

# Hydrogeology Related to Exempt Wells in Montana

A Report to the 2010–2012 Water Policy Interim Committee of the Montana Legislature



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### Introduction

Montana has over 200,000 wells on record with the Montana Bureau of Mines and Geology (MBMG) Ground Water Information Center database (GWIC; mbmggwic.mtech.edu) whose use has been identified as domestic. Some estimates show as much as 30 percent of the population relies on wells for water supply.

For the purposes of this discussion, it is important to note the difference between the terms domestic and exempt. When a well log is filed, the driller or well owner indicates the intended use of the well. Domestic use is one option; other options include, but are not limited to, stock, irrigation, public water supply, or monitoring. The term exempt refers to a groundwater development that, based on the maximum proposed annual volume pumped (currently 10 acre-feet per year) and the maximum pumping rate (currently 35 gallons per minute), is exempt from permitting; the

exemption is established by a certificate issued by the Montana Department of Natural Resources and Conservation. The use of the exempt well, whether it be domestic, irrigation, or stock, does not affect the exemption. Due largely to changes in the regulatory requirements regarding well log and water-right filing, there are many wells that indicate domestic use on the well log for which a certificate does not exist. More than 90 percent of all the wells for which a use has been reported are used for domestic or stock.

Figure 1 shows the distribution of all the wells across Montana; each well is represented by a small red dot. Population centers and river valleys are easily distinguished by areas of high well density. Although a geologic source or aquifer is not reported for all wells in the GWIC database, shallow basin-fill aquifers along river and stream valleys are subject to the greatest development.

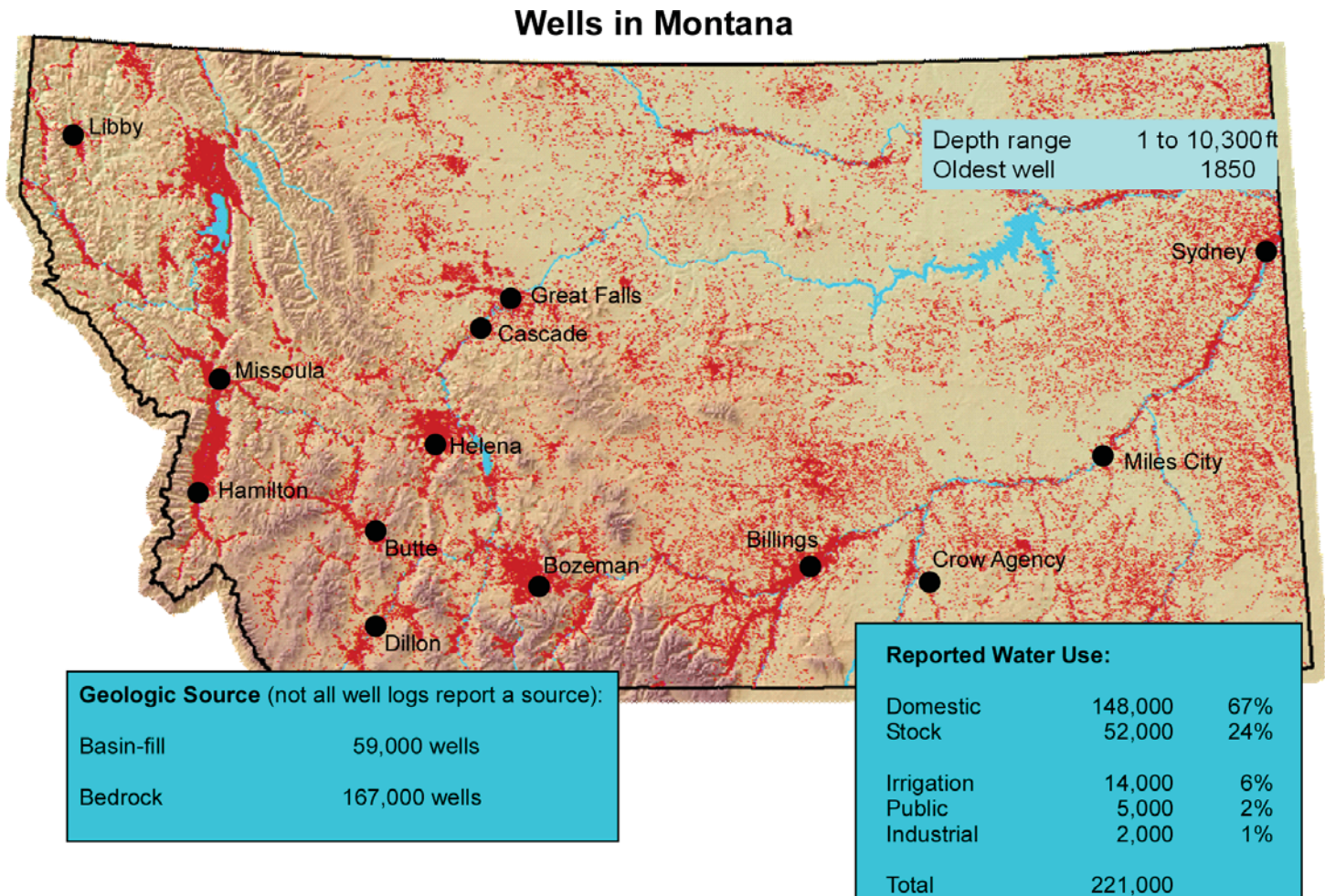


Figure 1. The Ground Water Information Center (GWIC) database contains more than 221,000 records for wells throughout Montana. Each well is represented by a small red dot on the map.



## Groundwater Sources

Montana is often described in terms of its contrasting physiographic or geologic provinces—the mountainous western third and the plains of the eastern two-thirds. An aquifer is permeable geologic material capable of storing and transmitting groundwater. An unconfined or water-table aquifer (bottom of fig. 2) is recharged directly by infiltration of precipitation or surface water; the water table typically ranges from a few feet to tens of feet below the surface. Unconfined aquifers are sensitive to changes in precipitation and withdrawal and are particularly vulnerable to contamination by surface sources such as septic systems and applied chemicals.

Confined aquifers (top of fig. 2) are overlain by a low-permeability material that limits the vertical flow of water into or out of the aquifer. In central and

eastern Montana, confined aquifers are typically consolidated, permeable sandstone or limestone formations overlain by low permeable shale. These aquifers extend for hundreds of miles, from the recharge areas in the mountains to the northern and eastern areas of the State. In the western Montana valleys, the deeper portions of the basin-fill aquifers may be confined or partially confined by layers of clay or silt.

It is important to note that confined aquifers must somewhere be unconfined or exposed to receive surface recharge; likewise, for groundwater to flow, the aquifer must discharge to the surface. The recharge areas for several of the important confined aquifers in eastern Montana are in the central mountains; the discharge areas are unknown, but certainly are north and east of the State. Recharge areas for the deep confined aquifers of the western Montana valleys are in the mountains that define the valley or unconfined aquifers in the upland valley margins.

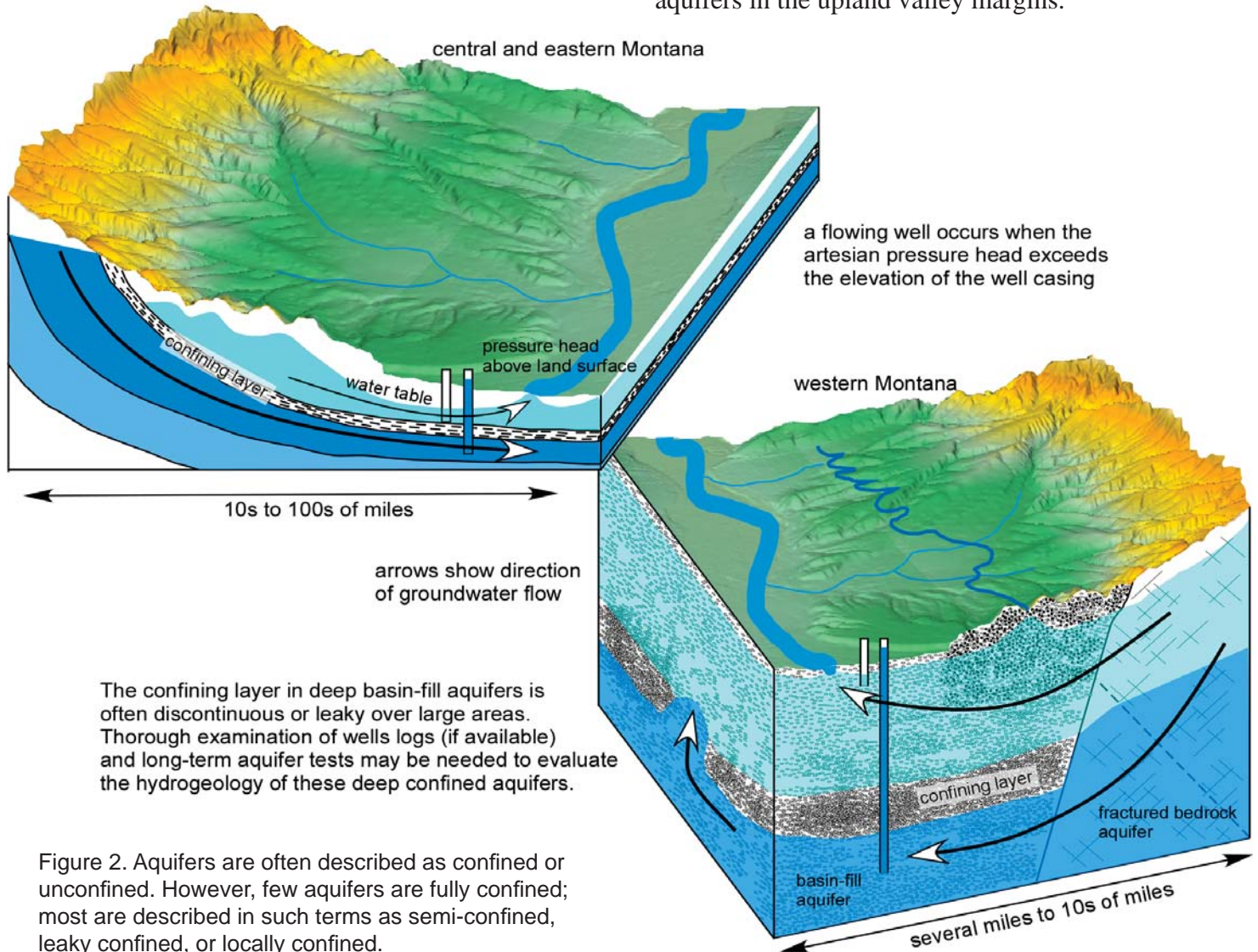
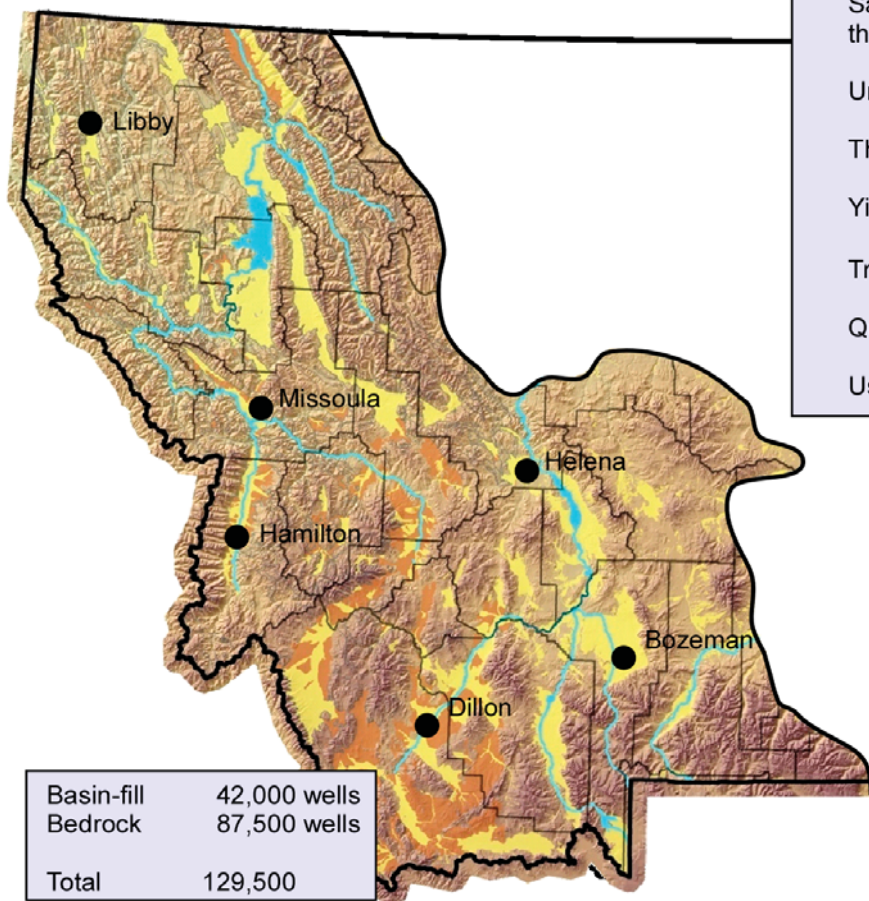


