2006

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Winter, Thomas C., "The Role Of Ground Water In Generating Streamflow In Headwater Areas And In Maintaining Base Flow" (2006). *USGS Staff -- Published Research*. 616.
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JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION

Vol. 43, No. 1 AMERICAN WATER RESOURCES ASSOCIATION February 2007

THE ROLE OF GROUND WATER IN GENERATING STREAMFLOW IN HEADWATER AREAS AND IN MAINTAINING BASE FLOW[1]

Thomas C. Winter[2]

ABSTRACT: The volume and sustainability of streamflow from headwaters to downstream reaches commonly depend on contributions from ground water. Streams that begin in extensive aquifers generally have a stable point of origin and substantial discharge in their headwaters. In contrast, streams that begin as discharge from rocks or sediments having low permeability have a point of origin that moves up and down the channel seasonally, have small incipient discharge, and commonly go dry. Nearly all streams need to have some contribution from ground water in order to provide reliable habitat for aquatic organisms. Natural processes and human activities can have a substantial effect on the flow of streams between their headwaters and downstream reaches. Streams lose water to ground water when and where their head is higher than the contiguous water table. Although very common in arid regions, loss of stream water to ground water also is relatively common in humid regions. Evaporation, as well as transpiration from riparian vegetation, causing ground-water levels to decline also can cause loss of stream water. Human withdrawal of ground water commonly causes streamflow to decline, and in some regions has caused streams to cease flowing.

(KEY TERMS: streamflow characteristics; ground-water and surface-water interactions; riparian zones.)

Winter, Thomas C., 2007. The Role of Ground Water in Generating Streamflow in Headwater Areas and in Maintaining Base Flow. *Journal of the American Water Resources Association* (JAWRA) 43(1):15-25. DOI: 10.1111/j.1752-1688.2007.00003.x

INTRODUCTION

Streams can originate from glacial-melt water, overland runoff derived from precipitation and/or snowmelt, shallow subsurface flow through the unsaturated zone, and ground-water discharge. Of these processes, ground-water discharge usually is the least variable source of water to streams. However, even the ground-water contribution to streams can be variable depending on the hydrogeologic and climate settings of a stream. Ground-water discharge to streams would be expected to be least variable, and the point of origin of a stream more stable, in areas where the streams drain large, permeable ground-water reservoirs. In contrast, ground-water discharge to streams and the point of origin of a stream would be expected to be highly variable where the streams drain ground-water reservoirs having low permeability.

To address the question posed by this featured collection that is, "what is the role played by headwaters in maintaining the physical, chemical, and biological integrity of waters in lower watershed positions," the purpose of this article was to examine how ground water affects the generation and maintenance of streamflow in a few selected hydrogeologic and

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[1] Paper No. J06016 of the *Journal of the American Water Resources Association* (JAWRA). Received February 3, 2006; accepted September 21, 2006. © 2007 American Water Resources Association. No claim to original U.S. government works.

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climatic settings. Understanding the interactions of ground water and surface water is fundamental to understanding and managing the chemical and biological characteristics of streams throughout their length. The article first presents background information on some fundamentals of stream and ground-water interaction. This is followed in turn by sections on (1) small headwater streams in mountainous terrain, (2) larger streams in different hydrogeologic terrain, and (3) causes for loss of stream water that affect its ability to reach lower watershed positions.

THE EFFECT OF GEOLOGIC SUBSTRATE ON THE INTERACTION OF GROUND WATER AND SURFACE WATER

Streams receive discharge from ground water where the hydraulic head of the stream is lower than heads in the contiguous ground-water system (Figure 1a). Conversely, streams lose water to ground water where the hydraulic head of the stream is higher than heads in the contiguous ground-water system (Figure 1b). In geologic formations that have high hydraulic conductivity, the gradients between the stream and the ground-water system generally are not large, but the quantity of water exchanged between the two water compartments can be substantial. Conversely, in geologic formations that have low hydraulic conductivity, the gradients between the stream and the ground-water system generally are large, but the quantity of water exchanged between the two water compartments usually is small.

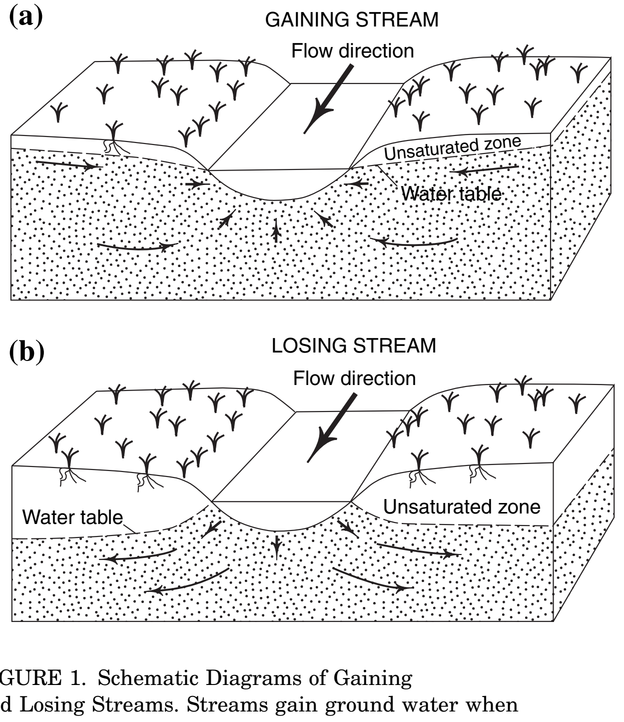

FIGURE 1. Schematic Diagrams of Gaining and Losing Streams. Streams gain ground water when ground-water hydraulic heads are higher than those in the stream (a) and lose water to ground water when stream heads are higher than those in ground water (b).

