CHAPTER 3
Hydrologic processes in riparian areas
By Mary Nichols

Introduction

Water is taken for granted in many parts of the world where abundant, almost continually replenished supplies support people, livestock, and agriculture. But water is scarce in arid and semiarid regions, and this fact alone heightens attention to its sources, supply, distribution, and management. In Arizona, water supply will remain a dominant concern against a backdrop of increasing demand as ranching, agriculture, wildlife, increasing population, urbanization, expanding industry, and needs of downstream water users all compete for limited water resources.

This chapter provides general information describing the sources, distribution, and circulation of water on and below the earth's surface and in the atmosphere, with emphasis on Arizona. The science dealing with these topics is termed hydrology, and the processes that act to move water through the atmosphere and the earth are termed ‘hydrologic processes.’ Water is moved from the earth to the atmosphere as water vapor through evaporation and transpiration, water vapor condenses and falls as rain or snow, then travels laterally and downhill across the land surface, or infiltrates to underground aquifers, and travels laterally underground occasionally surfacing as springs and streamflow. The same water has been transferred around the globe since the origin of the earth. This cycle is termed the ‘hydrologic cycle’ (Figure 1). The hydrologic cycle is driven by the sun, which provides energy, and gravity, which keeps water moving vertically and horizontally. Hydrologic processes in Arizona are characterized by highly variable precipitation, runoff, and infiltration. This variability is seen across a range of spatial scales. For example, an individual rainstorm may cover a very local area. In contrast, regional droughts and large scale floods can affect large areas. In addition to the inherent variability in these processes, the effects of land use and management can have both direct and indirect effects on hydrologic processes.

Precipitation

Precipitation in Arizona, and throughout the southwest, exhibits some of the greatest variability within the US. Precipitation varies temporally at several scales:
1) daily in response to summer thunderstorms,
2) seasonally,
3) annually with drought and flood cycles, and
4) in response to larger scale atmospheric circulation patterns such as El Nino and La Nina.

Precipitation also varies spatially both across the landscape and with elevation. The amount of precipitation that falls is typically measured using a rain gauge. This provides a point measurement. Several point measurements collected through a network of rain gauges can be used to interpret the volume of precipitation over a region. Rain gauge
technological spans a broad range from basic plastic graduated cylinders to tipping bucket gages and electronic weighing rain gauges. Traditional gage measurements are complimented with data collected through new technologies such as radar.

Generally, precipitation is the result of four types of storms: convective storms, tropical storms, uplift near mountains, and frontal storms. In southeastern Arizona approximately 2/3 of the annual precipitation falls during the summer "monsoon season" that typically last from July through mid September. Thunderstorms deliver most of the monsoon rainfall in the southwestern United States. These storms result from convection that lifts moist air. This rising air cools, causing condensation and ultimately precipitation. Thunderstorms are typically characterized by extreme spatial variability, limited areal extent, and short durations (Osborn, 1982). Topography influences summer thunderstorms in areas where higher-elevation mountains cause elevated heating and enhanced convection (Carleton, 1986).

Although annual precipitation volume is dominated by summer thunderstorm rainfall in southeastern Arizona, the general precipitation pattern is characterized by a bimodal precipitation distribution that provides both winter and summer rain. Winter precipitation results from storms characterized by long duration, low intensity, and large aerial
coverage (Sellers, 1960). These precipitation events generally result from air mass lift caused by slow moving storm fronts emerging from the Pacific Ocean into and across California and Arizona. The bimodal precipitation pattern is less pronounced at higher elevations and in northern regions of Arizona where snow plays an important part in the hydrologic cycle.

In addition to seasonal patterns of precipitation in Arizona, climate patterns across longer time scales affect precipitation. Within the last decade, connections between climate and larger scale atmospheric phenomenon have been the subject of scientific interest and research. Characterizing the climate of the southwestern United States has revealed connections between increasing sea surface temperatures in the eastern Pacific Ocean and above-average winter precipitation totals (El Niño) and the related atmospheric component that includes barometric pressure variations that drive air flow patterns (Southern Oscillation). On an interannual time scale El Niño has been identified as a cause of quasi-periodic climate variability. El Niño episodes, which are associated with wetter winters in the southwest, have been identified as a major source of variability in precipitation (Woolhiser et al., 1993; Andrade and Sellers, 1988; Carleton, et al., 1990; Redmond and Koch, 1991). A series of wetter winters since the 1970’s in the southwest has been linked to the more frequent occurrence of El Niño episodes, especially in the decade from 1980 to 1990 (Trenberth and Hoar, 1996).

