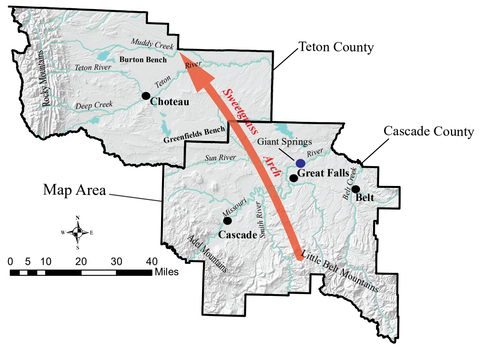


Figure 1. Index map showing principal cities, drainages, and physiographic locations in the Cascade–Teton Ground Water Characterization Program investigation. The potentiometric map covers the Madison Aquifer in Cascade County.

Potentiometric Surface in the Madison Group Aquifer, Cascade County, North-Central Montana

by

James P. Madison

Author's Note: This map is part of the Montana Bureau of Mines and Geology (MBMG) Groundwater Assessment Atlas for the Cascade–Teton Area groundwater characterization. It is intended to stand alone and describe a single hydrogeologic aspect of the study area, although many of the area's hydrogeologic features are interrelated. For an integrated view of the hydrogeology of the Cascade–Teton Area, the reader is referred to the other maps of Montana Groundwater Assessment Atlas 7. (http://mbmggwic.mtech.edu)

Introduction

The Madison Group aquifer (Madison Aquifer) is an important source of groundwater in Cascade County, north-central Montana (figs. 1, 2). Not only does it provide water for public supply, self-supplied domestic, self-supplied industrial and livestock purposes, it is also the source of water for Giant Springs (map).

Giant Springs is located on the south bank of the Missouri River and is among the largest springs in the United States (Meinzer, 1927). A discharge of 298 cubic feet per second (cfs;134,700 gallons/minute) was measured indirectly (USGS, 1974; Wilke, 1983), thus documenting it as the single largest volume discharge point from any aquifer in Montana.

As part of the MBMG Ground Water Characterization Program, a potentiometric-surface map for the Madison Aquifer was constructed. A potentiometric surface represents the altitude to which water will rise in wells penetrating an aquifer. The map provides a tool for evaluating groundwater flow directions and hydraulic gradients in the Madison Aquifer. Horizontal groundwater flow paths can be traced along lines drawn perpendicular to contours in a direction from high groundwater altitudes to low altitudes. Water-level trends were assessed using long-term hydrographs for several wells; water levels in one well have been measured since 1979.

Geographic Setting

Cascade County lies in the transition between the Great Plains to the east and Rocky Mountains to the west, and contains topographic characteristics of both. The land surfaces in most of the county are broad, gently sloping plateaus and terraces bordered by the Little Belt Mountains to the south and the Adel Mountains to the southwest (fig. 1). The plains are underlain by north-dipping sedimentary rocks consisting mostly of mudstone, shale, and sandstone.

The Little Belt Mountains, along the southeastern edge of Cascade County, are uplifted sedimentary rocks that dip northward about 15°–20° along the mountain front, but flatten north of the mountains to about 4° (fig. 3). The Madison Group is exposed in the Little Belt Mountains and where drainages have incised through younger rocks such as near Stockett (see map).

Cascade County is drained by the Missouri River, which exits the study area on the east side of the county (map). Important tributaries include the Sun and the Smith Rivers, and Belt Creek (figs. 1, 2, 4, 6, and the map). Where they flow directly over outcrop areas in the Little Belt Mountains, the Smith River and Belt Creek are important recharge sources to the Madison Aquifer.

Geologic Setting

The geology of Cascade County has been mapped in detail (Vuke, 2000; Vuke and others, 2002a, b; Reynolds and Brandt, 2005, 2007); the geology presented here is generalized from those sources. Bedrock exposed in the Little Belt Mountains is pre-Cambrian metamorphic (gneiss and amphibolite), igneous (diorite), sedimentary rocks, as well as Paleozoic sedimentary rocks; these rocks have been combined as map unit pre-Mmu. The Madison Group (Mmu) and Paleozoic and Cretaceous igneous and sedimentary rocks above the Madison Group, as map units PMsu, KJsu, Kk, Kcg, Kvt, Kthb, and TKi. Map unit PMzu is missing in the subsurface throughout much of Cascade County because of pre-KJsu erosion (fig. 3).