A stream that originates in an extensive, highly permeable aquifer commonly will have a relatively stable supply of water in its headwater area, resulting in a stable point of origin and relatively stable flow. Streams that flow across highly permeable aquifers also tend to have large recession indexes. Most precipitation infiltrates to recharge ground water, which is then slowly released to the stream, resulting in slowly diminishing streamflow between precipitation events. (Recession rates usually are discussed in terms of a "recession index," which is the time it takes for stream discharge to decrease across one log cycle when plotted on a semi-log graph.) Streams that originate in terrain having low permeability generally have highly variable flow, resulting in unreliable supplies of water not only to the headwater area, but also to downstream reaches. Such streams also tend to have small recession indexes because most precipitation runs off rather than recharging ground water, resulting in minimal release of ground water to the stream.

If a stream is initially large in its headwater area, that water is likely to flow for long distances to lower reaches, providing water for aquatic habitats throughout its length. However, if losses to evaporation and/or losses to ground water are large along the way, the stream would provide a far less reliable supply of water to aquatic organisms in downstream reaches.

The following are two examples of extreme conditions of ground-water contribution to streams. The Dismal River in Nebraska originates in, and continues to receive ground-water discharge from, a vast, permeable aquifer. In contrast, the Park River in North Dakota originates in glacial till having low permeability, and then flows across a clayey, glacial-lake plain having even lower permeability. The locations of the streams and rivers discussed in this article are shown in Figure 2.

Dismal River, Nebraska

The Dismal River originates in the eastern part of the Nebraska Sand Hills, which is an extensive area of sand dunes covering about 50,000 km^2 in the central and western part of the state. The dunes overlie the Ogallala Aquifer, which underlies much of the western high plains from Nebraska to Texas. A 38-year record of discharge of the Dismal River near Thedford, Nebraska shows very consistent annual variability

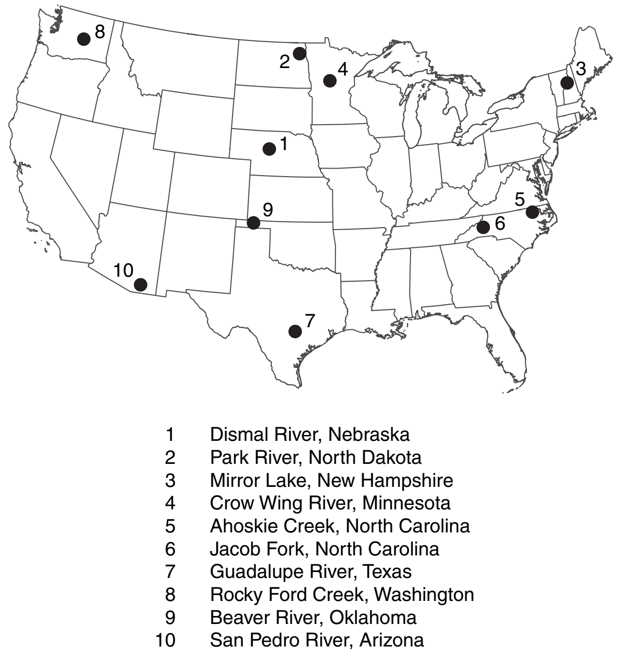

FIGURE 2. Map Showing the Locations of the Streams and Rivers Discussed in This Article.

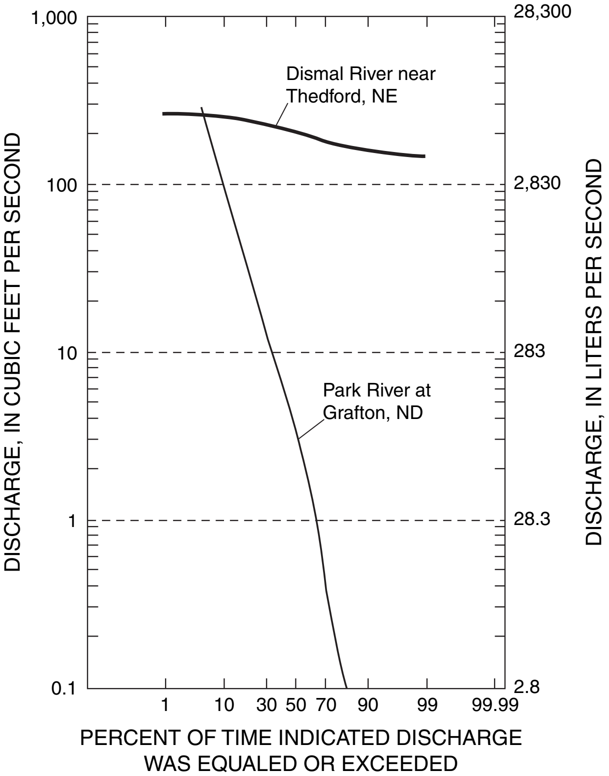

FIGURE 3. Flow-Duration Curves for the Dismal River Near Thedford, Nebraska (Drainage Area 2,500 km^2 (78 km^2 Directly Contributing); Period of Record 1966-2004) and the Park River at Grafton, North Dakota (Drainage Area 1,800 km^2; Period of Record 1950-2004).

and little change in the long-term trend. A summary of those data, especially with respect to determining the ground-water contribution to a stream, is shown most conveniently by a flow-duration curve. A flow-duration curve shows the percentage of time a given daily average discharge was equaled or exceeded for a given period of record. In the case of the Dismal River (Figure 3), the curve has a very low slope. Over the 38-year period of record, discharge of about 7,650 l/s [270 cubic feet per second (cfs)] was exceeded 1% of the time, about 5,950 l/s (210 cfs) 50% of the time, and about 4,250 l/s (150 cfs) 99% of the time. These data indicate the large and stable ground-water contribution to this stream.