**Runoff and Infiltration**

If the rate of precipitation that falls exceeds the capacity of the ground to absorb it, the excess rainfall becomes runoff. Runoff traveling across the surface of the landscape is termed sheetflow, or overland flow. Overland flow may be absorbed into soils further downslope through the process of infiltration, or it may reach the channel network as surface flow. Water that seeps, or infiltrates, through sediment in channels may contribute to groundwater recharge.

In southern Arizona, precipitation during the summer “monsoon” season causes most of the overland flow. Overland flow collects in the channel network, and the resulting flows are typically very flashy, have large peak discharge rates and are short lived (Lane, 1983; Boughton, et al., 1987; Goodrich et al., 1997). Snowmelt in higher elevations contributes to runoff.

In contrast to thunderstorm generated runoff, the consequences of precipitation during non-summer months are less dramatic, but are still important to semiarid ecosystems. Infiltration and soil moisture distribution dominate the hydrologic cycle from October through May. Precipitation during non-summer months is more likely to be gentle, long duration, soaking rain that produces very little runoff. Conditions during these cooler months are more favorable for soil moisture storage because during the summer months, high temperatures result in large evaporation losses. Vegetation in semiarid ecosystems has evolved to make efficient use of this temporally distributed precipitation. Land use...
and management strategies have been developed to accommodate dry periods and the subsequent “monsoons”.

**Evaporation and Transpiration**

Evaporation is the return of water to the atmosphere from surfaces such as streams, lakes, puddles, ponds, and soil pores. Plants contribute water vapor to the atmosphere through the process of transpiration. The combined contributions of these processes is termed "evapotranspiration". The rates of both evaporation and transpiration depend on temperature and humidity, which are influenced by longitude and latitude, elevation, and proximity to the ocean. In addition, local climate factors such as temperature and wind speed affect both evaporation and transpiration. Transpiration also varies by species with the amount and kind of vegetation, as well as with the growing season.

**Transmission losses**

In semiarid regions, ephemeral channels that flow only in response to rainfall or snowmelt make up many channel networks. Within these normally dry channels, transmission losses are an important component of the water budget. Transmission losses, also called abstractions, refer to the water that infiltrates into the channel bed and banks during stream flow.

As a flow travels through a normally dry channel, water that infiltrates into the channel reduces the runoff volume and the peak rate of flow downstream. Water lost to this infiltration can contribute to groundwater recharge, and at a minimum will affect soil moisture distribution in surface sediment layers. Groundwater recharge can be seen as increases in water levels in wells in and adjacent to channels following flood events. Runoff losses to this type of infiltration can be large.

An example of transmission losses from measurements taken on the Walnut Gulch Experimental Watershed follows (Figure 2). The watershed is instrumented to measure runoff along the main channel through a network of runoff measuring flumes. A runoff producing storm on August 27, 1982, was isolated in the upper 95 km² of the watershed (and not all of that produced runoff). No additional runoff entered the channel as it traveled through Flumes 6, 2, and 1. The runoff measured at Flume 6 amounted to 246,200 m³ with a peak discharge of 107 m³s⁻¹. Runoff traversing 4.2 km of dry streambed between Flume 6 and Flume 2 resulted in significant infiltration losses. For example, in the 4.2 km reach the peak discharge was reduced to 72 m³s⁻¹ and 48,870 m³ of water were absorbed in the channel alluvium. During the course of the 6.7 km from Flume 2 to Flume 1, the peak discharge was further reduced, and 41,930 m³ of runoff was infiltrated in the channel alluvium.

Ephemeral channel transmission losses play an important role in ground water/surface water dynamics in arid and semi-arid basins in the southwest. However, identifying the processes driving these dynamics is difficult. Quantifying recharge with greater certainty
is a critical need for managing basins whose primary source of water supply is derived from groundwater. Currently, an intensive research effort to estimate groundwater recharge using a variety of direct measurement and chemical, isotopic, tree sap flux, micrometeorological, and microgravity techniques is underway in the San Pedro River Basin (Goodrich et al., 2004). Wet monsoon seasons in 1999 and 2000 caused substantial changes in near-channel groundwater levels. Results indicate relatively good agreement between the average estimates from each of the methods, in that they differ by less than a factor of three. This range is not surprising given the limitations of the various methods, and the differences in time scales over which they are applicable. Crudely scaled to the basin level, this recharge would constitute between 20 and 50% of basin recharge as estimated from a calibrated groundwater model.