Figure 2. Aquifers are often described as confined or unconfined. However, few aquifers are fully confined; most are described in such terms as semi-confined, leaky confined, or locally confined.

### Major Aquifers of Western Montana



**Basin-fill:**

Sand and gravel along major and tributary valleys, thick basin-fill deposits in intermontane basins

Unconfined aquifers

Thickness: 30 to >1,000 feet

Yield: 1 to 3,500 gpm; average is 35 gpm

Transmissivity: 500 to 200,000 feet<sup>2</sup>/day

Quality: < 500 mg/L (total dissolved solids)

Use: domestic and stock, some irrigation

**Bedrock:**

metamorphic rocks, shale, limestone, granite, volcanic rocks, shallow on valley margins

Unconfined on valley margins

Thickness: generally unlimited, but yield decreases with depth

Yield: 1 to 5,000 gpm; average is 5 gpm

Transmissivity: 50 to 10,000 ft<sup>2</sup>/day

Quality: < 100 mg/L (total dissolved solids)

Use: domestic and stock, rare irrigation

### Western Montana

Domestic wells in western Montana are most often completed in the shallow basin-fill aquifers composed of unconsolidated sand and gravel in the major valleys or along tributary valleys. Basin-fill aquifers, shown as yellow and tan in figure 3, are typically thick (>1,000 ft); well yields are usually far greater than the demand of a typical domestic user. Natural water quality is generally very good, but the shallow unconfined nature of these aquifers makes them vulnerable to contamination.

As population growth continues and development expands into the foothills and valley margins, wells in the fractured-bedrock aquifers will become an important source of water for domestic use. Wells in the fractured-bedrock aquifers tend to have low or marginal yield for domestic use, which will limit growth in some areas.

Figure 3. GWIC reports about 130,000 total wells in western Montana. The bedrock aquifers consist of igneous, metamorphic, and sedimentary rocks.



### Major Aquifers of Eastern Montana

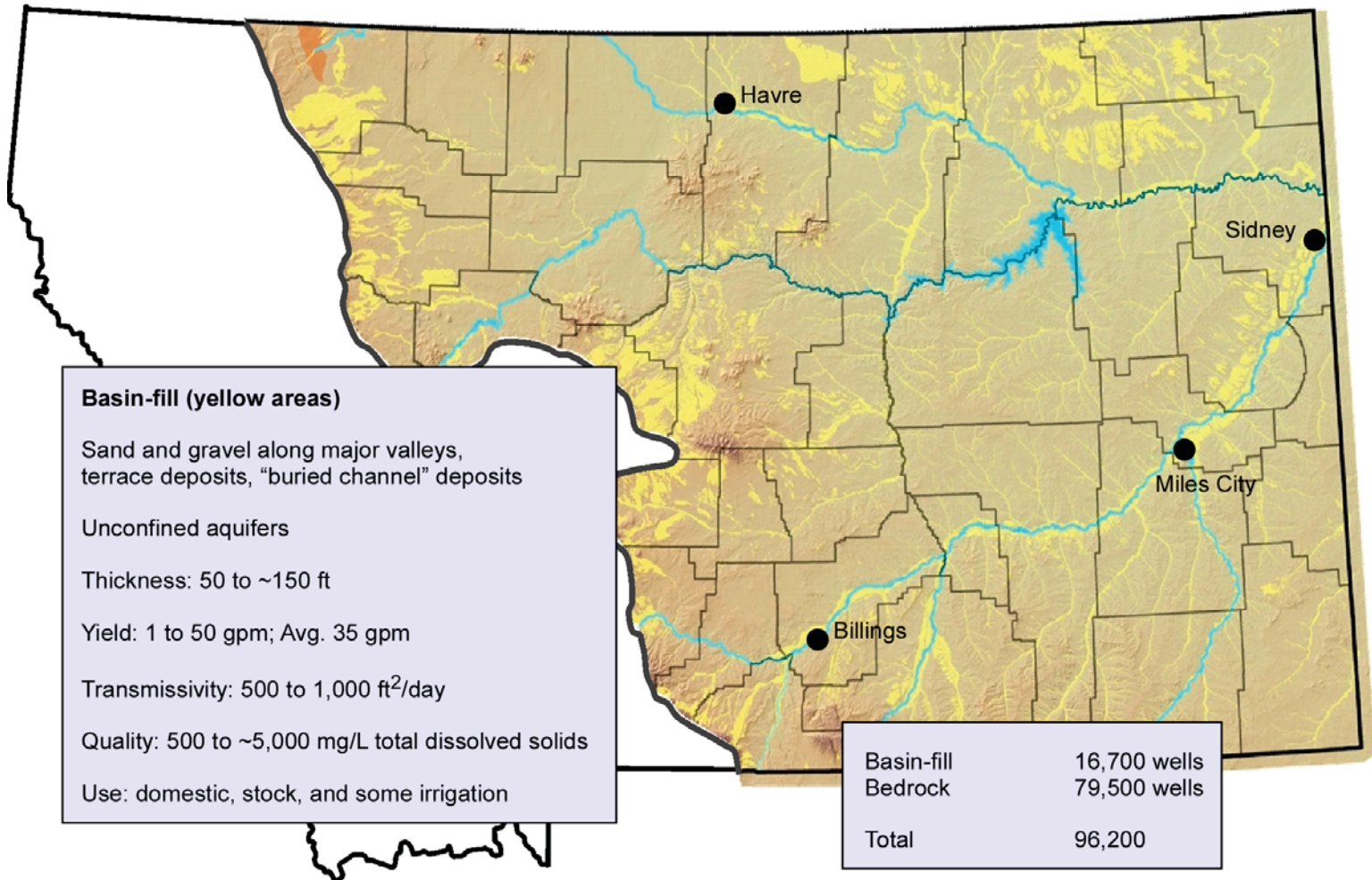


Figure 4. Productive basin-fill aquifers are generally restricted to river valleys. Most areas outside the major river valleys rely on bedrock aquifers for water supply.

### Eastern Montana

Population centers in central and eastern Montana have developed along the major river valleys; surface water is the typical source for cities and towns. Outside the population centers, domestic wells are the principal source of water. The unconsolidated basin-fill aquifers of eastern Montana, shown in yellow in figure 4, are notably thin compared to those of the western valleys and are vulnerable to overpumping and contamination by surface sources.