The Mississippian Madison Group in Cascade County is a marine carbonate sequence composed of two formations: the upper formation is the Mission Canyon Limestone, and the lower formation is the Lodgepole Limestone. The Lodgepole Limestone consists of thin- to medium-bedded fossiliferous dolomite, limestone, and shale (Weed, 1899). The Mission Canyon consists of alternating thin argillaceous dolomite beds and massive fossiliferous limestone (Peterson, 1966). The Mission Canyon was sub-aerially exposed as a low-relief landscape within which karst developed. Features associated with karst recognized in the Mission Canyon include enlarged joints, sinkholes, caves, and solution breccia (Sando, 1974). Karst features occur in the upper 400 ft of the Madison Group, and are responsible for the great yield of water to Giant Springs and some wells; below 400 ft, permeability is not influenced by karst but restricted to normal fracture permeability. Total thickness of the Madison Group in Cascade County is estimated to be about 1,000–1,500 ft (Weed, 1899; Witkind, 1971; Peterson, 1966, 1981; Noble and others, 1982).

The Sweet Grass Arch, a broad northwest-plunging anticlinal structure that trends northward from the Little Belt Mountains, controls the depth below land surface of the Madison Group and other strata. The top of the Madison Group is generally nearest land surface along the axis of the arch. This explains why many wells in Cascade County completed in the Madison Aquifer are within a few miles of the arch's axis and less than 500 ft deep. However, some wells on the flanks of the arch penetrate more than 1,000 ft of overlying Cretaceous rock to reach the top of the Madison Group (fig. 4).

Map Construction

The potentiometric map was constructed by drawing equal-altitude contours based on 69 water-level altitudes measured in wells by the MBMG Ground Water Assessment Program (GWAP) between 2005 and 2012 (most were measured May–July 2012). Measured water levels from other projects (Duaime and others, 2004; Kuzara and others, in prep) were also used. All water-level data are available from the MBMG's Ground Water Information Center (GWIC, http://mbmggwic.mtech.edu). The potentiometric surface has a contour interval of 100 ft near the Little Belt Mountains and 5 ft near Great Falls. Typically, the representation of a regional-scale potentiomtric surface is not greatly influenced by water-level data collected during multi-year periods because changes in altitudes are insignificant and/or the contour interval is such that even tens of feet of change may only slightly shift the position of a contour. This is the case for areas of the Madison Aquifer with water-level altitudes above about 3,400 ft above mean sea level (amsl).

However, water-level altitudes in many Madison Aquifer wells were between 3,300 ft and 3,400 ft amsl (map); the altitude in many wells was approximately 3,325 ft amsl as of May–July 2012. The lowest water levels were within the cone of depression around Giant Springs. Because water-level altitudes measured in Madison Aquifer wells during the initial inventory between March 2005 and July 2008 (Carstarphen and others, 2011) could vary as much as 12 ft (figs. 6, 7), this could affect map accuracy in this area. To alleviate the time differences in water-level measurements, a subset of Madison wells inventoried during the initial part of the project was revisited in May–July 2012 and water levels in the wells re-measured.

The land-surface altitude is used to calculate water-level altitude; this can influence the accuracy and interpretation of the potentiometric map. During the 2005–2008 inventory, land-surface altitudes at well locations were interpreted from U.S. Geological Survey (USGS) 1:24,000 topographic maps and are generally accurate to 5 to 10 ft (based on 10- and 20-ft contour intervals). For most regional scale maps, this level of accuracy is adequate. To alleviate the error associated with altitude determination using topo maps, especially for 67 wells where water-level altitudes were less than 3,400 ft amsl, land-surface altitudes were determined with a Leica Model 1200 survey-grade GPS accurate to within ±3 in.

Potentiometric Surface

The potentiometric surface shows that groundwater in the Madison Aquifer generally flows northward towards Great Falls and that a cone of depression has developed around Giant Springs where flow lines converge on the springs. It's reasonable to assume that the Madison Group outcrop receives diffuse recharge from rain and snowmelt that infiltrates through fractures and other openings. Probably more significant is the large constant volume of water that leaks from the Smith River and Belt Creek where these two streams flow across the Madison Group outcrop. Low-flow investigations on the Smith River show that it may be losing about 140 cfs and that Belt Creek may lose 14 cfs as they cross the Madison Group in the Little Belt Mountains (Kuzara and others, in prep).

Fisher (1909) speculated that recharge to the Madison Aquifer and the source of Giant Springs was underflow from the Missouri River into the buried pre-glacial Missouri River channel near the mouth of Sand Coulee Creek (fig. 8); based on Darcy's law, underflow through this area is calculated to be approximately 2.3 cfs and does not explain Giant Springs' discharge.