The water balance - an accounting method

How do we summarize the amount of water that is cycling from the atmosphere, across the land surface, into the ground, through plants, into the ocean, back to the atmosphere through evaporation? One commonly used method is a water balance. This convenient method of book keeping is a good framework for understanding hydrologic processes. An example water balance is provided to illustrate the accounting of water within the Walnut Gulch Experimental Watershed which is an ephemeral tributary watershed within the large San Pedro River Watershed.
The Walnut Gulch Experimental Watershed water balance (Figure 3), although variable from year to year as well as across the area, is obviously controlled by precipitation. The annual water balance is illustrated for average conditions. Given the average 305 mm precipitation input, approximately 254 mm is detained on the surface. Surface water may infiltrate, or it may evaporate. Because potential evaporation is approximately 2600 mm per year, which is approximately 7.5 times the annual precipitation, essentially all of the infiltrated moisture is either evaporated or transpired by vegetation back to the atmosphere. Based on data collected from small watersheds less than 1.5 hectares in area in Walnut Gulch, approximately 51 mm of the incoming precipitation is in excess of that which is intercepted and/or infiltrates. This is referred to as "onsite runoff." As the runoff moves over the land surface and into dry alluvial channels, transmission losses begin. Approximately 45 mm of transmission losses occur and less than 10 mm of surface runoff are measured at the watershed outlet. The 45 mm of transmission losses result in some ground water recharge and some evaporation and transpiration from vegetation along the stream channels. Quantities for ground water recharge and evaporation and transpiration of channel losses are not shown because their quantification is difficult and very site specific. This is an area of active research. The geology along and beneath the stream channel creates some reaches that are underlain by impervious material, whereas in other locations, the channel extends to regional groundwater and permits appreciable recharge. In areas where the channel is underlain by impermeable material, riparian aquifers connected to the channel can become saturated and will support phreatophytes.

Figure 3. Annual water balance for the USDA-ARS Walnut Gulch Experimental Watershed in southeastern Arizona (illustration from Renard et al., 1993).
Floods and Droughts

Floods and droughts are common in Arizona. Although the destructive effects of floods in eroding and reshaping channels receive much attention, floods provide critical out-of-bank deposits in riparian areas that replenish nutrient supplies. Floods occur on both local and regional scales. Local floods occur with greater frequency largely in response to summer thunderstorms. Historically, regional flooding in Arizona generally has occurred between September and March, largely as the result of the cumulative effects of precipitation and runoff across many small watersheds. Precipitation lasting for several days and covering large areas causes runoff over large areas that accumulates as flow travels through the channel network.

Although floods are more dramatic in their suddenness and destruction, the persistence of droughts can cause more severe consequences. Droughts may initially be associated with a lack of precipitation, but long-term consequences such as soil moisture deficit, reduced surface water flow, and a drop in groundwater level have severe impacts on ecosystems and water supply. A summary of the major and other memorable floods and droughts in Arizona from 1862-1988 (Paulson et al. 1989) is presented in Table 1.