Park River, North Dakota

The Park River in North Dakota is at the other extreme in showing the effect of ground-water contribution to a stream. After originating in, and flowing over, a gently undulating plain underlain by till having low permeability, the river passes across a narrow band of thin, sandy beach ridge deposits, and then flows across a glacial lake plain consisting of clay having extremely low permeability. The flow-duration curve for the Park River at Grafton, North Dakota (Figure 3) has a very steep slope. Over the 54-year period of record, discharge of about 8,200 l/s (290 cfs) was exceeded about 5% of the time, about 88 l/s (3.1 cfs) 50% of the time, and 2.3 l/s (0.1 cfs) 80% of the time. The stream was dry about 20% of the time. These data indicate that the stream has very little inflow from ground water.

These two examples indicate the usefulness of flow-duration curves for understanding streamflow, especially the extent to which a stream is supported by ground-water contributions. The flatter the curve, the more the stream is supported by ground-water inflow. The steeper the curve, the less it is supported by ground-water inflow.

SMALL STREAMS IN HEADWATER AREAS

Long-term monitoring of streamflow in the Hubbard Brook Valley in New Hampshire, together with extensive studies of ground water near Mirror Lake at the lower end of the valley, provides a useful dataset for examining the effect of ground water on streamflow in small headwater catchments. The Hubbard Brook Valley is underlain by fractured crystalline bedrock. Glacial deposits that range in thickness from less than one to several meters overlie the bedrock throughout much of the valley. The glacial deposits tend to be thicker lower on the hillsides and toward the lower end of the valley, near Mirror Lake. Mau and Winter (1997) examined the ground-water contribution to three streams in the Hubbard Brook Valley. Hubbard Brook watershed 3 (HB3) is high on the valley side, has an area of about 42 ha, and has glacial deposits generally <2 m thick. Mirror Lake watershed W (MLW) has an area of about 24 ha, and has glacial deposits as much as 18 m thick. Mirror Lake watershed NW (MLNW) has an area of about 35 ha, and has a greater extent of thick glacial deposits compared with the other two watersheds, reaching thicknesses of 30 m (Winter, 1984; Tiedeman *et al.*, 1997).

The recession indexes and the flow-duration curves for the three streams draining these watersheds reflect the effect ground water has on their flow characteristics. The recession index is about 125 days per log cycle for the stream draining watershed MLNW, about 85 days per log cycle for the stream draining watershed MLW, and about 28 days per log cycle for the stream draining watershed HB3. These recessions indicate the relatively greater contribution of ground water to the stream draining watershed MLNW compared with the other two streams, and the small contribution of ground water to the stream draining watershed HB3. The flow-duration curves clearly show the distinctions between the streams (Figure 4). The curve for the stream draining watershed MLNW indicates that the stream never goes dry, having discharge >0.8 l/s (0.028 cfs) 99% of the time. The stream draining watershed MLW goes dry about 4% of the time, and the stream draining watershed HB3 goes dry about 15% of the time. The high ends of the curves are of interest also because they show the considerably higher discharge in the stream draining watershed HB3 compared with the Mirror Lake streams, which reflects the greater precipitation in that higher watershed and the lesser recharge to ground water.

LARGER STREAMS IN DIFFERENT HYDROGEOLOGIC AND CLIMATIC SETTINGS

Although it is useful to examine the contribution of ground water to streamflow generation in very small catchments, such as at Hubbard Brook, for purposes of this special issue it might be of more interest on a national scale to examine larger watersheds. The following are examples showing the effect of ground water on streamflow in different types of hydrogeologic and climatic settings. The examples are of glacial terrain in Minnesota, the piedmont and coastal plain in North Carolina, carbonate terrain in Texas, and volcanic basalt terrain in Washington.

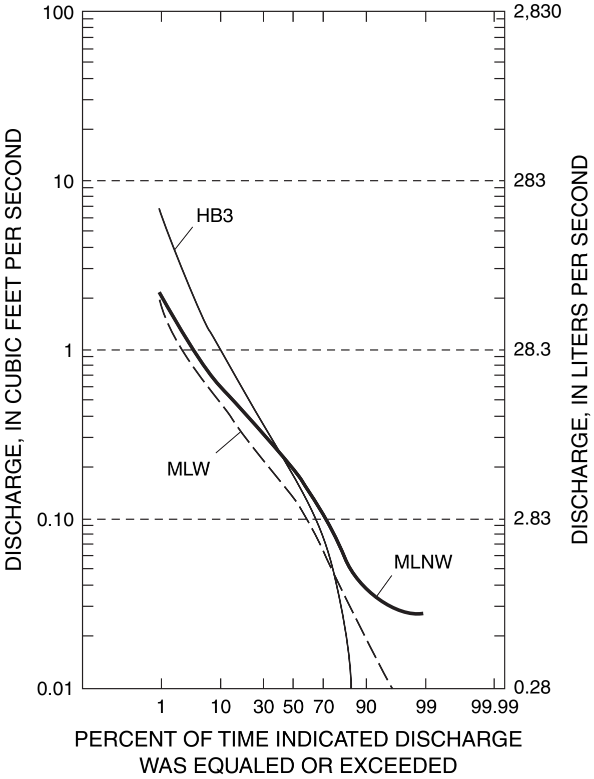

FIGURE 4. Flow-Duration Curves for Three Streams Near Mirror Lake in the Hubbard Brook Valley in New Hampshire. The northwest watershed of Mirror Lake (MLNW) has a drainage area of 35 ha. The west watershed of Mirror Lake (MLW) has a drainage area of 24 ha. Hubbard Brook watershed 3 (HB3) has a drainage area of 42 ha. The period of record is 1980-90.