There are several important bedrock aquifers in eastern Montana (not shown); these include the sandstone and coal beds of the Fort Union (14,000 wells), the sandstone beds of the Fox Hills–Hell Creek (5,500 wells), the Judith River (2,700 wells), and the Eagle–Virgelle Formations (2,200 wells). As discussed in the previous section, the bedrock aquifers in the central and eastern part of the state are generally extensive and confined; aquifers in the eastern part of the state

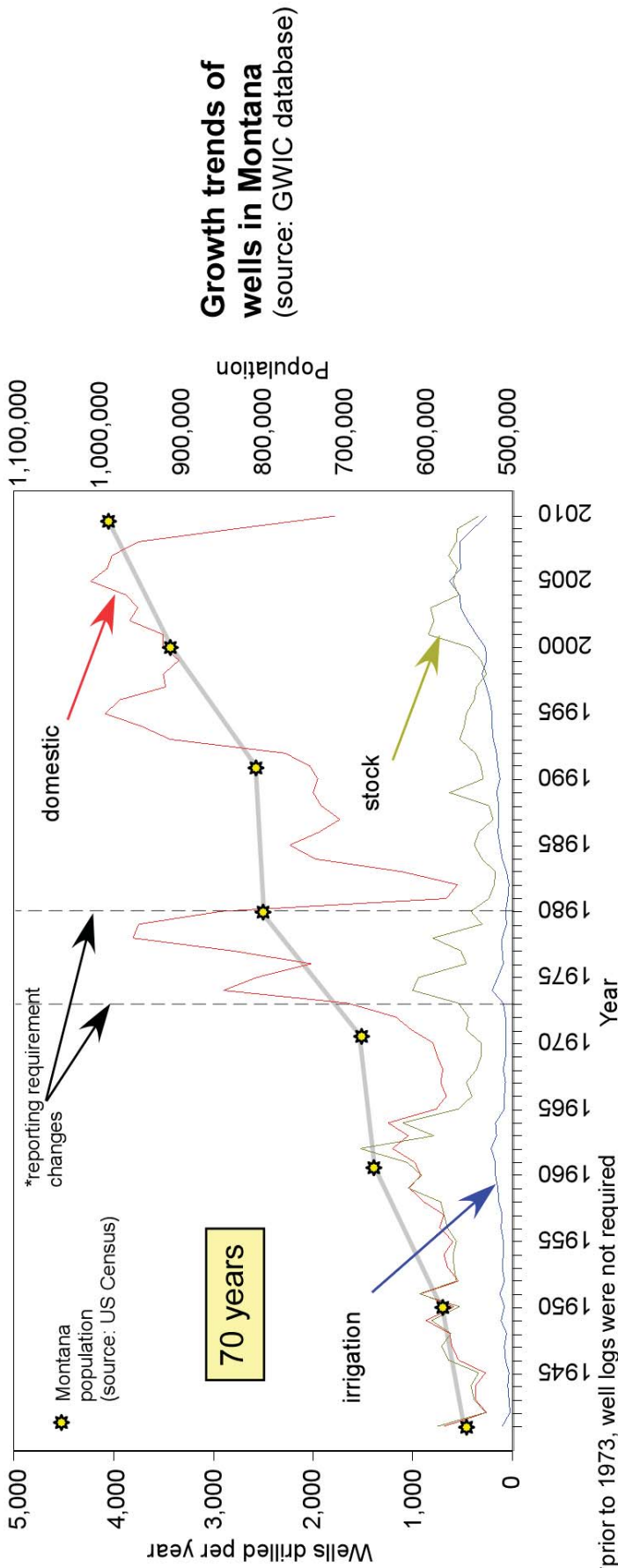
are confined and flowing wells are common. These aquifers are generally the sole source of water for domestic and stock use throughout eastern Montana.

### Growth Trends

More than half of the 200,000 wells in Montana were drilled in the past 20 years, and more than 6,000 wells were drilled in 2004, a trend that appeared likely to continue, but was disrupted by the (temporary?) economic downturn of 2008 (fig. 5).

Although changes in reporting requirements over the past 70 years affect the accurate account of drilling activity, the trend of the number of domestic wells appears to mimic population growth. By far, the highest rate of growth has been for domestic wells, which accounts for 85 to 90 percent of all wells drilled in a given year; there has also been a notable increase in the number of wells for which irrigation is the reported use (top graph of fig. 5).





\*prior to 1973, well logs were not required  
1980 to 1983, "well use" was not recorded

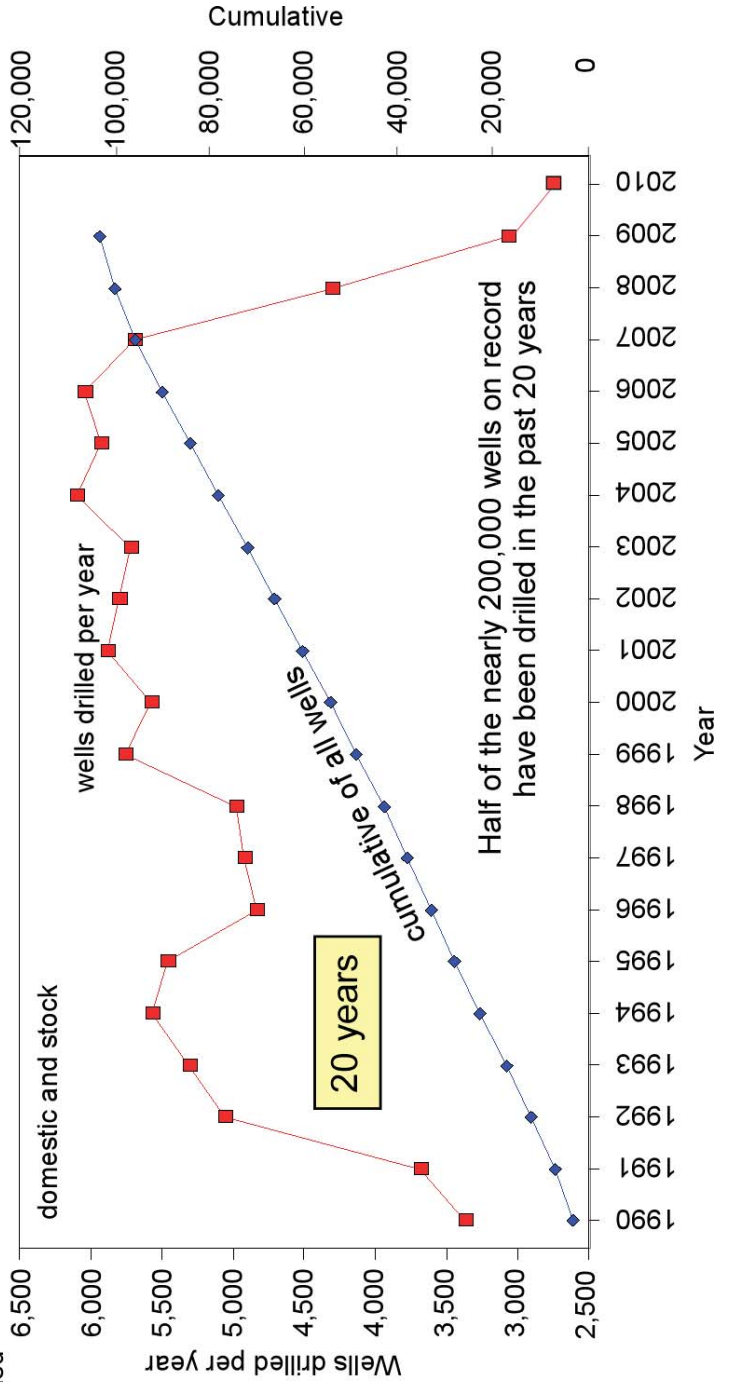


Figure 5. Changes in reporting requirements affect short-term changes in growth trends, but the steady long-term growth in the number of wells is evident.

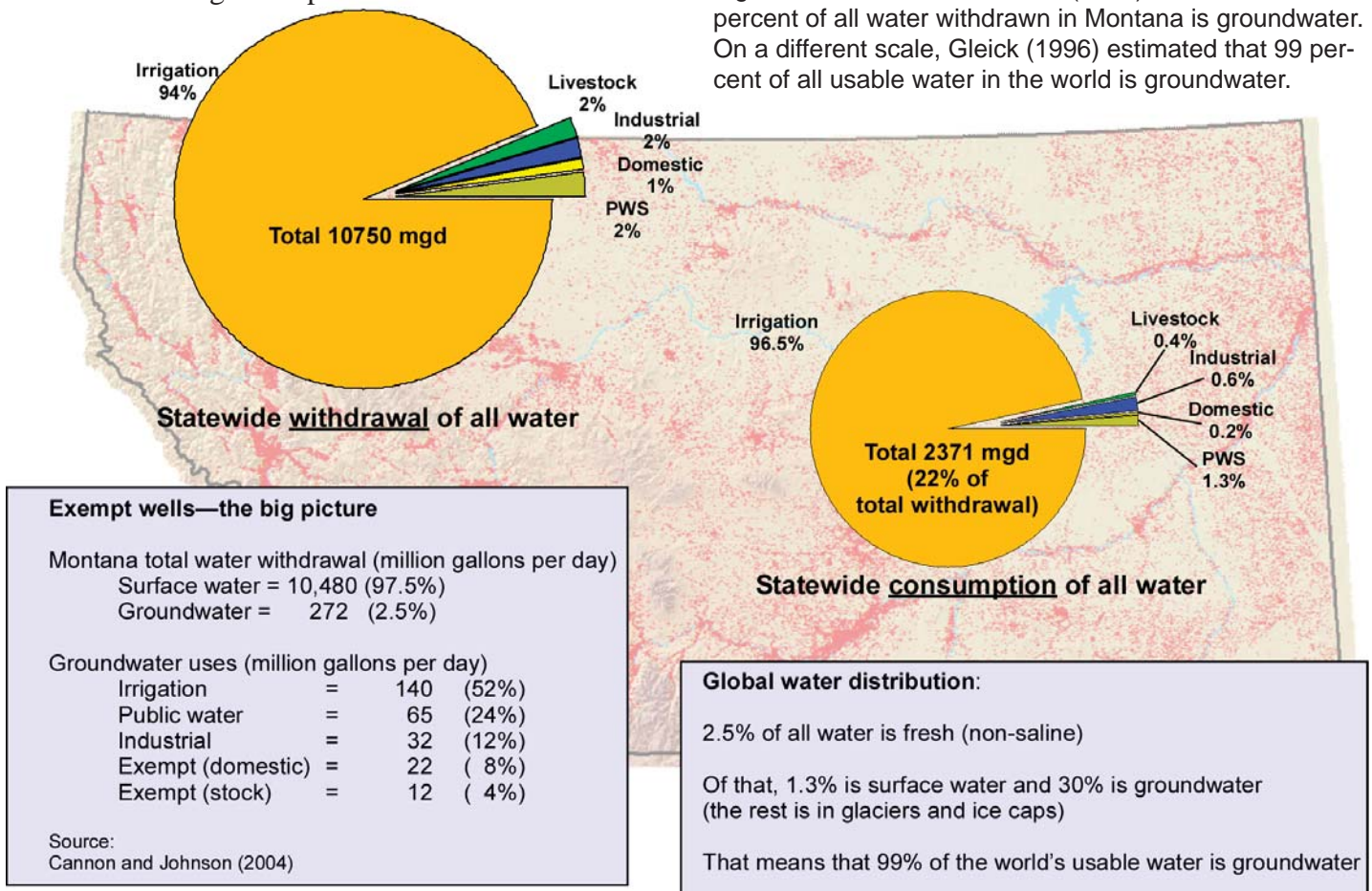
## Hydrologic Budgets— The Importance of Scale