Drillers' logs for some wells completed in the Madison Aquifer describe caverns, voids, and fractures in the upper part of the Madison Group consistent with karst development. In some areas, the caverns and voids are above the potentiometric surface, which can hinder drilling; wells 180017 and 186947 in T. 18 N., R. 4 E. are examples. Figure 5 shows areas where the potentiometric surface is below the top of the Madison Group, leaving the upper part unsaturated. Voids in this part of the aquifer can make well drilling difficult.

Hydrographs (figs. 6, 7) for wells completed in the Madison Aquifer were analyzed for water-level trends. The hydrographs show that water levels increase during the summer months because of recharge from precipitation and stream leakage; they decrease during the winter months when recharge is less. Besides seasonal variation, multiyear trends related to wet and dry climatic periods are apparent. During a dry cycle from 1995 to 2005, water levels dropped by about 30 ft; from 2005 to 2013, water levels recovered by a comparable amount (fig. 6). The hydrographs in figure 6a were also compared to the 12- and 24-month departures from normal precipitation, but the 36-month departure correlates the best. The comparison between the water levels and 36-month departure from normal precipitation shows that long-term water levels are influenced more by 36-month precipitation anomalies than by any single precipitation event.

The similarity in water-level responses indicates that the Madison Aquifer is highly interconnected (figs. 6a, 7b) in an area bounded by the 3,325-ft potentiometric contour. Wells 181868 and 2315 are located about 24 mi apart, yet water levels at both sites respond almost identically. Well 28054 (fig. 7a) is located near the Madison Group outcrop in the Little Belt Mountains and, although it shares similar seasonal variations and increasing water-level trend with the wells in figure 7b, water levels in well 28054 respond differently than the wells completed in the highly connected zone of caverns, voids, and fractures bounded by the 3,325-ft amsl contour.

Acknowledgements

This work was supported by the Ground Water Assessment Program at the MBMG. Well owners who allowed collection of the necessary data for the map, and the people who collected the data, are gratefully acknowledged. Cartography assistance was provided by Susan Smith. The text, map, and supporting figures were improved by reviewers including Russell Levens, Thomas Patton, John LaFave, and Phyllis Hargrave. Edited by Susan Barth.

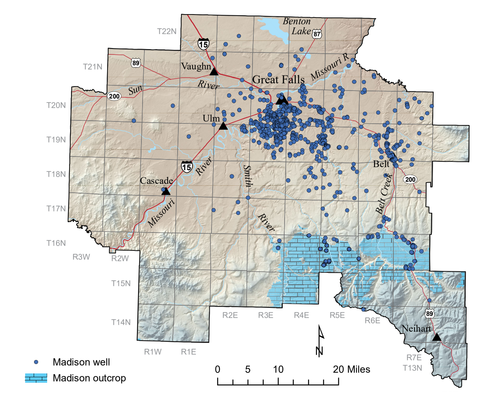


Figure 2. As of September 2012, the Ground Water Information Center (GWIC) database contained records for 968 wells completed in the Madison Aquifer in Cascade County. Most wells are located near Great Falls, Montana.

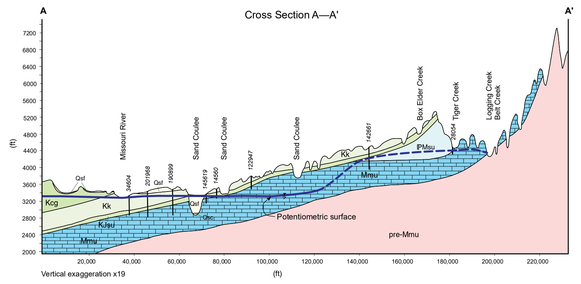


Figure 3. Geologic cross section from just north of Great Falls (A) to the Little Belt Mountains (A') showing geologic units including the Madison Group. The Madison Group outcrops in the Little Belt Mountains and in Sand Coulee near Stockett.

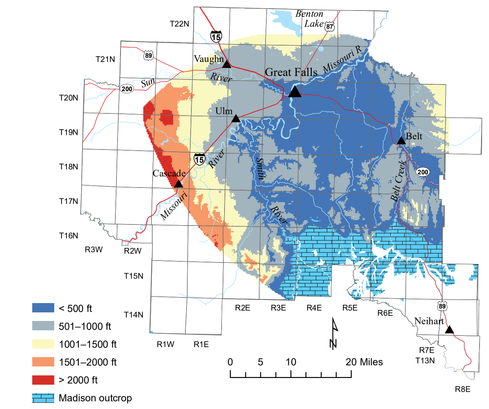


Figure 4. The depth from land surface to the top of the Madison Group is less than 500 ft along the Sweetgrass Arch, but is greater than 2,000 ft along its east and west flanks. This map was produced by subtracting the altitude of the top of the Madison Group (Smith, 2008) from the land-surface altitude.