Crow Wing River, Minnesota

The Crow Wing River watershed covers nearly 10,000 km^2 in central Minnesota. The watershed contains extensive sand and gravel outwash plains in the northern part and a mix of smaller outwash plains and till plains in the southern part (Lindholm *et al.*, 1972). Ground-water contribution to the Crow Wing River is substantial in the northern part, as indicated by the continually increasing average discharge in the downstream direction from the headwater area near the town of Park Rapids to the town of Motley (Figure 5). The watershed of the Crow Wing River at Nimrod, which lies at the south end of the largest outwash plain in the northern part of the area, covers about 2,616 km^2. The substantial contribution of ground water to the river upstream from this location is indicated by the relatively low slope of the flow-duration curve of the Crow Wing River at

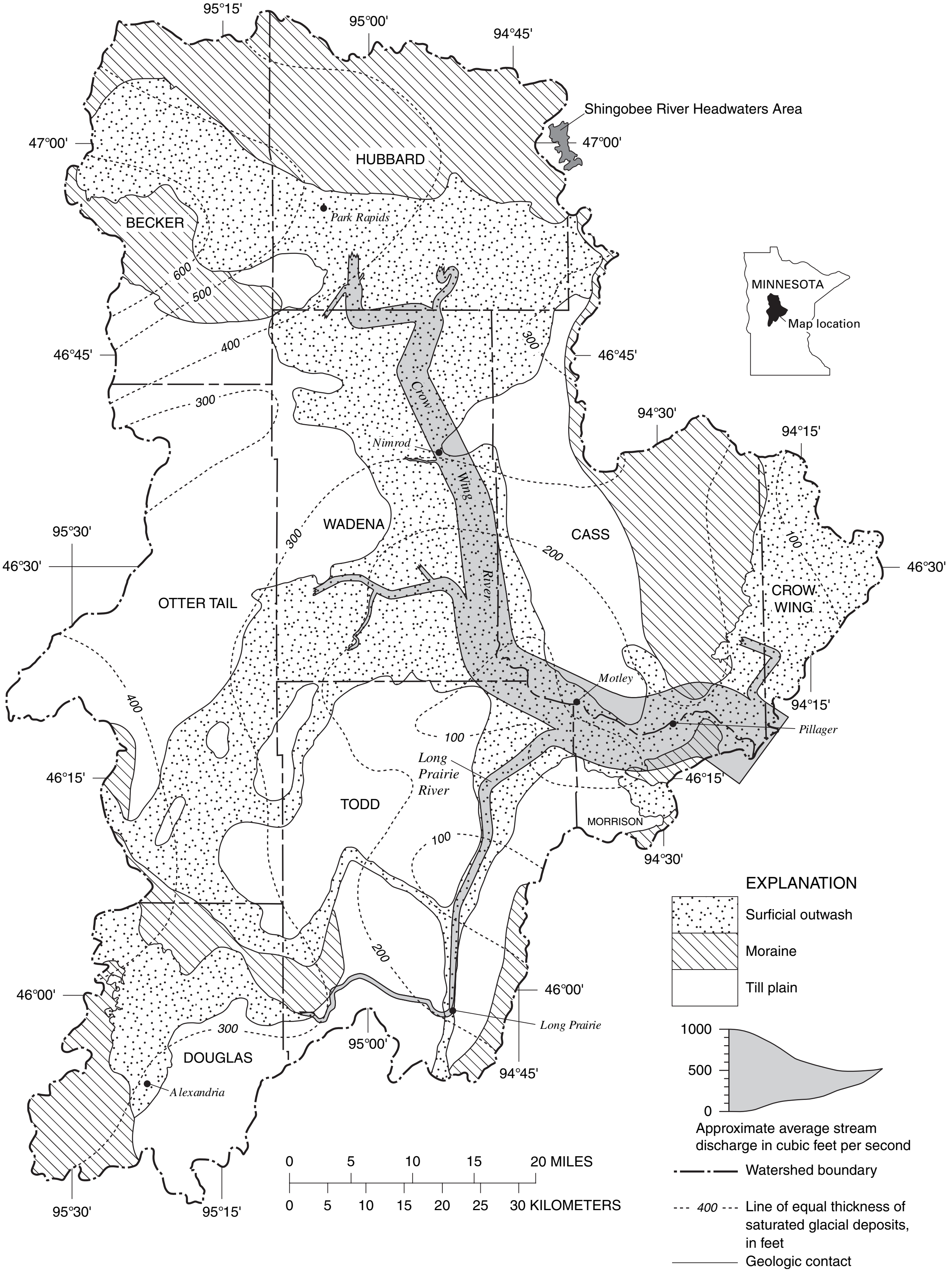

FIGURE 5. Geologic Map and Average Discharge of Streams in the Crow Wing Watershed in Minnesota. Modified from Lindholm *et al.* (1972).

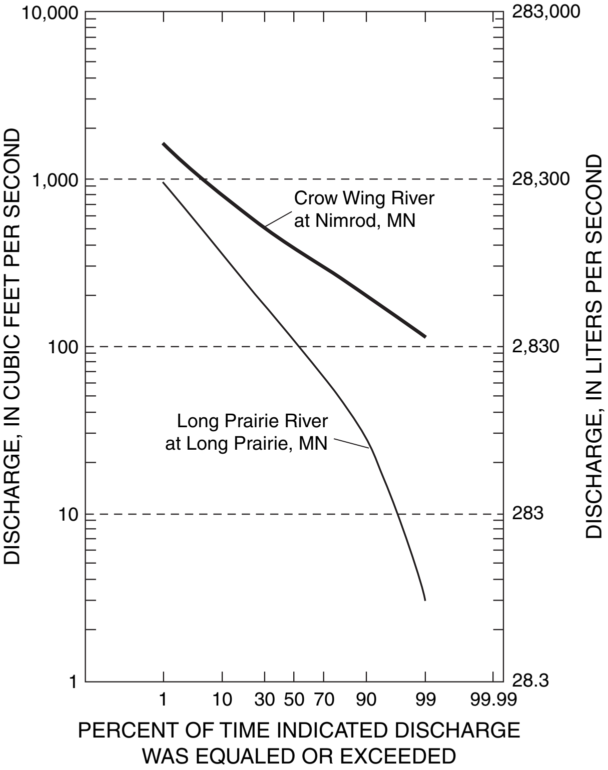

FIGURE 6. Flow-Duration Curves for the Crow Wing River at Nimrod, Minnesota (Drainage Area 2,616 km^2; Period of Record 1910-2004) and the Long Prairie River at Long Prairie, Minnesota (Drainage Area 1,124 km^2; Period of Record 1971-2004).

