling transmission losses in HEC-HMS

Several methodologies for modeling transmission losses can be found in the published literature. Some methods do not route the flood hydrograph along the channel, but focus on predicting outflow volume (Geith and Sultan, 2002; Wheater, 2007; Greenbaum et al., 2001) and peak discharge (Lane et al., 2007). Rew and McCuen (2010) developed a model that accounts for transmission losses using Horton's infiltration methodology while routing a hydrograph downstream. Another model capable of flood wave routing was published by Costa et al. (2012), and uses a modified form of the Green-Ampt method to estimate transmission losses. Batlle-Aguilar and Cook (2012) used results from a reach-scale infiltration experiment to calibrated a 2-dimensional infiltration model built in Hydrus 2-D.

Transmission losses are rarely the main focus of analysis in the southwestern United States, with some exceptions, such as research based on the Walnut Gulch experimental Watershed in Arizona (Goodrich et al. 2004). Many hydrologic design manuals published by regulatory agencies in Colorado, Nevada and New Mexico do not mention transmission losses (UDFCD, 2016; CoRR, 2009; CABQ, 2008; CCRFCD, 1999). Transmission losses are mentioned under limitations of the recommended hydrology procedures in the drainage design manual for Maricopa County, Arizona (FCDMC, 2013). The design manual for Yavapai County, Arizona (YCFCD, 2015) has a section on transmission losses, and – where applicable – recommends use of the percolation method available in HEC-HMS.

This study has shown that transmission losses have a significant impact on flood peaks and runoff volumes, and should therefore be included in hydrologic models, even if the main focus of the model is flood control or infrastructure design. Methodologies for simulating transmission losses are available in various hydrologic modeling programs, and some examples are listed below. *HEC-1* (USACE, 1998) and *HEC-HMS* (USACE, 2015) can account for channel infiltration using a unit loss rate. *MIKE 11*, coupled with the groundwater model *MIKE SHE*, can simulate transmission losses by assigning a river bed leakage coefficient (Thompson et al., 2004). *FLO-2D* estimates transmission losses from the floodplain using the Green-Ampt method (FLO-2D Reference Manual, 2016). The *Soil and Water Assessment Tool (SWAT)* simulates for transmission losses from ephemeral channels using the effective hydraulic conductivity of the alluvium (Neitsch et al., 2009).

HEC-HMS was selected for this case study, because it is the recommended software for hydrologic analyses in the study area (NMOSE, 2008; CoRR, 2009), and because a comprehensive HEC-HMS model for the watershed draining to the study reach already existed (SSCAFCA, unpublished data).

The existing model of the Montoyas watershed (HEC-HMS version 4.0) was modified to account for transmission losses in the 13 km reach between gauging stations one and three. The arroyo was divided into 25 sub-reaches, each approximately 0.5 kilometers in length. The average width of each reach was determined by mapping the arroyo bottom area based on aerial photography, and dividing the total area of each reach by its length. Reach slopes were estimated from a digital elevation model for the watershed, and Manning's roughness coefficients were determined by field investigation. Reaches were modeled with rectangular cross-sections; this simplifying assumption can be justified since the arroyo bottom is generally very flat, and field observations by the author confirm that even during small flows (discharges less than 0.5 cms), the entire channel bottom is inundated. The percolation loss methodology available in HEC-HMS was utilized to model transmission losses for the two storms observed in 2015. A constant infiltration rate was assigned to each of the 25 routing reaches. At each reach, the model multiplies infiltration rate and inundated area to estimate transmission losses for each time step (USACE, 2015, pg. 192). The inundated area is computed based on reach geometry and flow depth for each time step. Losses are then subtracted from the flood hydrograph. The hydrographs measured at gauging station 1 during the June 16 and July 7 storms were routed through the model, and model results were compared to measured data. Three transmission loss scenarios were evaluated; results are displayed in Figs. 9 through 13.

1. No transmission losses

   The hydrograph measured at gauging station 1 was simply routed through the arroyo without accounting for infiltration into the channel bed.

2. Transmission loss = 3.8 cm/hr for each reach

   All reaches were assigned a uniform loss rate of 3.8 cm/hr; this loss rate was found iteratively by comparing observed and modeled peak discharges and runoff volumes at gauging stations 2 and 3.

3. Transmission loss = 35 percent of measured infiltration

   Measured infiltration rates for each reach based on the corresponding double ring infiltrometer test were adjusted iteratively until model peak discharges and runoff volumes most closely matched observed data. The closest match was achieved by using 35 percent of the measured rate for each reach (reach specific infiltration rates ranged from 0.4 cm/hr to 6.8 cm/hr, with an average rate of 3.4 cm/hr).