A budget, whether it be for finances or water, relates the income/inflow to expenses/outflow at a specific scale of time or space; it provides a means to evaluate the availability and allocation of the supplies and demands. A change in the scale of the budget can drastically change the emphasis. For example, compare the financial budget of Montana (about \$4 billion) with that of the US (about \$1.4 trillion). Montana’s budget, at 3% of the national budget, is much smaller than that of many Federal agencies. However, a budget change of \$1 billion would have a much greater impact in Montana than at the Federal level. Similarly, farmers and businessmen appreciate that the amount of money in the bank, or in the field, or in stock, differs widely on a daily, monthly, or annual scale. Just like comparing a small business budget to that of a large corporation, the monthly financial budget for a retail business can tell a much different story than that of the annual budget. The same analysis can be applied to hydrologic budgets. It is critical for the discussion of budgets to examine the scale, both temporal and spatial, of the budget and to appreciate the importance of individual budget components.

## Large Area Budgets

The U.S. Geological Survey (USGS; Cannon and Johnson, 2004), estimated that 94 percent of all water withdrawn in Montana each was for irrigation and 1 percent was for domestic purposes (fig. 6). Consumption of that water followed a similar pattern; irrigation consumed almost 96 percent of the water withdrawn and domestic about 0.2 percent. Cannon and Johnson also point out that about 2.5 percent of all water withdrawn is groundwater; the rest is surface water. On the scale of the entire State, on an annual basis, groundwater withdrawal or consumptive use, for any purpose, is a minor component of the budget. However, if the scale of the budget is changed, the importance of groundwater can drastically change. Consider the global scale of water storage: only 2.5 percent of all the water on the planet is fresh; almost 69 percent of that fresh water is inaccessible as ice. Of the remaining, useable water, 99 percent is available as groundwater and only 1 percent is surface water (Gleick, 1996; inset box of fig. 6).

Figure 6. Cannon and Johnson (2004) estimate that 2.5 percent of all water withdrawn in Montana is groundwater. On a different scale, Gleick (1996) estimated that 99 percent of all usable water in the world is groundwater.



## Groundwater Consumptive Use at the Basin Scale

Consumptive use is water removed from the hydrologic system without replacement or return. Water consumed by plants, known as transpiration, and evaporation from the soil and surface water bodies are the largest consumptive uses. Plant transpiration and soil evaporation is termed evapotranspiration. Estimates of the evapotranspiration component of a water budget are typically taken as consumptive use.

As noted, Canon and Johnson (2004) estimated that 2.5 percent of all the water withdrawn in Montana annually is groundwater. Within that 2.5 percent, they estimate that about 21 percent of the water withdrawn for irrigation is consumed, about 21.5 percent of the water withdrawn for industrial use is consumed, and 37 percent of the water withdrawn for public water supply is consumed. Consumption of water for domestic and livestock use was assumed to be 100 percent of the water withdrawn. When these percentages are applied to reported withdrawals on the basin scale (fig. 7), the relative consumptive use rates change dramatically from those presented on a statewide scale.

Consumptive use by domestic wells in southwest Montana ranges from 15 to over 50 percent of the total groundwater consumed (fig. 7). Irrigation consumptive use has a similar range, but in different basins. Total consumptive use ranges from less than 1 million gallons per day (mgd) to about 15 mgd.

## Consumptive Use at the Sub-Basin Scale

Domestic consumptive use is attributed largely to lawn and garden watering; in-house consumptive use is small. In this analysis, the in-house consumptive use was considered zero; that is, domestic consumptive use was attributed entirely to evapotranspiration by lawns. Agriculture consumptive use is attributed to water consumption by crops irrigated by one of three methods: (1) center pivot, (2) flood irrigation by canals and turnouts, or (3) sprinkler.

Consumptive use of both surface water and groundwater was estimated for the six MBSMG Ground Water Investigation Program areas for each of the three agriculture irrigation categories and for domestic use. The monthly crop-water demand was multiplied by the estimated area irrigated by each of the three methods for agricultural land and for each lot served by a domestic well. Crop-water demand data for each area was obtained from the local AgriMet station (U.S. Bureau of Reclamation, 2011) for the 2010 water year; alfalfa was used to represent agricultural use and lawn was used to represent domestic use. The area of each agricultural application was determined from GIS coverages (Montana State Library's Natural Resource Information System, 2011). The lawn area assigned to domestic wells was determined from air photos showing late summer or fall irrigation for a randomly selected 10 percent of the total number of lots in the sub-basin. The results are summarized in the table in figure 8. Where data were available, the average irrigated area for domestic use estimated from the air photos for the entire area was compared to data from local subdivisions. The Helena (North Hills) project area included several subdivisions with public water supplies. In their evaluation of the water budget, Waren and others (2010) determined a consumptive use equivalent to 0.25 acres irrigated. This compares well to the 0.23 acres determined by the method used for this analysis. Similar comparisons showed good agreement in the lower Beaverhead and Belgrade study areas. The pie charts in figure 8 present the total annual consumptive use by each land use type. At this scale, with project sub-basins ranging from 7,000 to 78,000 acres, the impact of domestic wells used for lawn irrigation is markedly different from that presented at a statewide scale.



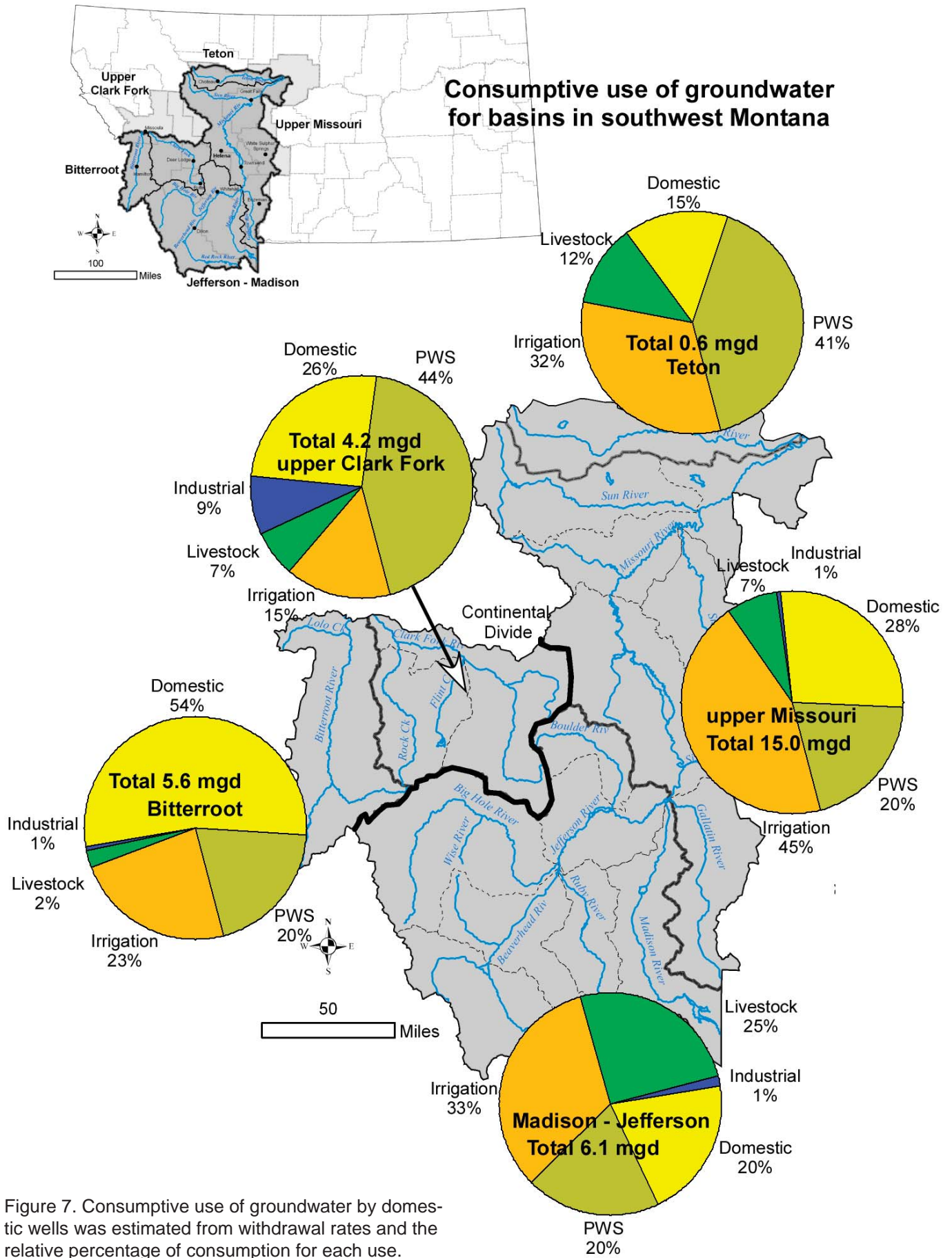


Figure 7. Consumptive use of groundwater by domestic wells was estimated from withdrawal rates and the relative percentage of consumption for each use.