Nimrod (Figure 6). Discharge of the river at Nimrod is >3,250 l/s (115 cfs) more than 99% of the time.

In contrast, the average discharge of the Long Prairie River in the southern part of the area increases very little as it flows from its headwater area to its confluence with the Crow Wing River near Motley (Figure 5). The flow-duration curve for the Long Prairie River at Long Prairie (Figure 6) has a fairly steep slope, and it shows that the river comes close to being dry about 1% of the time. Discharges <85 l/s (3 cfs) occurred about 1% of the time and discharges <3,100 l/s (110 cfs) occurred about 50% of the time. The drainage area above the gauge at Long Prairie is about 1,124 km^2.

These two streams provide good examples of the importance of ground water in generating and maintaining streamflow throughout the length of a stream. The Crow Wing River is already as large where it is first gauged near Park Rapids as the Long Prairie River is where it joins the Crow Wing River near Motley (Figure 5). Furthermore, the Crow Wing River becomes increasingly larger as it flows through extensive areas of outwash. In contrast, although the Long Prairie River begins in a small outwash plain, it gains little ground water as it crosses a till plain on its way to Long Prairie. Even though the river flows through a narrow strip of outwash downstream from Long Prairie, the outwash is not areally extensive and it contributes only a small amount of additional ground water to the stream.

As a result of the substantial inflow of ground water, aquatic organisms in the Crow Wing River benefit from a reliable source of water throughout its length. The period of record for the gauge at Nimrod extends from 1910 to the present; therefore, the data indicate that the river discharge was not less than about 2,850 l/s (100 cfs) even during the worst droughts of the 20th century. The Long Prairie River has a much less reliable source of water for organisms in its downstream reaches because of the minimal input of ground water.

Ahoskie Creek and Jacob Fork, North Carolina

Ahoskie Creek originates in the Atlantic Coastal Plain near the upper end of Albemarle Sound in North Carolina. The geologic deposits in this area consist of unconsolidated sand containing some silt and gravel. The flow-duration curve for Ahoskie Creek at Ahoskie, North Carolina (Figure 7) has a relatively steep slope, indicating that the surface

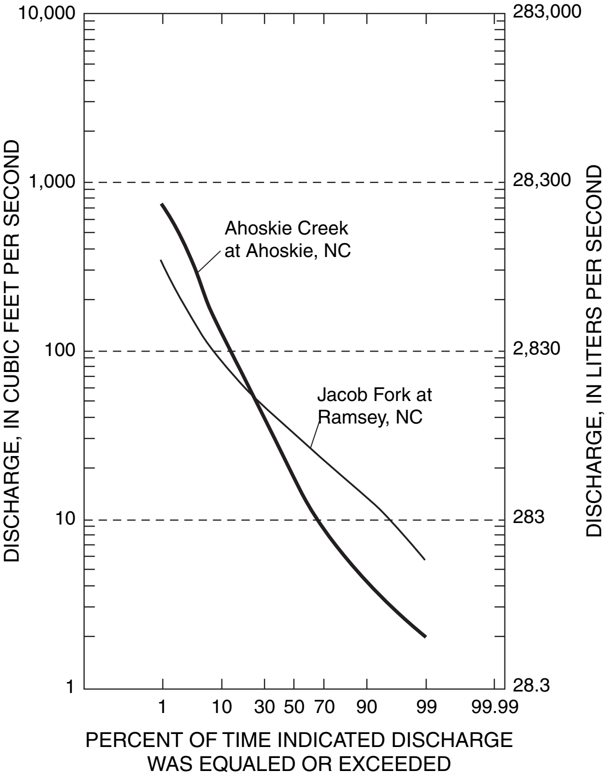

FIGURE 7. Flow-Duration Curves for Ahoskie Creek at Ahoskie, North Carolina (Drainage Area 163 km^2; Period of Record 1964-2004) and Jacob Fork at Ramsey, North Carolina (Drainage Area 67 km^2; Period of Record 1962-2004).

aquifers in this watershed, which covers 163 km^2, provide limited amounts of ground water to the stream.

Jacob Fork originates in the piedmont of North Carolina east of Charlotte. The geologic deposits in this area consist of fractured crystalline rocks overlain by regolith, which is a layer of weathered rock, alluvium, colluvium, and soil (Trapp and Horn, 1997). The flow-duration curve for Jacob Fork at Ramsey, North Carolina (Figure 7), has a flatter slope than the curve for Ahoskie Creek, indicating that the fractured rock and regolith provide a more reliable source of ground water to this stream than the coastal plain sediments do to Ahoskie Creek. Both streams, however, receive a lower percentage of their average discharges from ground water than do the streams in dune terrain in Nebraska or outwash sand and gravel in Minnesota discussed above.

Guadalupe River, Texas

Carbonate bedrock is common in the United States. This type of hydrogeologic setting is known for its high secondary permeability that is a result of the abundance of interconnected fractures and solution cavities. Streams flowing over carbonate terrain can disappear into cavities in the streambed, and then reappear as substantial springs elsewhere. Because of the ease of movement through fractures and solution openings, streams draining carbonate terrain can have highly variable flow. These variable flow characteristics are reflected in the flow-duration curve for the Guadalupe River above its confluence with the Comal River at New Braunfels, Texas. The Guadalupe River flows across part of the Edwards-Trinity Aquifer, a carbonate aquifer that covers nearly 200,000 km^2 across central Texas (Ryder, 1996).