Fig. 9 compares simulated and observed peak discharges at stations 2 and 3 for the storms of June 16 and July 7. Data points to the right of the line of agreement (dotted line) indicate that the model over-predicted measured data.

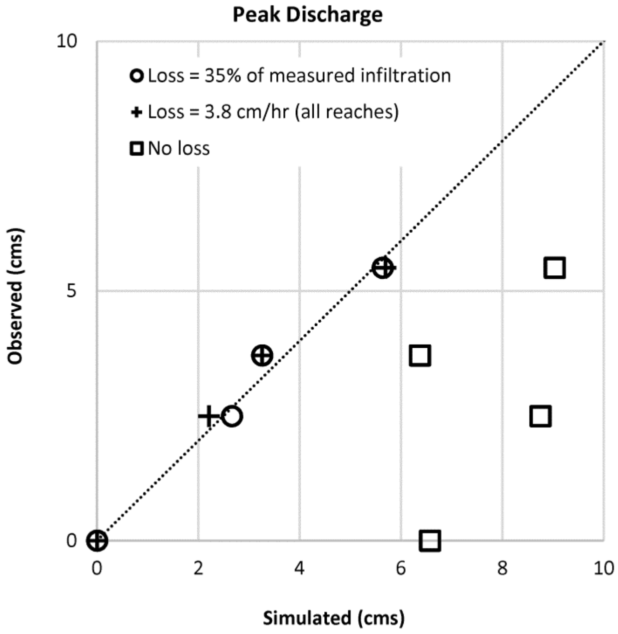

Fig. 9. Comparison of simulated and measured peak discharges based on three transmission loss scenarios.

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Points that fall on the line indicate agreement between the model and measured flows. Not surprisingly, model peak flows were higher than observed data when transmission losses were ignored (Fig. 9, squares). Using 35 percent of measured infiltration rates (circles), and using a constant loss rate of 3.8 cm/hr for each reach (crosses) both yielded model results that were close to measured data (points fall close to the line of agreement).

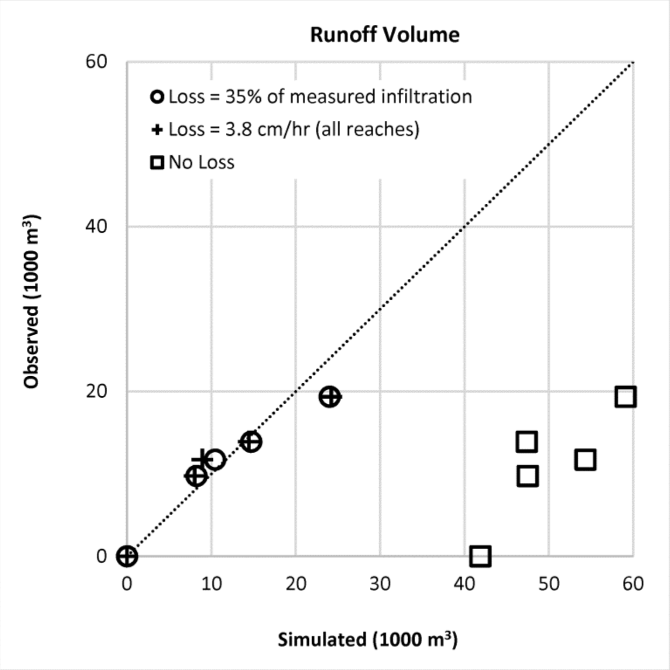

Fig. 10. Comparison of simulated and measured runoff volumes based on three transmission loss scenarios.

Fig. 10 compares simulated and observed runoff volumes at stations 2 and 3 for both storms, as well as volumes at the temporary pond for the June 16 storm. Again, model results overestimated runoff volumes when transmission losses were ignored (Fig. 10, squares). Using 35 percent of measured infiltration rates (circles), and using a constant loss rate of 3.8 cm/hr for each reach (crosses) both resulted in simulated volumes that closely matched measured data.

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Fig. 11 shows the measured hydrograph (solid line) at gauging station 2 for the June 16 storm compared to the model hydrograph with no transmission losses (dash-dotted), with uniform transmission losses of 3.8 cm/hr for all reaches (dashed), and losses equal to 35 percent of the measured rate for each reach (dotted). The comparison illustrates that both loss scenarios were almost identical.