### Consumptive use of groundwater and surface water in six sub-basins

Project	Total Acreage*	Irrigated acreage: lawns (average lawn / total)	Irrigated acreage: agricultural
L Beaverhead	78,000	0.5 / 450	29,000
Four Corners	12,000	0.8 / 635	3,500
Belgrade	31,000	0.61/ 1100	4,000
Helena	19,000	0.23/ 475	3,000
Eightmile	7,000	0.91/ 600	500
Threemile	19,000	0.89/ 800	5,600

\* values are approximate and based on each study area boundary

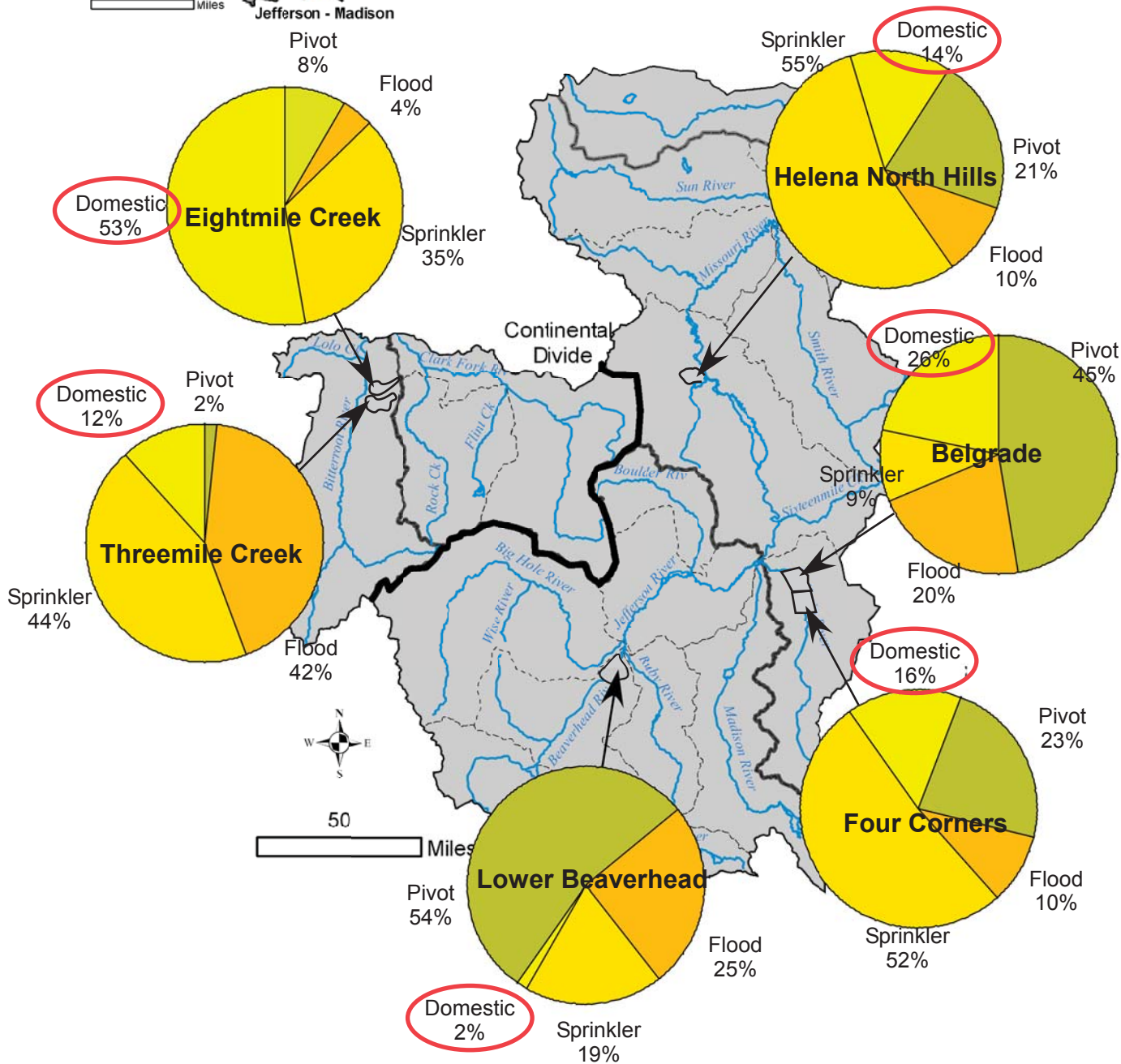


Figure 8. Consumptive use of all water was estimated for each of six sub-basins within southwest Montana.

## **The Importance of the Temporal Scale**

Water budgets are most often presented on an annual basis; generally the changes in the hydrologic system respond to annual climate cycles. Consumptive use, particularly by human activities, varies significantly daily, monthly, or seasonally depending on local conditions and activity. Overall, consumptive use by lawns in the six study areas showed the greatest variance at a monthly temporal scale. With the exception of the lower Beaverhead, all the study areas were focused in areas of high domestic well density.

The pie charts in figure 9 compare the annual consumptive use to an early summer, monthly consumptive use. In Eightmile Creek, the peak consumptive use month did not vary much from the annual, but in the Four Corners area, there is considerable difference. Identifying where and when these seasonal differences are important may help manage water use during the months of high demand and low supply.

Another aspect of the temporal scale is the time between the diversion of the water and the consumption of the water. Reduction of stream flow from a surface-water diversion is immediate; reduction of stream flow from a pumping well can take days or decades depending on the aquifer properties and the distance between the stream and the well. Thus, the timing of consumptive use may be very different than the impact of that consumptive use on stream flow or groundwater levels. A more detailed discussion of the factors affecting the timing of groundwater pumping is presented later.



### Comparison of annual consumptive use to early summer consumptive use

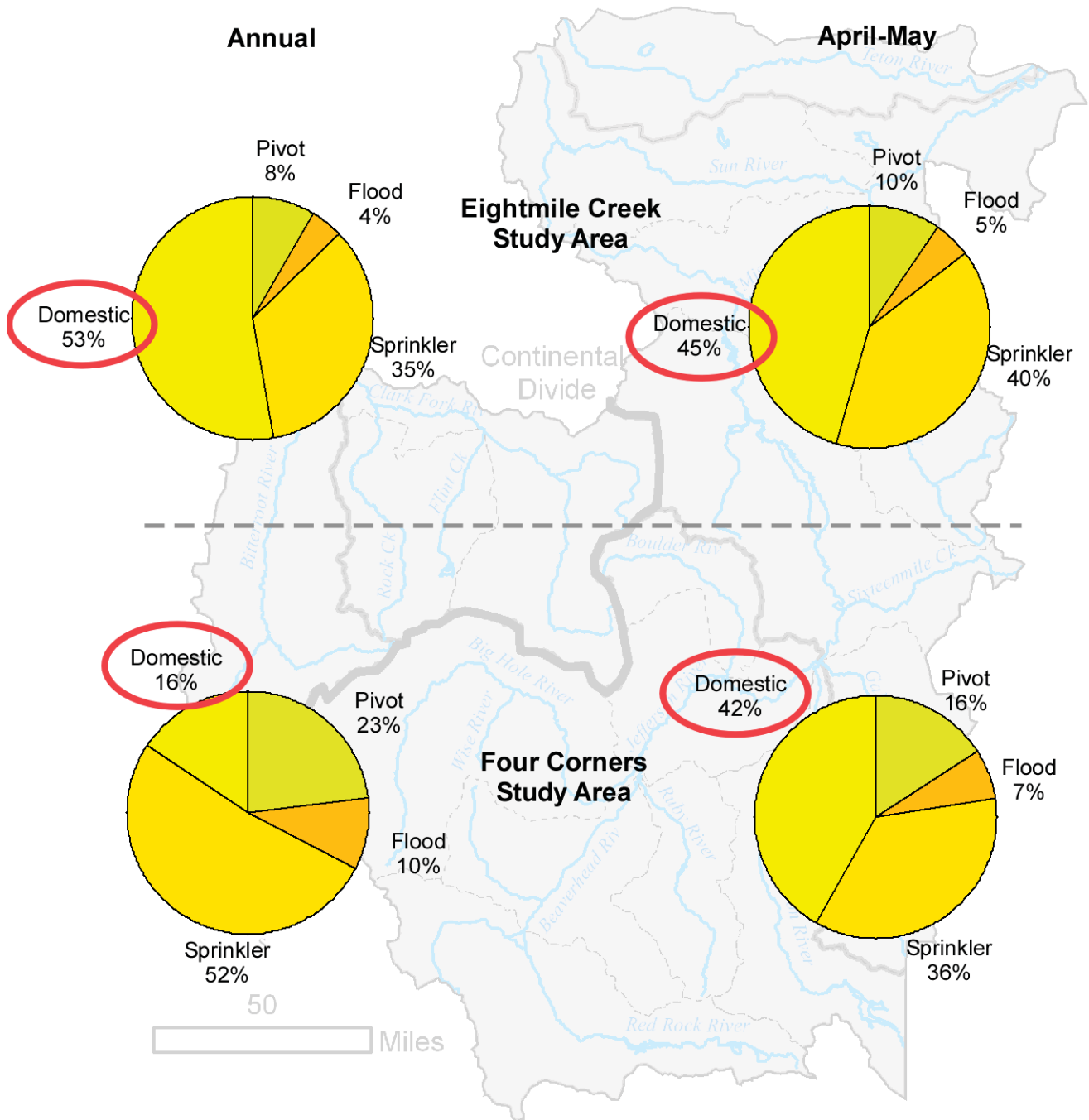


Figure 9. Consumptive use was compared for two different time scales at two of the study areas. In Eightmile Creek the high-use months did not differ from the annual total, whereas in the Four Corners area, the difference was markedly different.

