Infiltration to Groundwater at High Altitude

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Abstract. Infiltration (or recharge) is the ultimate source of groundwater, and controls mine inflow, groundwater supply, and flow and solute transport behavior in large-scale groundwater systems. However, infiltration is rarely directly measurable, and is difficult to quantify. An 18 square kilometer area at 3,000 meters above sea level in the Rocky Mountain Cordillera of North America has been dewatered for the last century by a system of drainage tunnels, which has provided a rare opportunity to directly measure infiltration. Infiltration to deep groundwater was found to average 175 mm per year to the district, or 39% of the total precipitation of approximately 445 mm per year. These infiltration rates are significantly higher than the normal range of 5% to 10% of total precipitation that are identified at lower altitudes in this region, due to the effects of altitude, temperature, storm intensity, and thin soil cover in the district.

Setting

The setting of the study is the central Rocky Mountain Cordillera, in central Colorado, USA. At 3,000 meters elevation on the western flank of Pike's Peak near the town of Cripple Creek is located one of the world's great gold ore bodies, the Cripple Creek Mining District. Approximately 40 million ounces of gold has been recovered from this district since 1890.

The geology of the Cripple Creek Mining District is characterized by a large diatreme plug that intruded the Pikes Peak Granite and metamorphic gneiss and schist during the late Oligocene. Initial emplacement of the diatreme was followed by several episodes of volcanism resulting in a brecciated rock mass with intrusive igneous rocks (e.g., numerous phonolite and lamphrophyre dikes and sills). The dikes generally trend northwest through the diatreme complex. The void spaces within the volcanic breccia were mineralized by hydrothermal solutions associated with the rising magma body (Pontius, 1997). Post-Laramide erosion has exposed a portion of the diatreme at the surface where it now out outcrops over approximately 18 square kilometers.

The occurrence and movement of groundwater within the Mining District is controlled primarily by the diatreme complex and surrounding Precambrian country rocks. The relatively permeable diatreme complex receives a significant quantity of water from local precipitation, which averages 445 mm per year. Groundwater is stored in the fractured volcanic breccia within the diatreme where flow is restricted by the surrounding less permeable Precambrian strata. Although the volcanic breccia is well cemented and relatively impervious, groundwater movement within the diatreme complex occurs primarily through secondary permeability features such as faults, fractures, joints, contacts between the dikes and breccia, and likely, the old underground mine drifts and shafts.

Regional Drainage

Gold and silver tellurides were first discovered in the Cripple Creek Mining District in 1891. During the early 1890's mining of the ore body was conducted near the ground surface in shallow shafts and drifts. Starting in 1895, mining occurred below the water table and mine dewatering became necessary. Early accounts by Lindgren and Ransome (1906) indicate that the mean water table elevation was at 2,926 meters above mean sea level (mAMSL) and depth to water ranged from 10 to 300 meters below ground surface prior to dewatering.

As mining advanced to greater subsurface depths, several drainage tunnels were driven through the Mining District. Some of the major drainage tunnels within the Mining District include the Standard Tunnel (completed in 1896), the Moffatt Tunnel (1903), the El Paso Tunnel (1903), the Roosevelt Tunnel (1910), and the Carlton Tunnel (1941). Historical accounts suggest that these tunnels were relatively dry when driven through the low permeability Precambrian country rocks that surround the diatreme complex. Significant quantities of water were encountered when the tunnels were driven into the diatreme breccia. Maximum flow rates generally occurred on initial break-through of the tunnels into the diatreme, and into mine workings. The peak flows were significant: 500 liters per second (L/s) in the Roosevelt Tunnel, 1,100 L/s in the Standard Tunnel, and 1,600 L/s in the Carlton Tunnel (Lindgren and Ransome, 1906; Vivian, 1941). The deepest drainage tunnels within the District, the Roosevelt and Carlton Tunnels, were driven at approximate elevations of 2,470 mAMSL and 2,100 mAMSL, respectively

The Roosevelt and Carlton Tunnels had the biggest dewatering impacts on the hydrology of the diatreme. For example, from 1917 to 1918, the discharge from the Roosevelt Tunnel dropped from 500 L/s to 250 L/s, while water levels were lowered 200 meters across the Mining District (Vivian, 1941).

The deeper Carlton Tunnel produced a large flow of water after being driven through the New Market Fault, which is located below the Ajax Mine shaft. This effectively drained 200 meters of standing water in the Ajax Mine in approximately 2 weeks (Vivian, 1941b). Flow within the tunnel decreased steadily, and by 1949 was ineffective in draining some portions of the Mining District. Two drainage tunnels, the Vindicator and Cresson Laterals, were subsequently driven through the Portland Independence structural zone to promote more widespread drainage. The two laterals increased flow in the Carlton to approximately 370 L/s by 1955, but flow gradually diminished to approximately 125 L/s by 1959. Since 1959, flow has generally decreased slightly, stabilizing at approximately 100 L/s.