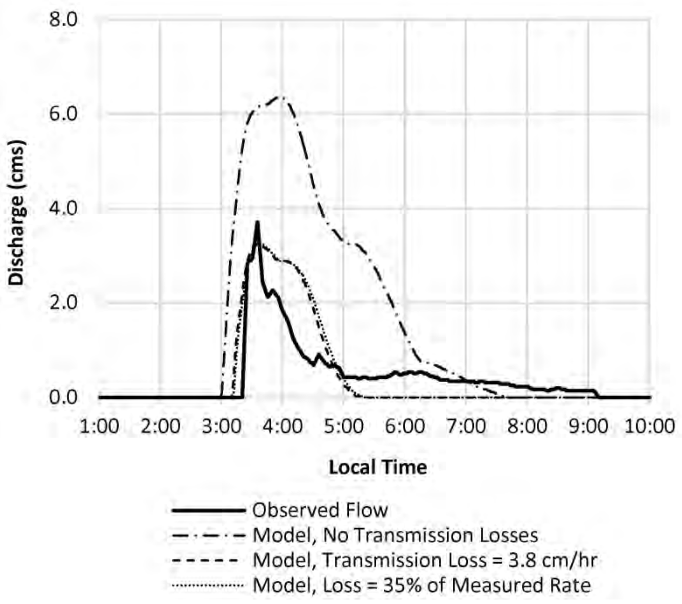

Fig. 11. Comparison of measured (solid) and simulated hydrographs (dotted, dashed, dash-dotted) at gauging station 2 for the storm of June 16, 2015.

The receding limb of the modeled hydrograph differs from the observed hydrograph in that the observed flow recedes faster initially, but tapers off more gradually after reaching a flow rate of approximately 0.5 cms. This discrepancy is due to the location of gauging station 2 at the outlet structure of a flood control dam. In HEC-HMS, flow through the dam is modeled using a simple storage-discharge relationship. This can causes problems during small flow events due to routing effects in the flood pool. When inflow into the dam is small (approximately 0.5 cms or less), a low flow channel conveys all discharge directly to the outlet structure, and no attenuation occurs. If the capacity of the low flow channel is exceeded, stormwater spreads out over the 3 hectare flood pool. At the receding end of the hydrograph, water slowly drains from the flood pool, which is essentially flat, towards the outlet. This phenomenon cannot be simulated with one storage-discharge curve, since the same discharge value can be associated with different storage values in the rising and receding limb of the hydrograph. For this study, the model was calibrated based primarily on peak discharge, runoff volume, and timing of the peak at station 2. Discrepancies in the receding limb of the hydrograph were accepted as limitations of the hydrologic model.

Fig. 12 displays the measured hydrograph (solid, lateral inflow removed) at gauging station 2 for the July 7 storm compared to the model hydrograph with no transmission losses (dash-dotted), with uniform transmission losses of 3.8 cm/hr for all reaches (dashed), and losses equal to 35 percent of the measured rate for each reach (dotted).

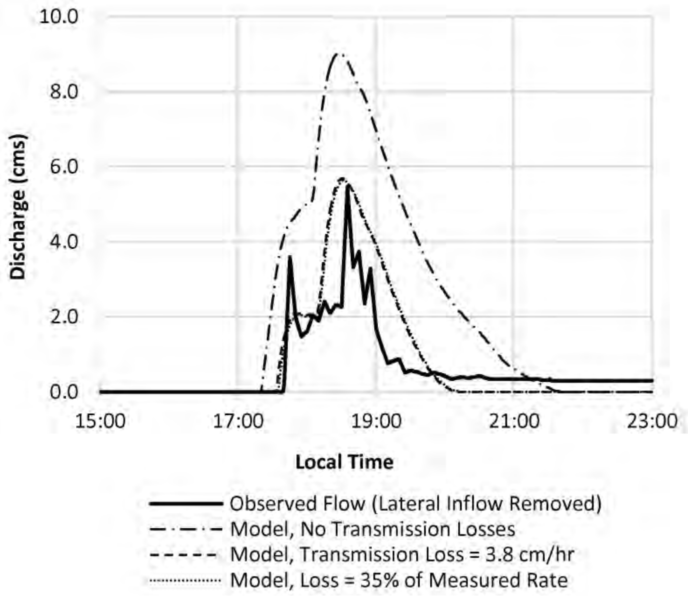

Fig. 12. Comparison of measured (solid) and simulated hydrographs (dotted, dashed, dash-dotted) at gauging station 2 for the storm of July 7, 2015.

Fig. 13 shows the same comparison at gauging station 3. The example illustrates that the difference between modeled and observed flows becomes larger going downstream when transmission losses are ignored. Both scenarios of accounting for transmission losses adequately replicated measured hydrographs, with exception of the receding limb of the hydrograph at station 2.