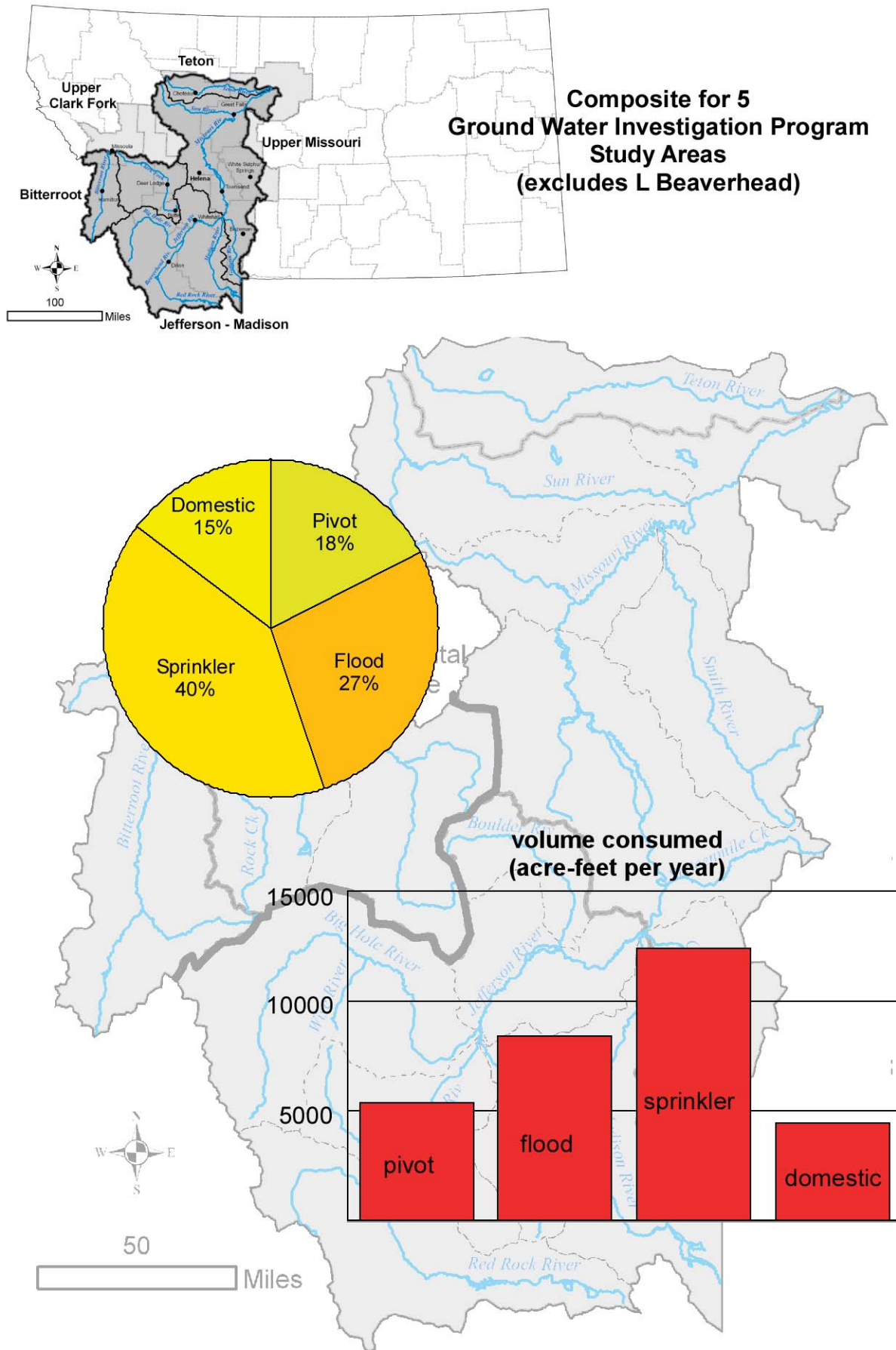


Figure 10. Consumptive use was compiled for the study areas in which the growth of domestic wells is of concern: Florence–Eightmile Creek, Florence–Threemile Creek, Helena–North Hills area, Bozeman–Four Corners area, and the Belgrade area.

## Summary of Study Area Budgets

A composite of data for the five sub-basins shows that domestic lawn use accounts for 15 percent of the annual consumptive use of groundwater (fig. 10). This is notably higher than the 0.2 percent consumptive use based on a statewide average reported by Canon and Johnson (2004). That is not to say the data or analyses of the data are in conflict, or that there is no impact at the basin or statewide scale; it demonstrates the importance of the scale of observation. Data collected and analyzed for local conditions in a sub-basin will likely reveal potential issues sooner than those of the basin scale.

## Altered Watersheds

Montana has more than 3,000 miles of irrigation canals that carry 11.6 million acre-feet to irrigate about 2.2 million acres of crop and pasture on an annual basis. Crop water demand ranges from 1 to 3 acre-feet per year (Bauder and others, 1983); the average consumptive use rate for all crops and pasture is about 1.2 acre-feet per year (Cannon and Johnson, 2004). Thus, almost 9 million acre-feet of the 11.6 million acre-feet, or 77 percent, of the water diverted for irrigation is available for return flow as run off or recharge to groundwater. Table 1 shows the ditch loss reported by MBMG investigations throughout the State.

The volume of groundwater recharge from irrigation ditch loss often overwhelms the natural recharge processes. For example, the East Bench Irrigation Canal in the lower Beaverhead River may lose as much as 398 acre-feet per season; with a length of about 17 miles between Dillon and Beaverhead Rock, the seasonal ditch loss would be about 6,800 acre-feet. Additional recharge occurs from direct flood irrigation.

The groundwater flow systems in nearly all of the watersheds of western Montana and the large watersheds of eastern Montana have been substantially altered by recharge from irrigation canals (fig. 11).

Table 1. Ditch loss reported by MBMG investigations throughout Montana.

<b>Figure 11 Inset Map Reference: Source</b>	<b>Ditch Loss (cubic feet per second per mile)</b>	<b>Ditch Loss (acre-feet per year per mile)*</b>
A: Osborn and others (1983)	0.45–4.7	81–850
B: Madison (2006)	0.6	114
C: Abdo and Metesh (2005) Abdo and Roberts (2008)	0.15–1.5	27–271
D: GWIP Beaverhead	2.2	398
E: GWIP Belgrade	0.40–4.3	72–778
F: Kuzara and others (2012)	1.1–1.8	199–326
G: Olson and Reiten (2002)	0.05–0.5	9–90

\*Assumes the ditch is active 3 months per year.



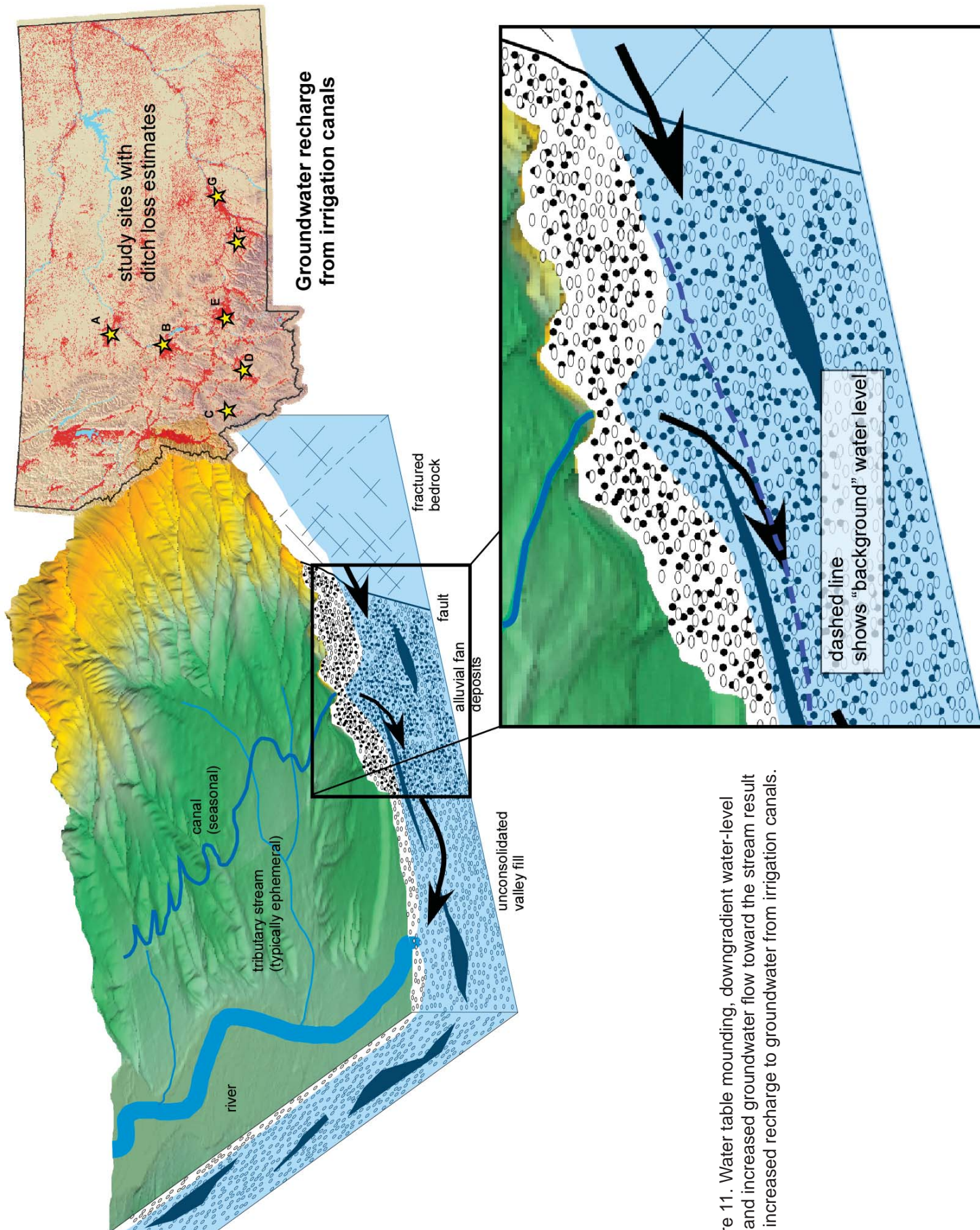


Figure 11. Water table mounding, downgradient water-level rise, and increased groundwater flow toward the stream result from increased recharge to groundwater from irrigation canals.



### Effects of Irrigation Canals on Groundwater Levels

Nearly all of the intermontane valleys of western Montana are irrigated and sub-irrigated (recharged) by surface-water diversions. Recharge to groundwater from irrigation ditch loss is substantial; in many areas, the irrigation system is more than 100 years old and has established an artificial recharge system. There are several examples of wetlands and groundwater-dependent ecosystems that rely on recharge from these irrigation systems.