The history of all flows from dewatering tunnels and flows pumped from mines in the district is presented in Figure 1. This shows the increase in inflow resulting from the installation of the Standard and El Paso Tunnels, the Roosevelt Tunnel, and the Carlton Tunnel. Each tunnel system is approximately 300 meters deeper than the prior tunnel system, resulting in drainage of additional storage water from the rockmass. By about 1960, all the stored water in the rockmass had been removed, resulting in an approximate steady-state regional flow of 100 L/s. This outflow is equal to the infiltration to the diatreme surface.

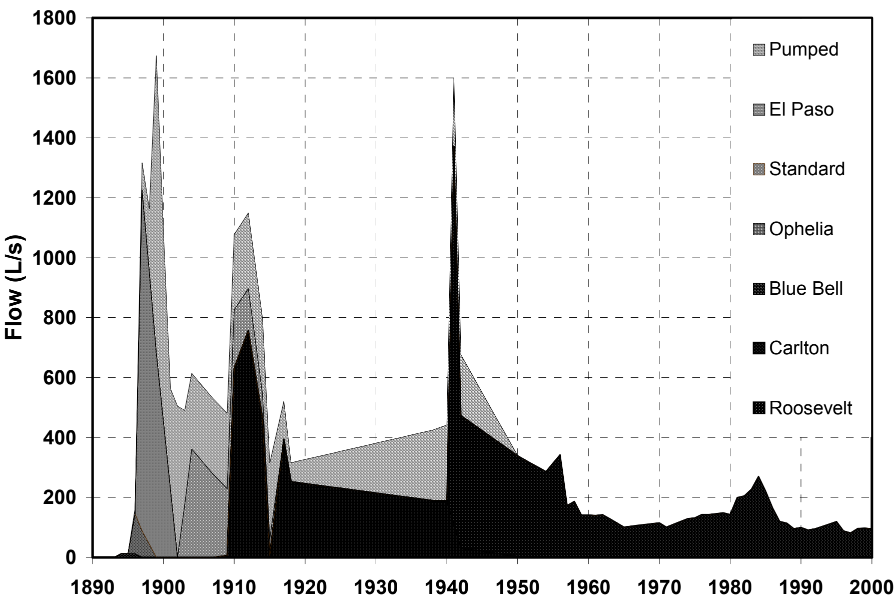

Fig. 1. Diatremal drainage flow from the Cripple Creek Mines 1890-2000.

Infiltration

The rate of deep groundwater infiltration to the diatremal area can be determined by dividing the steady-state flow rate into the area that is being drained:

- Infiltration flow to diatreme = 100 L/s
- Ground surface diatreme area = 18 km^2
- Infiltration rate to diatreme = 175 mm/yr

The actual infiltration to the diatreme is probably slightly smaller than this value; some of the water that is flowing from the Carlton Tunnel is being drawn from the immediately adjacent granitic rockmass. Monitoring well information indicates that the zone of capture from the dewatering of the diatreme extends only a very short distance into the granite, and this has been ignored in this evaluation.

The infiltration rate of 175 mm/year can be compared to the average annual precipitation of 445 mm/year (based on records at two adjacent weather stations, Cripple Creek and Victor). The ratio of infiltration to precipitation is computed to be:

Infiltration rate to diatreme	= 175 mm/yr
Total precipitation to diatreme	= 445 mm/yr
Percentage of precipitation infiltrating	= 39%

This is a very high infiltration rate; typical infiltration rates on similar terrain at lower elevations in Colorado (around 2,000 mAMSL) are 5% to 10% of incident precipitation (see for example Musgrave 1955). The high infiltration rate appears to be the result of the following factors:

1. Low temperatures. The average annual temperature in the mining district is 5.7°C. Five months have average temperatures below or at freezing. This limits the amount of plant growth, and correspondingly limits evapotranspiration. Vegetation on the diatreme is limited, with sparse conifer forest and open dry grassland predominating.
2. Permeable soils and rocks. The soils that cover the area are sandy, and are underlain by relatively permeable rocks. This combination increases shallow infiltration; surface runoff in the area is rare. It also reduces retention time near the surface, further limiting opportunities for evaporation or evapotranspiration.
3. Montane weather. Weather patterns in the mountains of Colorado are highly variable. Most precipitation occurs in the district as summer thunderstorms, and 39% of the total precipitation occurs in storms delivering in excess of 10 mm per day. This precipitation pattern encourages infiltration due to surface flooding.