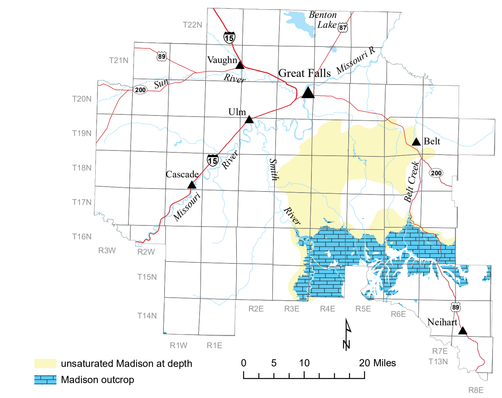


Figure 5. The Madison Group is saturated with water in most places. Between the Little Belt Mountains and Great Falls, there is an area where the top of the water table is below the top of the Madison Group. Drillers' logs for some wells in this area note numerous unsaturated caverns. This map produced by subtracting the potentiometric surface altitude from the top of the Madison Group altitude (Smith, 2008).

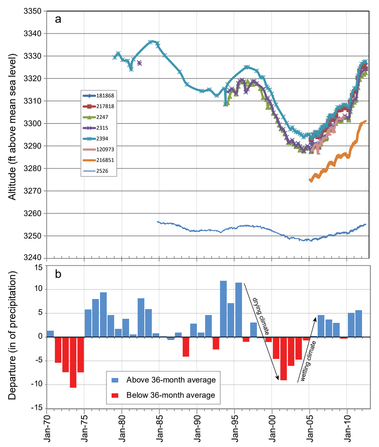


Figure 6. (a) Hydrographs from six wells completed in the Madison Group show almost identical response to recharge and climate; well pair 181868 and 2315 and well pair 2394 and 2315 are more than 24 mi apart. The response in the hydrographs indicates that the Madison group is highly interconnected (has high hydraulic conductivity) by the karst and solution features that developed in the upper part of the Madison Group when it was subaerially exposed. Well 2526 is about 600 ft southwest of Giant Springs; it is completed in the Kootenai Formation with fractures that connect it to the Madison Aquifer (T.W. Patton, Montana Bureau of Mines and Geology, oral commun., 2015), accounting for the difference in water levels between well 2526 and the other six wells. The drawdown is caused by discharge to the springs.
(b) 36-month departure from normal precipitation (1895–2012) in Cascade County
(http://www.cefa.dri.edu/Westmap/Westmap_home.php). Water levels increase during wetting climates (2002–2012) and decline during drying climates (1995–2002).

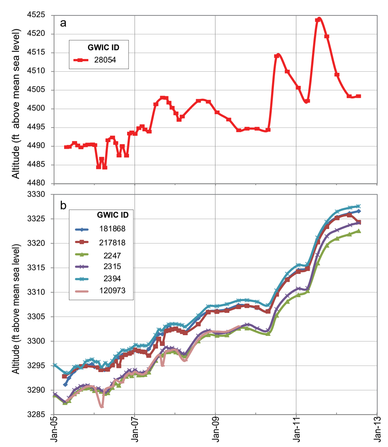


Figure 7. (a) Hydrograph for well 28054, which is located near the Madison Group outcrop—the recharge zone—in the Little Belt Mountains for 2005 through 2012. Water level fluctuates seasonally by about 5–20 ft, and responds closely to seasonal precipitation and long-term climatic trends (fig. 7b).
(b) Expanded-scale plots for the same wells in figure 7a show similar but more subdued response to seasonal precipitation, reflecting the greater amount of storage in the part of the aquifer where these wells are completed.