The hydrograph in figure 12 shows water levels in a well influenced by the East Bench Irrigation Canal in the lower Beaverhead River drainage. The water levels

(red squares) show a 40 ft water-level rise in response to flow in the canal. The canal was shut off for about 2 years (2003 through mid-2005) for lack of water; water levels dropped nearly 30 ft due to the lack of precipitation in the area and the lack of recharge from the canal.

Similar water-level responses to irrigation canals have been observed in other areas of Montana. Wren and others (2012) observe a 15- to 20-ft response near the Helena Valley Irrigation District canal, and Kuzara and others (2012) observed an 18-ft response in the Stillwater River drainage. Smith (2006) discussed water-level response to irrigation in wells of the Bitterroot Valley.

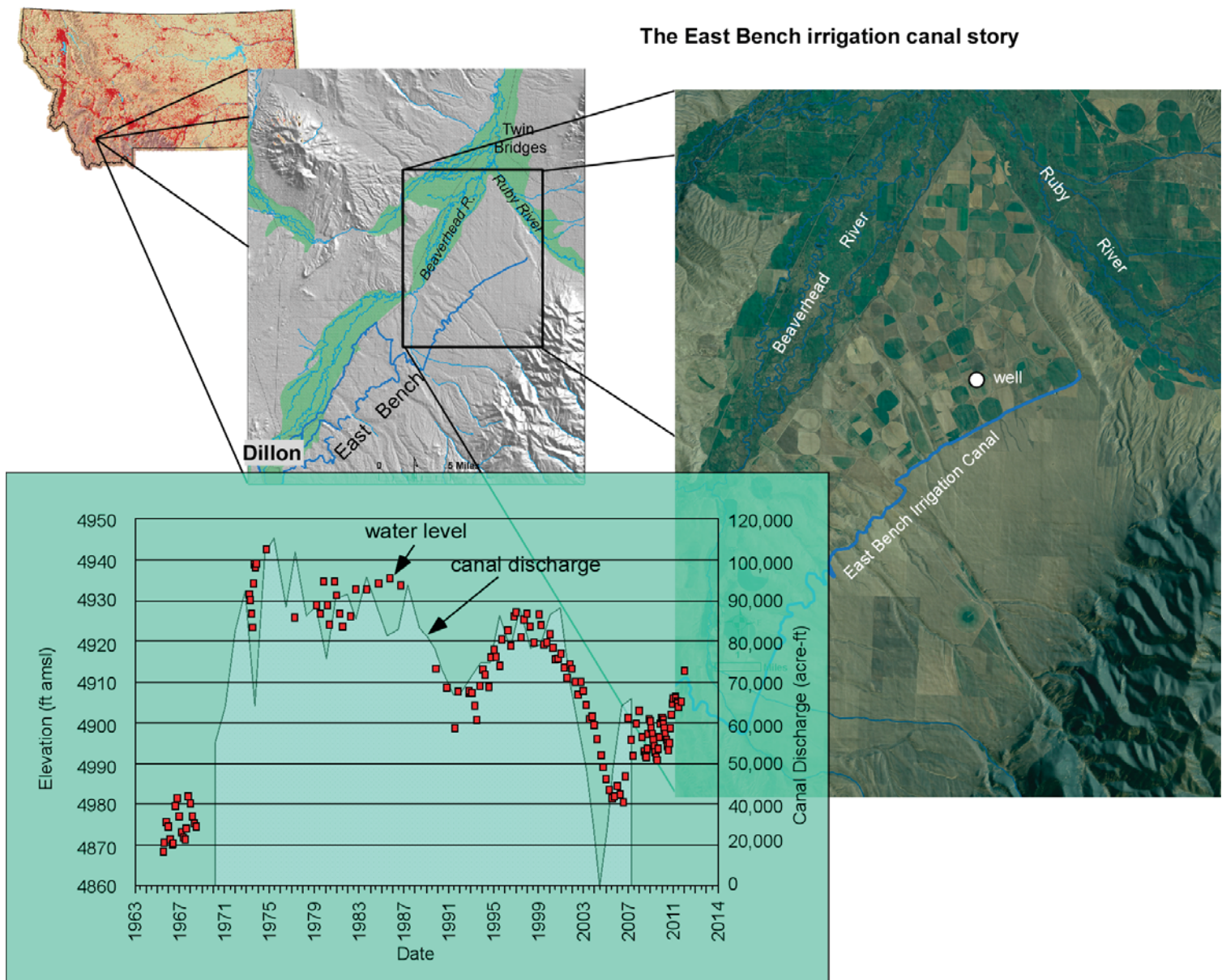


Figure 12. The East Bench irrigation canal provides one of many examples of groundwater recharge by irrigation. In addition to groundwater levels, the pattern of stream discharge has also been changed.

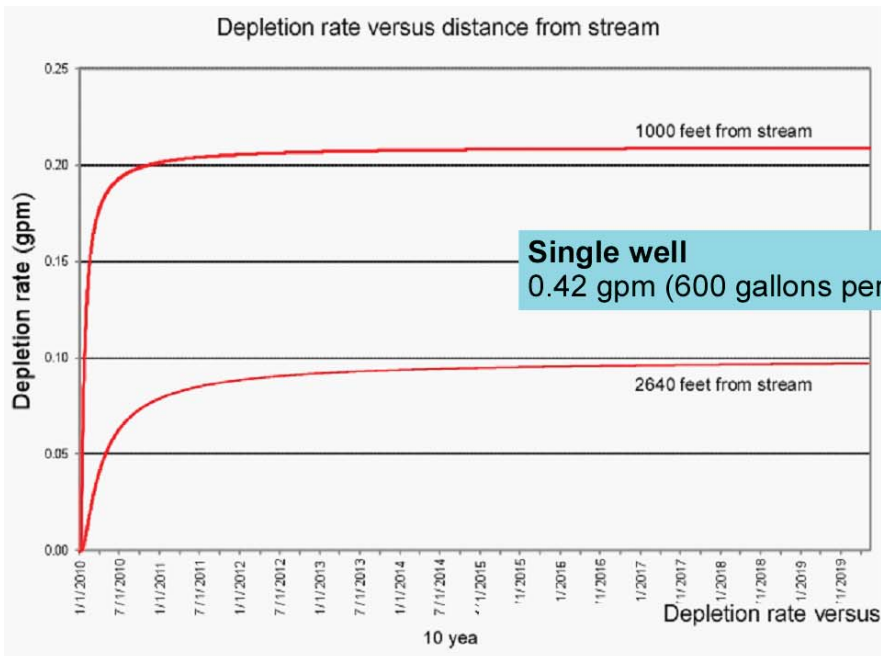
As land use changes from one type of irrigated agriculture to another or from irrigated agriculture to domestic use, recharge to the local groundwater flow system is likely to be affected. When irrigation canals are abandoned, the reduction to groundwater recharge may be substantial. Water levels in wells may decline, even to the point of wells going dry, groundwater flow to tributary streams and wetlands may be reduced, and the effects of stream depletion by existing pumping projects may be exacerbated.

### **Stream Depletion by One Well or Many**

Stream depletion or stream-flow reduction from groundwater withdrawal presents a complex challenge to management of water. Stream depletion is ultimately equal to the discharge rate of the well as it relates to the periodicity of that discharge. For example, pumping 400 gpm for 3 of every 12 months will establish a depletion rate of 100 gpm. Stream depletion is independent of stream discharge; the 100 gpm depletion in the example will be the same whether the stream discharges 1000 cubic feet per second (cfs) or 10 cfs. The ultimate volume of depletion is independent of distance from the stream; however, the rate and timing of depletion is dependent on distance, aquifer properties (transmissivity and storage coefficient), as well as the pumping rate. There is no difference between pumping from one or many wells; one well pumping at 1,000 gallons per minute (gpm) is equivalent to 100 wells pumping at 10 gpm; however, the location of the well(s) can be very important.

Figure 13 presents the effect of well placement and other factors such as septic drain fields on stream depletion. The top figure shows the difference between two wells, pumping at the same rate of 600 gallons per day (gpd) for in-house use, at different distances from the stream. The second figure shows the same wells pumping 600 gpd for in-house use plus cyclical pumping for lawn irrigation for 90 days each year. Under the same hydrogeologic conditions, the difference between a well at 1,000 versus 2,620 feet from a stream changes the peak stream depletion by a full month. That is, instead of depleting the stream during critical low flows in August (red line), it could be delayed until September when stream flows are not as critical (blue line). The third figure shows stream depletion rates for a case where the well is 2,640 feet from the stream, but the septic drain field is 1,000 feet from the stream. In this example, installing the supply well away from the stream and using near-stream recharge from the drain field to offset consumption reduces stream depletion by 60 to 75% each year (green line). The latter example is not always practical for individual homes, but demonstrates a potentially useful strategy for managing a public water supply with properly installed individual septic systems in a multi-home subdivision.