The flow-duration curve for the river (Figure 8) is relatively steep, indicating that the carbonate rocks release ground water readily to the stream. The curve shows the extreme flow conditions that characterize the river, ranging from discharges as high as nearly 141,600 l/s (5,000 cfs) 1% of the time and as low as 170 l/s (6 cfs) 1% of the time. The flow characteristics of this stream are in sharp contrast to those of the Dismal River in Nebraska, where the porous media slowly but consistently releases ground water to the stream.

Rocky Ford Creek, Washington

Rocky Ford Creek lies on the Columbia Plateau, which covers much of southeastern Washington and northeastern Oregon. The Columbia Plateau is underlain by a massive aquifer consisting of thick layers of basalt that commonly have highly permeable zones. Carved into the basalt are deep valleys, some of which contain thick alluvial deposits of sand and gravel (Whitehead, 1994). Rocky Ford Creek flows in one of the filled valleys and receives substantial inflow from ground water. The source of the ground water is the alluvial aquifer, which is recharged by precipitation and by lateral inflow to the alluvial deposits from the basalt aquifer.

As a result of the connection to the vast basalt aquifer and the alluvial deposits, the base flow of Rocky Ford Creek is substantial, as evidenced by the flow-duration curve for Rocky Ford Creek near Ephrata, Washington (Figure 8). The curve has a slope nearly as flat as that for the Dismal River in Nebraska (also shown for comparison in Figure 8). The curve indicates that the creek's discharge near Ephrata is greater than about 850 l/s (30 cfs) 99% of the time. Although the stream had naturally high base flow, it is likely that base flow is greater than under natural conditions because of irrigation in the uplands. Irrigation water in excess of evaporation

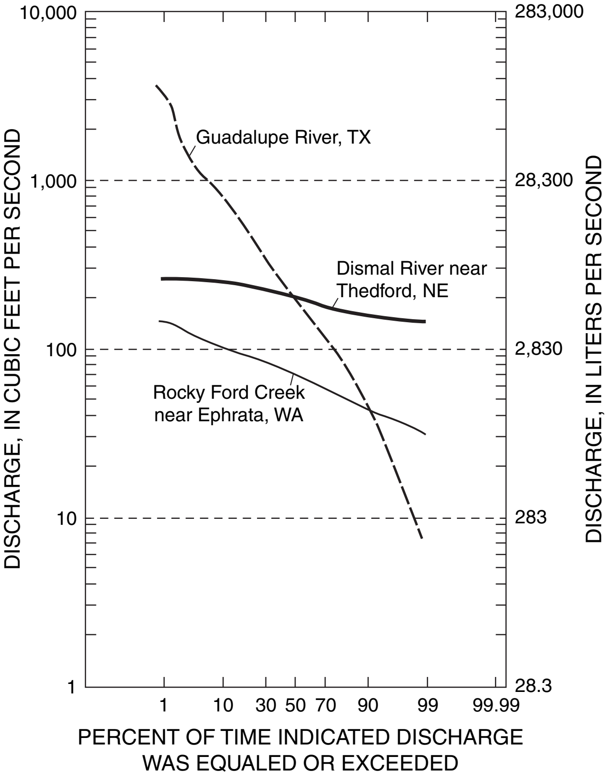

FIGURE 8. Flow-Duration Curves for Rocky Ford Creek Near Ephrata, Washington (Drainage Area 31 km^2; Period of Record 1943-91), Guadalupe River Above Comal River at New Braunfels, Texas (Drainage Area 3,932 km^2; Period of Record 1927-2004), and the Dismal River Near Thedford, Nebraska.

and crop transpiration percolates to the aquifer and raises the water table, causing additional ground-water discharge to the stream.

CAUSES FOR LOSS OF STREAM WATER THAT REDUCE OR DISCONNECT FLOW IN HEADWATERS FROM FLOW IN STREAM REACHES LOWER IN A WATERSHED

Even if a stream initially has substantial flow in its headwater area, natural and human-related processes can deplete flows before they reach lower watershed positions. The most common natural causes for streamflow depletion are natural water tables lower than the stream level and evapotranspiration. The most common human causes for streamflow depletion are surface-water diversions and withdrawals of ground water.

Natural Water Table Lower Than Stream Level

It is common in arid climates for streams to recharge ground water. For example, streams that originate in mountains, and are gaining streams in mountainous terrain, generally lose water to ground water when they reach an alluvial fan at the mountain/plains transition (Bartolino and Cole, 2002). This phenomenon is not unique to arid climates, however, because it was also found to be common in streams crossing alluvial fans in the Appalachian Mountains in New England (Al Randle, USGS, personal communication). In humid climates the stream losses might not be large, but in arid climates the streams may completely disappear. The water lost to ground water from tributary streams at the valley edge eventually will discharge to wetlands, lakes, or streams lower in the landscape. In general, it is not uncommon for streams originating in mountain headwater areas to be disconnected at the surface from surface-water bodies lower in the landscape, but ground water provides hydrologic connectivity between the upgradient and downgradient surface waters.

Evapotranspiration

The water table generally is close to land surface in riparian areas, so the roots of plants can easily reach the capillary fringe to transpire water directly from ground water. In many riverine settings in humid regions, riparian areas receive substantial amounts of ground water from flow systems underlying the surrounding terrain. However, riparian areas in these regions also receive water from the stream during times of high stream stages and when the flood plain becomes flooded. In drier climates, the largest source of water to riparian areas may be from the stream. In these cases, transpiration can draw enough water from the stream to substantially reduce streamflow. An example of this effect can be seen in the stage of the San Pedro River in Arizona.