Summary

Knowledge of hydrologic processes is critical for understanding the sources, distribution, and circulation of Arizona’s water resources. The need for information describing Arizona’s hydrologic processes will continue to escalate as demand increases across a broad range of users competing for limited water resources. Throughout the semiarid southwest, water resource management is challenging because precipitation, runoff, and infiltration exhibit great variability in time and space. However, measurements to quantify these hydrologic processes can be used to develop water budgets. This type of information will play a critical role in managing Arizona’s riparian areas.
<table>
<thead>
<tr>
<th>Flood or Drought</th>
<th>Date</th>
<th>Area Affected</th>
<th>Recurrence Interval (in years)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flood</td>
<td>Jan. 19-23, 1862</td>
<td>Gila and Colorado Rivers</td>
<td>Unknown</td>
<td>Severe at Yuma. Wet year in Verde and Bright Angel basins, but not in upper Salt.</td>
</tr>
<tr>
<td>Flood</td>
<td>Feb. 18-26, 1891</td>
<td>Central Highlands</td>
<td>25 to 100</td>
<td>Phoenix and Yuma flooded. In Clifton, deaths, 18; damage, $1 million.</td>
</tr>
<tr>
<td>Flood</td>
<td>Nov. 27-30, 1905</td>
<td>San Francisco to Verde Rivers</td>
<td>5 to 10</td>
<td>Several moderate to severe floods, particularly at Phoenix and along the lower Gila River.</td>
</tr>
<tr>
<td>Flood</td>
<td>Jan. 19-22, 1916</td>
<td>Central Highlands</td>
<td>10 to 0</td>
<td>Intense rain on melting snow produced large flows in central Arizona. Deaths, 4; damage, $300,000.</td>
</tr>
<tr>
<td>Flood</td>
<td>Aug. 21, 1921</td>
<td>Phoenix (Cave Creek)</td>
<td>Unknown</td>
<td>Six inches of rain in two days flooded 1,600 hectares and the State capitol building. Damage $240,000</td>
</tr>
<tr>
<td>Flood</td>
<td>Sept. 27-29, 1926</td>
<td>San Pedro River and Mexico</td>
<td>&gt;100</td>
<td>Tropical storm. Peak flow 2 - 3 times larger than any other in 70 years. Damage, $450,000</td>
</tr>
<tr>
<td>Drought</td>
<td>1932-36</td>
<td>Statewide</td>
<td>10 to 20</td>
<td>Effects differed among basins.</td>
</tr>
<tr>
<td>Flood</td>
<td>Mar. 14-15, 1941</td>
<td>Central Arizona</td>
<td>5 to 40</td>
<td>One of several storms that caused general runoff and filled reservoirs</td>
</tr>
<tr>
<td>Drought</td>
<td>1942-64</td>
<td>Statewide</td>
<td>&gt;100</td>
<td>Second most severe in 350 years, on the basis of tree-growth records.</td>
</tr>
<tr>
<td>Flood</td>
<td>Sept. 26-28, 1962</td>
<td>Brawley and Santa Rosa Washes</td>
<td>&gt;100</td>
<td>Deaths, 1; damage, $3 million, mostly to agriculture near Casa Grande.</td>
</tr>
<tr>
<td>Flood</td>
<td>Dec. 22, 1965 to Jan. 2, 1966</td>
<td>Verde, Salt, and Gila Rivers and Rillito Creek.</td>
<td>10 to 50</td>
<td>First large flow through Phoenix since reservoirs were built on Verde River (1939). Damage, $10 million.</td>
</tr>
<tr>
<td>Flood</td>
<td>Dec. 5-7, 1966</td>
<td>Grand Canyon to southwestern Utah.</td>
<td>&gt;100</td>
<td>Mudflows and channel erosion damaged Indian ruins that had been undisturbed for 800 years.</td>
</tr>
<tr>
<td>Flood</td>
<td>Sept. 5-7, 1970</td>
<td>Tonto Creek to Hassayampa River.</td>
<td>40 to 100</td>
<td>Labor Day weekend floods in recreation areas. Reservoirs stored most runoff. Deaths, 23; damage, $8 million</td>
</tr>
<tr>
<td>Flood</td>
<td>Oct. 17-21, 1972</td>
<td>Upper Gila River</td>
<td>10 to 40</td>
<td>Tropical storm. Deaths, 8; damage, $10 million.</td>
</tr>
<tr>
<td>Drought</td>
<td>1973-77</td>
<td>Statewide</td>
<td>15 to 35</td>
<td>Most severe in eastern Arizona.</td>
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<tr>
<td>Flood</td>
<td>July 17, 1974</td>
<td>Safford (Holyoke Wash)</td>
<td>&gt;100</td>
<td>Thunderstorm produced flow of 1,740 cubic feet per second from 0.85 square mile.</td>
</tr>
<tr>
<td>Flood</td>
<td>Oct. 1977 to Feb. 1980</td>
<td>Central and southeastern Arizona</td>
<td>5 to 100</td>
<td>Seven regional floods. Phoenix declared a disaster area three times. Deaths, 18; damage, $310 million.</td>
</tr>
<tr>
<td>Flood</td>
<td>July 26, 1981</td>
<td>Tucson (Tanque Verde Falls)</td>
<td>less than 2</td>
<td>Flash flood at recreation area on Sunday; deaths, 8. Two larger peak discharges in the same week were not noticed.</td>
</tr>
<tr>
<td>Flood</td>
<td>June 20 to Aug. 17, 1983</td>
<td>Colorado River</td>
<td>20 to 40</td>
<td>Upper basin rain and snowmelt. First reservoir spill since Hoover Dam was built (1935). Damage, $80 million.</td>
</tr>
<tr>
<td>Flood</td>
<td>Oct. 1-3, 1983</td>
<td>Santa Cruz to San Francisco Rivers</td>
<td>10 to &gt;100</td>
<td>Record floods on 18 streams; two peak discharges doubled 65-year-old records. Deaths, 8; damage, $226 million.</td>
</tr>
</tbody>
</table>
References