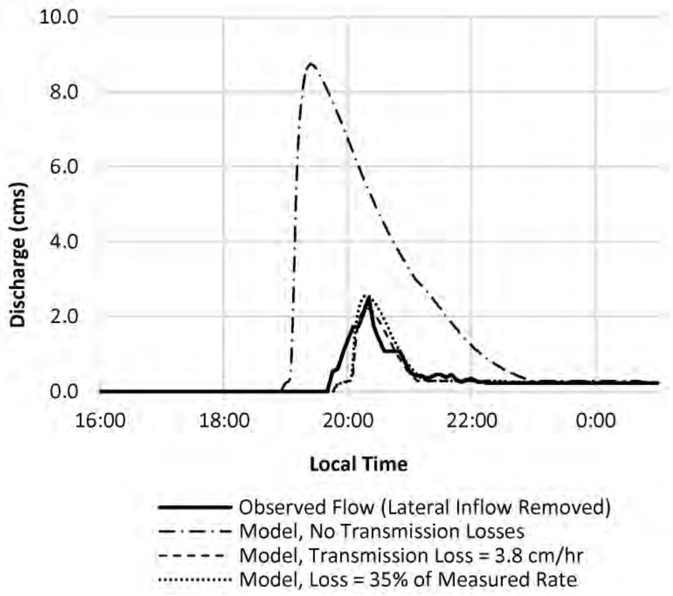

Fig. 13. Comparison of measured (solid) and simulated hydrographs (dotted, dashed) at gauging station 3 for the storm of July 7, 2015.

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Conclusions

This study shows that transmission losses can have a significant impact on flood hydrographs by reducing peak discharges and runoff volumes. Borings and soil testing in the Montoyas Arroyo revealed that channel bottom sediments are composed of sands with small amount of fines. Sandy layers are underlain by sediments with more fines and lower infiltration rates. However, due to the depth of the sand layer and relatively short duration of many storms, infiltration rates are expected to remain high for the duration of most runoff events.

Quantifying channel bottom infiltration rates using a double ring infiltrometer proved to be challenging. Although arroyo bottom soils were found to be fairly uniform, measured infiltration rates varied considerably between test sites, and no correlation between particle size characteristics and measured infiltration rate could be established. Variations in test results are likely due to problems with the test method itself (Lain and Ren, 2006; Swartzendruber and Olson, 1960), as well as the selection of test sites, and local variations in soil characteristics such as soil density and layering. On average, infiltrometer results overestimated reach-scale loss rates by 60%.

Measuring flood hydrographs at various locations along the arroyo proved to be the best method for determining actual transmission losses. Results from two storms observed during June and July of 2015 clearly show how flood hydrographs decreased in size as they traveled downstream. During the June 16 storm, storm flows did not even reach the outlet of the watershed. This study also demonstrates that transmission losses can be modeled successfully with the simplified method available in HEC-HMS. The loss methodology assumes a constant infiltration rate into the channel bed; over longer periods of time (days or weeks), this assumption may be violated due to sediment layers with a reduced hydraulic conductivity, or if the channel sediments became fully saturated. The latter is unlikely in case of the Montoyas Arroyo, since the regional water table is at significant depth below the channel surface, and impermeable sediments that would allow formation of a shallow, perched aquifer were only encountered at one site outside of the study reach. Typical runoff events in New Mexico only last hours, and assuming a constant loss rate therefore seems justified.

Modeled hydrographs closely matched observed flows with respect to peak discharge, runoff volume, timing, and overall hydrograph shape. Assigning reach specific loss rates based on a percentage of infiltration rates measured with a double ring infiltrometer did not improve model results. Applying a constant loss rate of 3.8 cm/hr for all reaches resulted in the best agreement between observed and modeled flows.

Transmission losses not only impact flood hydrographs, they also have a beneficial impact on water quality, especially in urbanized areas, where pollutants associated with hard surface runoff are of concern. Natural, unlined arroyos act as natural infiltration galleries, reducing the volume of runoff, and thereby the pollutant loads to the receiving water body.

Moreover, transmission losses are thought to be an important source of groundwater recharge in arid environments (Shanafield and Cook, 2014; Goodrich et al., 2004; Greenbaum et al., 2001; Geith and Sultan, 2002). Many communities in western states rely on groundwater as their sole source of potable water. Increasing urbanization is putting more strain on an already limited resource. Urbanization, however, also increases the frequency and magnitude of runoff events due to an increase in impervious surfaces. If arroyos prove to be important recharge zones for aquifers, quantifying transmission losses could have far reaching consequences for water management in the future.

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Notations

The following symbols are used in this paper:

cm/hr = centimeters per hour (infiltration rate);
D_{10} = grain diameter (in millimeters) for which 10 percent of the sample (by weight) is finer;
D_{50} = median grain size, grain diameter for which half the sample (by weight) is smaller and half is larger;
C_u = coefficient of uniformity;
C_c = coefficient of curvature;
cms = cubic meters per second (flow rate);
m^3 = cubic meters (runoff volume);

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