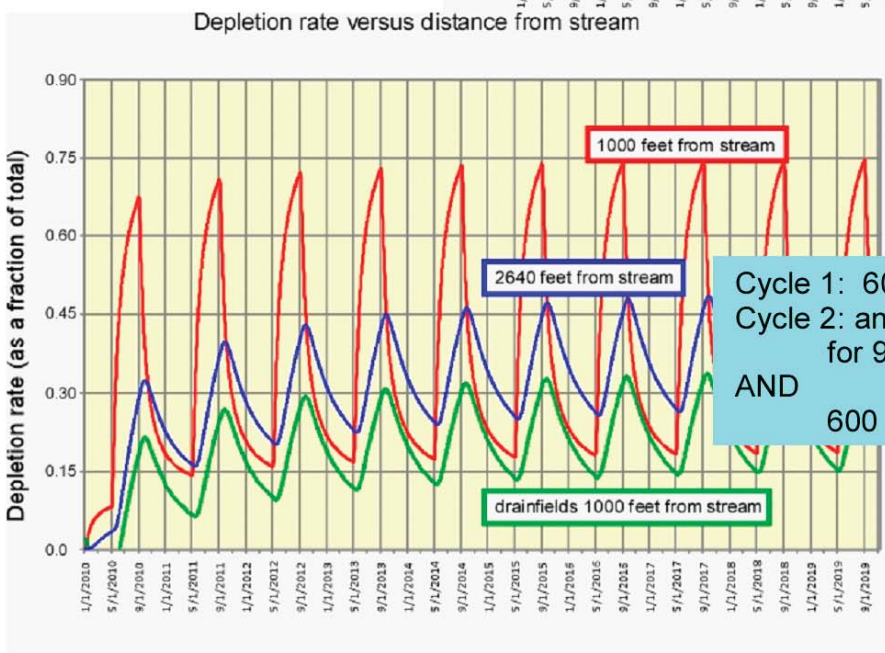
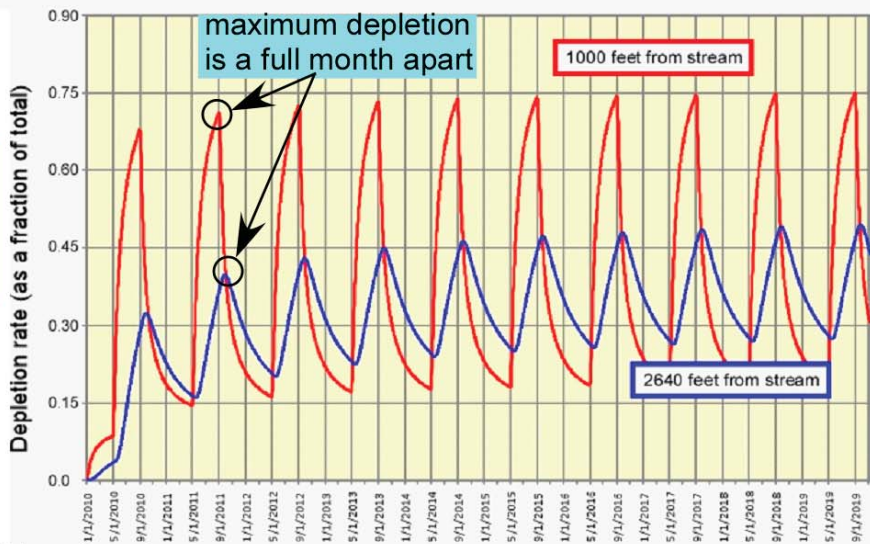




**Stream depletion:  
one well versus many**

**Single well**  
0.42 gpm (600 gallons per day)

**Single well**  
0.42 gpm (600 gpd all year)  
pump an additional 4800  
gpd for 90 days per year



Cycle 1: 600 gallons per day every day, all year  
Cycle 2: an additional 10 gpm for 8 hours per day  
for 90 days each year (600 + 4800 gpd)  
AND  
600 gpd recharge every day, all year

Figure 13. The rate of stream depletion by pumping groundwater is largely affected by the distance between the well and the stream.

## **Stream Depletion Zones**

As discussed, stream depletion is affected by aquifer properties, the discharge of the well, and the distance between the well and the stream. Using predictive modeling to estimate stream depletion for each and every proposed well can be onerous and expensive. Alternatively, modeling data from hydrogeologic studies with representative or anticipated values for well discharge can be used to map zones that represent stream depletion rates and volumes.

Figure 14 shows an example of a map where stream depletion zones were established for various areas in the aquifer near the stream. The hydraulic conductivity and storage coefficient of the aquifer were used to map areas where stream 80% of the total depletion would occur within 1 month, between 1 and 2 months, and within 3 months at a specific pumping rate. In addition to those presented, zones of peak-month depletion or zones of average annual stream depletion can also be constructed. Where data are sufficient for more detailed modeling, groundwater recharge as affected by climate variation can also be evaluated.



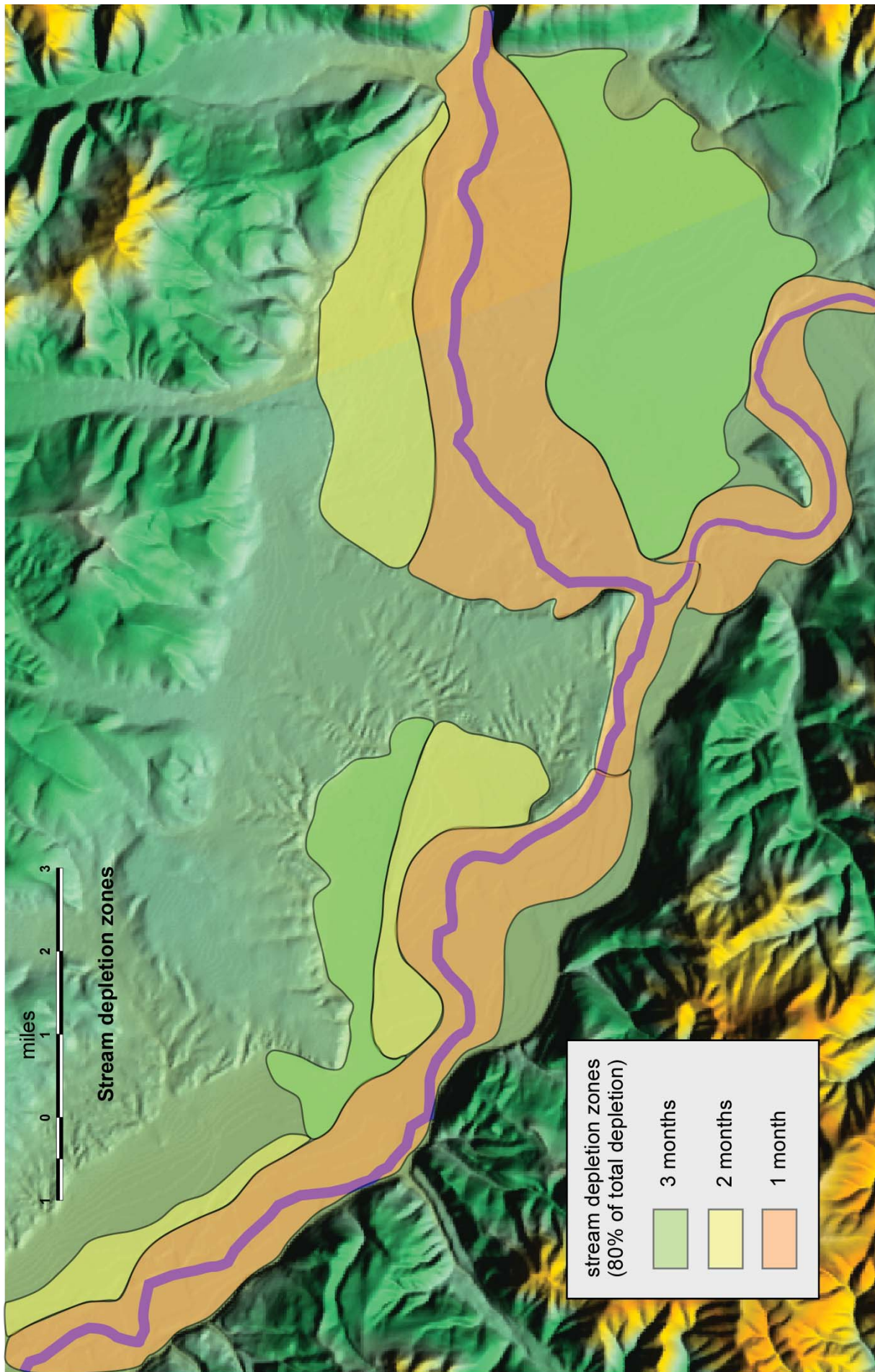


Figure 14. Stream depletion zones can be established based on aquifer properties and groundwater flow modeling.



## References

- Abdo, G. N., and Metesh, J., 2005, Big Hole Watershed Management Study, Report submitted to the Beaverhead County Conservation District, 51 p.
- Abdo, G.A., Roberts, M., 2008, Ground water and surface water in a study area within the upper Big Hole River basin, Montana Bureau of Mines and Geology: Open-File Report 572, 85 p.
- Bauder, J.W., King, L.D., Westesen. G.L., 1983, Montguide: Using evaporation tubs to schedule irrigations. Montana State University Cooperative Extension Service Publication C-1 MT8343
- Cannon and Johnson, 2004, Estimated water use in Montana in 2000, U.S. Geological Survey Scientific Investigations Report 2004-5223 49p.
- Gleick, P. H., 1996, Water resources, In Encyclopedia of Climate and Weather, ed. by S. H. Schneider, Oxford University Press, New York, vol. 2, pp.817-823.
- Kuzara, S., Meredith, E., Gunderson, P., 2012, Aquifers and Streams of the Stillwater–Rosebud Watersheds, Montana Bureau of Mines and Geology: Open-File Report 611, 130 p.
- Madison. J.P., 2006, Hydrogeology of the North Hills, Helena, Montana, Montana Bureau of Mines and Geology: Open-File Report 544, 41 p., 3 sheet(s), 1:24,000.
- Montana State Library's Natural Resource Information System (NRIS), 2001, MT Department of Revenue coverages of irrigation methods, <http://nris.mt.gov/gis/> (accessed November 2011).
- Olson, J.L., and Reiten, J.C., 2002, Hydrogeology of the West Billings area: impacts of land-use changes on water resources, Montana Bureau of Mines and Geology Report No. 206, 32 p.
- Osborne, T.J., Noble, R.A., Zaluski, M.H., and Schmidt, F.A., 1983, Evaluation of the ground-water contribution to Muddy Creek from the Greenfields Irrigation District, Montana Bureau of Mines and Geology Open-File Report 113, 141 p. + appendices.
- Smith, L.N., 2006, Patterns of water-level fluctuations, Lolo-Bitterroot area, Mineral, Missoula, and Ravalli counties, Montana (open-file version), Montana Bureau of Mines and Geology: Ground-Water Assessment Atlas 4B-10, 1 sheet(s), 1:350,000.
- U.S. Bureau of Reclamation, 2011, The Great Plains Cooperative Agricultural Weather Network, <http://www.usbr.gov/gp/agrimet> (accessed November, 2011).
- Waren, K., Bobst, A., Swierc, J., Madison. J.D., 2012, Hydrogeologic Investigation of the North Hills Study Area, Lewis and Clark County, Montana, Interpretive Report, Montana Bureau of Mines and Geology: Open-File Report 610, 99 p.