A hydrograph of the stage of the San Pedro River at Charleston, Arizona, for 1 month during the summer of 2005 is shown in Figure 9. For the latter half of June, evapotranspiration caused a daily decline of stream stage of about 3 cm. During a particularly hot and dry period from June 28 to July 5, daily declines were as great as 7.6 cm. Although stream stage recovered substantially at night, it seldom equaled the magnitude of the decline. The overall effect of the evapotranspiration was a gradual decrease in stream stage of about 30 cm over the 1-month period. Therefore, regardless of the flow of the stream in the headwater area, evapotranspiration from the riparian zone along the way resulted in the stream providing an unreliable source of water to downstream reaches.

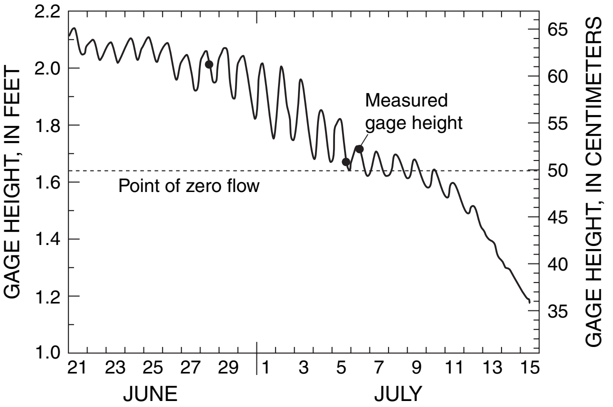

FIGURE 9. Hydrograph of the San Pedro River at Charleston in Arizona for June 21 to July 15, 2005, Showing the Substantial Effect of Transpiration by Riparian Vegetation on Stream Stage.

Human Withdrawals of Ground Water

Ground-water development can have a profound effect on streamflow. Streams that cross the High Plains in the vicinity of the Ogallala Aquifer provide excellent examples of the effect ground-water withdrawals can have on streamflow. The Beaver River is located in the Panhandle of Oklahoma. In this part of the High Plains, withdrawals of ground water by irrigation wells have caused ground-water levels to decline 7-15 m in many places, and as much as 30 m locally. In examining the long-term record (1937-88) of the river's discharge at Guymon, Oklahoma, Wahl and Wahl (1988) found that the stream was perennial most of the time prior to the 1960s, having periods of no flow lasting no more than 60 days during droughts. Average annual discharge of the river from 1937 to 1960 was about 900 l/s (32 cfs). The average annual discharge decreased to about 200 l/s (7 cfs) during 1977-86. After about 1968, the river has dried up for extended periods every year, and by 1988 it averaged 300 days of no flow every year.

In a broader study of the High Plains, Sophocleous (2000) showed the extent that streams have been affected by ground-water withdrawals from the Ogallala Aquifer. Declines of ground-water levels of more than 30 m over a 30-year period were common in parts of Kansas, Texas, and New Mexico. The effect of this ground-water development on streams is shown in Figure 10. Many streams in western Kansas that flowed across the Ogallala Aquifer in 1961 became disconnected from downstream reaches, shorter, or ceased to flow altogether by 1994.

DISCUSSION

The specific streams presented in this article were selected to provide a brief overview of the importance of ground-water contributions to streamflow. Ground water underlies the earth's surface everywhere, and in most places, especially in humid climates, it is in direct contact with surface-water bodies. Ground water is in constant motion through flow systems of various magnitudes, and these flow systems commonly interact with surface-water bodies. As a result, ground-water flow systems can be thought of as subsurface tributaries of streams. The rate at which ground water moves, and the distances from a surface-water body that a volume of ground water can be considered an effective tributary of a stream is discussed by Winter and LaBaugh (2003). Even headwater streams have ground-water contributing areas, many of which are the cause of initiation of streamflow. Furthermore, the boundaries of ground-water flow systems (or ground-water watersheds) commonly are much different than surface watersheds, and they can change dynamically with time (Winter *et al.*, 2003), which makes it very difficult to know the size of a ground-water watershed that contributes to a stream whether it is in a headwater area or anywhere along the length of a stream.

It is fairly obvious that substantial contributions of ground water to streams result in relatively stable flow conditions whether the contributions are in the headwater area or throughout the length of a stream.