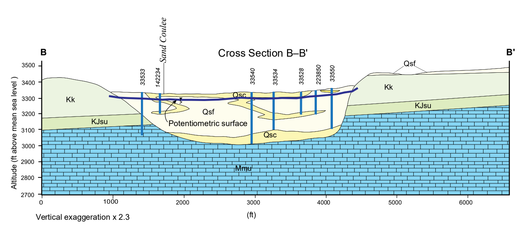
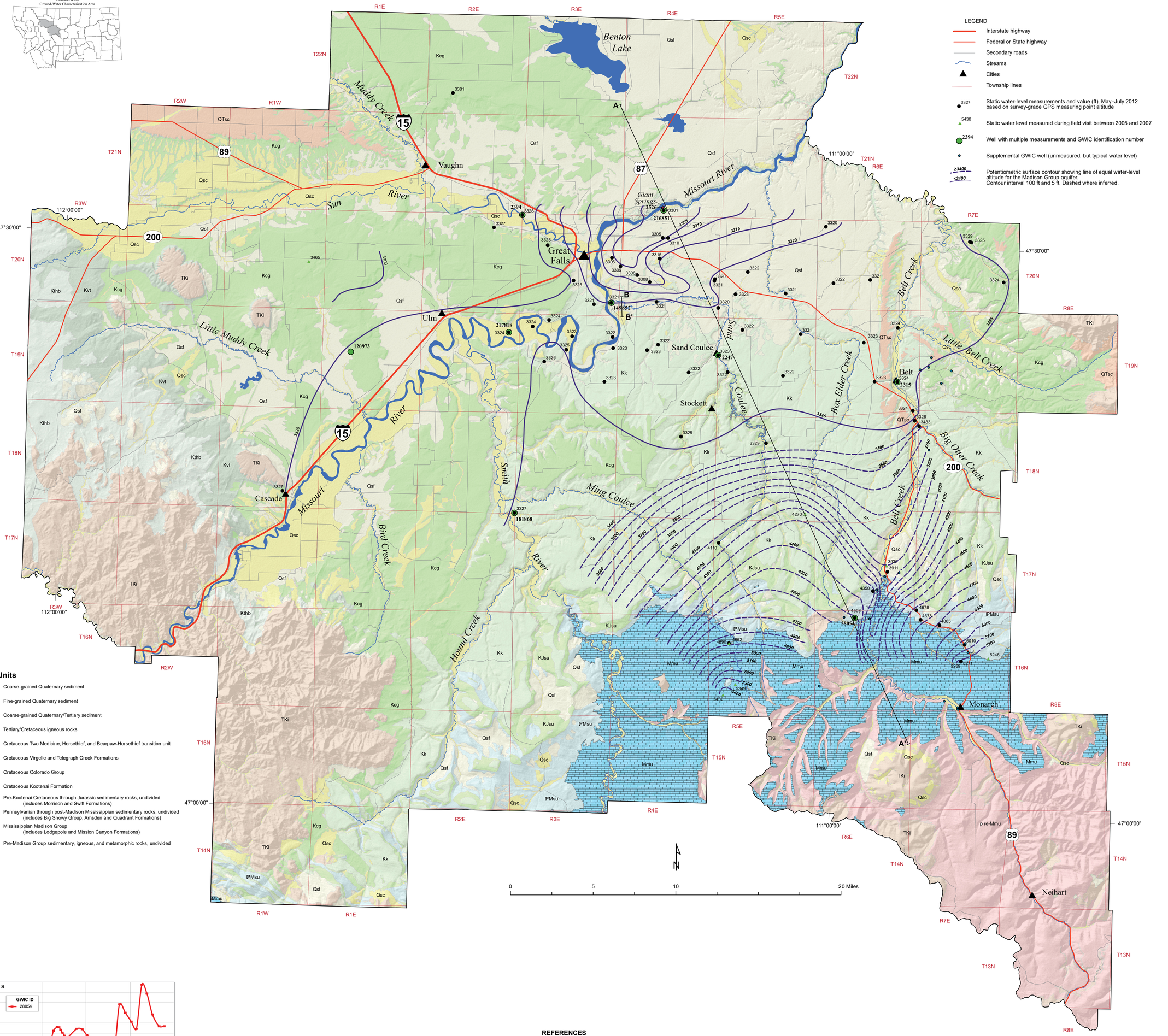


Figure 8. Geologic cross section across Sand Coulee near Great Falls. The pre-glacial Missouri River cut a channel into the top of the Madison Group. Glacial Lake Great Falls sediments and other alluvium filled this ancestral channel. Assuming a hydraulic conductivity of 100 ft/day, a hydraulic gradient of 0.002, and a cross-sectional flow area of 990,000 ft² (3,300 ft x 300 ft), a maximum of about 2.3 cfs of groundwater may move through the ancestral Missouri River channel, which is not enough flow to explain the discharge of Giant Springs as speculated by Fisher (1909).



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