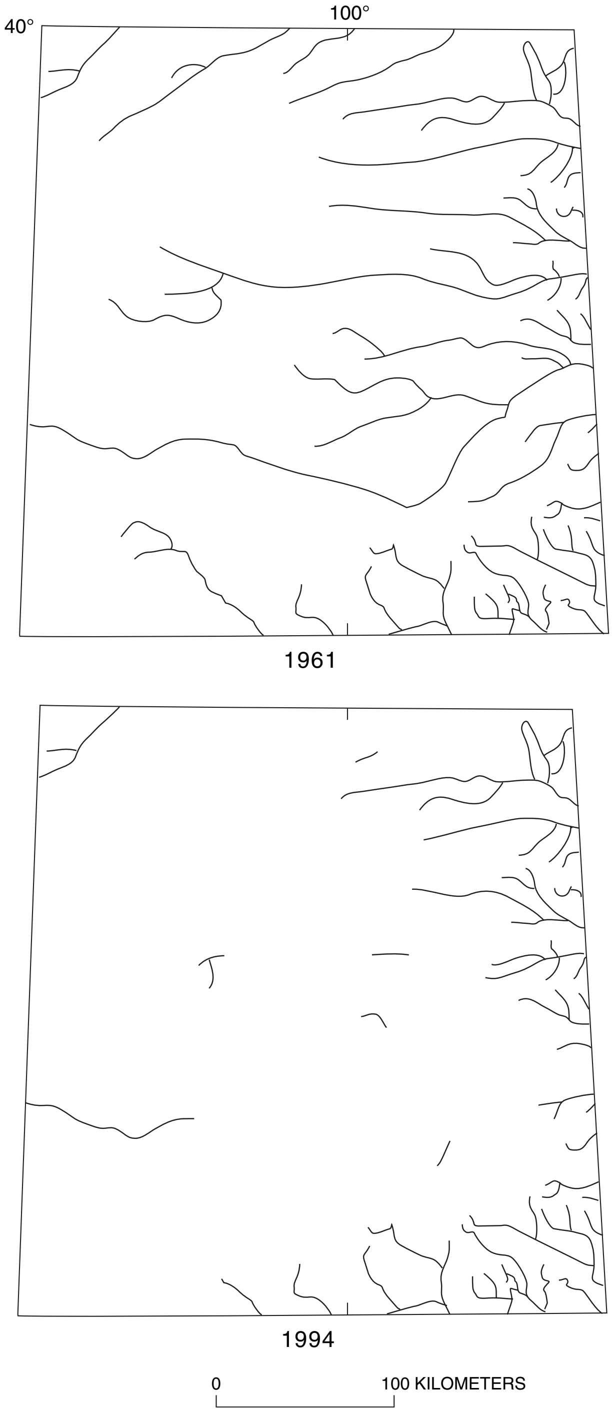

FIGURE 10. Extent of Flowing Reaches of Streams in Western Kansas Prior to Ground-Water Development From the Ogallala Aquifer (1961) and Following Ground-Water Development (1994). Modified from Sophocleous (2000).

The streams that show the greatest stability of flow (those that have the flattest duration curves), such as the Dismal River in Nebraska, Rocky Ford Creek in Washington, and the Crow Wing River in Minnesota, have large, regional ground-water contributing areas.

These streams are the least vulnerable to climate variability because of the large buffering capacity of those ground-water reservoirs. Another factor that helps control the stability of ground-water contribution to those streams is that they all have large volumes of sand and gravel directly contiguous to the stream, which modulates the rate at which ground water seeps into the streams.

The Long Prairie River in Minnesota provides a contrasting example. Even though the river flows on outwash between Long Prairie and Motley, the volume of outwash is small for most of this distance. As a result, the river receives ground water largely from the local flow systems within the outwash. Being a relatively small volume of ground water, the river flow is relatively unstable, as reflected in the fairly steep flow-duration curve.

The Guadalupe River in Texas also is an interesting contrast to the Dismal River in Nebraska. Both rivers are in areas where evaporation exceeds precipitation by about 50 cm. The wide range of flow conditions in the Guadalupe River are partly in response to the rapid rate at which ground water moves through the carbonate rock. This part of Texas receives intense rainfall during two times of the year. The water infiltrates and quickly passes through the ground-water system through solution openings, resulting in high stream discharges during the wet periods. The stream quickly recedes to low flows during the dry periods. In contrast, ground water passing through the porous media in the Nebraska sand hills provides a very stable source of water to the Dismal River.

The importance of ground-water flow systems as avenues of hydrologic connectivity also affects streams and other surface-water bodies that are disconnected either by natural or by human activities. For example, it was stated earlier in this article that streams emanating from mountains can disappear as they flow across alluvial fans. Although the stream is disconnected on the surface, the water becomes part of a ground-water flow system that provides hydrologic continuity to areas downgradient, where the ground water eventually discharges back to the surface, usually to wetlands, lakes, or to another stream. The time it takes for the ground water to move from the top of the alluvial fan to its base or to another surface-water body depends on the size of the fan, hydraulic conductivity, and hydraulic gradients; the time could be weeks to years.

Another example of the interconnectedness of ground water and surface water is the case of flow in the streams that cross the central plains of the United States. It was presented earlier in this article that ground-water withdrawals in Oklahoma and Kansas have caused many reaches of streams on the high plains to cease flowing. Conversely, surface water has been used as a source of water for irrigation in the Platte River valley in Nebraska. The excess application of surface water has caused water in excess of evapotranspiration to recharge ground water. This has caused ground-water levels to rise and contribute ground water to the river. As a result, the Platte River now has perennial flow, largely because of irrigation practices, whereas, in its natural condition, the river commonly dried up during most summers.

SUMMARY AND CONCLUSIONS

The stability of the point of origin of a stream and the stability and quantity of ground-water discharge is determined by the size and permeability of the ground-water basin that contributes water to the incipient stream. Streams that begin as discharge from extensive aquifers have a stable point of origin and substantial discharge in their headwaters. In contrast, streams that begin as discharge from rocks and sediments having low permeability have a point of origin that moves up and down the channel seasonally and have small incipient discharge. The effect of ground-water contribution to headwater streams on the volume of streamflow lower in a watershed is related partly to the volume of ground water contributed in the headwater area; that is, the larger flow is initially, the farther downstream that water will extend. However, ground water contributed to a stream in its headwater area generally will not be enough to maintain base flow throughout the full length of the stream because losses, such as evaporation, transpiration by riparian vegetation, and seepage to ground water, will deplete the flow in the stream. To maintain base flow throughout the length of a stream, it is generally necessary to have ground-water discharge to the stream throughout much of its length.

ACKNOWLEDGMENTS

Information on streamflow characteristics and flow duration have been provided by U.S. Geological Survey colleagues Mark Anderson, Jerad Bales, Ben Dietsch, Mark Mastin, Greg Mitton, Greg Wiche, Tara Williams-Sether, Addis Miller, George Ozuna, and John Vaccaro. Data for all stream discharge presented herein, except the data for the Mirror Lake area, are from the U.S. Geological Survey, National Water Information System (available at http://waterdata.usgs.gov/nwis). Discharge data for the stream draining Hubbard Brook watershed 3 are from the U.S. Forest Service. Discharge data for the streams draining Mirror Lake watersheds NW and W are from the U.S. Geological Survey, Hydrology of Lakes Project.

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