Even taking these factors into account, the infiltration rate is high, and suggests that infiltration evaluations in modeling and other processes may be understated, at least in elevated areas.

Other Parameters

The mine flow information collected over the years of observation allow estimates of key hydraulic parameters for the diatreme rockmass, including hydraulic conductivity and drainable porosity.

Hydraulic Conductivity

The hydraulic conductivity of the overall diatreme rockmass has been computed using the responses to the installation of the drainage galleries during the mining campaigns. Based on these data, the bulk hydraulic conductivity of the diatremal rock is computed to be 4x10-7 meters per second (m/s).

Drainable Porosity

The drainage of the rock prior to reaching steady state allows a computation of the drainable porosity of the rock in the diatreme. The total stored water removed by the mine dewatering is computed by subtracting the infiltrating water (assumed constant) from the removed water for the period 1890 to 2000:

Total volume dewatered	= 1.24×10^9 m^3
Total infiltration during dewatering	= 0.34×10^9 m^3
Total volume removed from storage	= 0.90×10^9 m^3

The total rock volume from which the water was removed is computed by multiplying the area of the diatreme by the total groundwater level reduction:

Area of diatreme	= 1.81×10^6 m^2
Groundwater level reduction	= 800 m
Volume of rock dewatered	= 14.5×10^9 m^3

The drainable porosity of the rock is computed by dividing the storage water by the volume of rock from which it was obtained:

Total volume removed from storage	= 0.90×10^9 m^3
Volume of rock dewatered	= 14.5×10^9 m^3
Drainable porosity of rock	= 6.2%

Computed Infiltration

In many situations it is not possible to directly measure infiltration to the deep groundwater system. In such cases, computational methods are used to evaluate the infiltration that will occur. These methods in general rely on water balance analyses, applying precipitation to the ground surfaced, and partitioning it into runoff, evapotranspiration, and infiltration. A widely used method of performing this complex calculation is the U.S. Environmental Protection Agency’s Hydrologic Evaluation of Landfill Performance (HELP) Model (Peyton and Schroeder 1994). This model was used to compute the expected infiltration to the Cripple Creek Diatreme, using the following parameters:

1. Daily precipitation data for 10 years for the area, duplicated to provide a synthetic 20 year record (Earthinfo 1997).
2. Daily temperature data for 10 years for the area, duplicated to provide a synthetic 20 year record (Earthinfo 1997)

3. Monthly solar insolation information for Colorado Springs, a nearby city where this parameter is measured).
4. Monthly evapotranspiration data synthetically generated (Miller et al. 1973).
5. A typical geological section for the diatremal area (Pontius 1997).
6. Geohydrology parameters obtained from site testing, and from typical values for site materials (Peyton and Schroeder 1994).

Using this information, a one-dimensional flow model was created and run in the HELP Model. The results are indicated in Table 1.

Table 1. HELP model results for infiltration to Cripple Creek Diatreme.

Run	20A	20B	20C	20D	20E
Depth: 0m-0.15m	Loam	Loam	Co Sand	Gravel	Gravel
Depth: 0.15m-1m	Loam	Loam	F Sand	F Sand	Co.Sand
Depth: 1m-3m	Rock	Rock	Rock	Rock	F. Sand
Depth: 3m-6m	Rock	Rock	Rock	Rock	Rock
Depth: 6m-15m	Rock	Rock	Rock	Rock	Rock
Leaf Index	2	1	1	1	1
Evaporation Depth (m)	0.5	0.4	0.4	0.4	0.4
Precipitation (mm/y)	445	445	445	445	445
Runoff (mm/y)	2	2	2	2	2
Evapotranspiration (mm/y)	425	409	392	382	353
Storage (mm/y)	0	0	1	1	7
Infiltration (mm/y)	17	34	50	60	83
Infiltration/Precipitation	4%	8%	11%	14%	19%

The HELP analyses performed cover a wide range of possible soil types, and evapotranspiration options, including very high permeability soils and very low evapotranspirative conditions. The infiltration rates computed with this model range from 17 mm/year (4% of precipitation) to 83 mm/year (19% of precipitation). These values are significantly less than the measured infiltration of 175 mm/year. Accordingly, it appears that at least in this case, which is one of the few where actual infiltration is known, an accepted tool that is widely used for computing infiltration greatly underestimates infiltration.

Conclusion

Infiltration to the deep circulating groundwater system has been measured in a high altitude setting in Colorado, using steady state flow to a drainage system beneath an 18 square kilometer area. The infiltration rate was found to be 175 mm/year, approximately 39% of the total precipitation to the area of 445 mm/year.

This measured infiltration rate is significantly higher than normally expected infiltration rates, which are 5% to 10% of incident precipitation. It is also significantly higher than the range of infiltration rates computed using standard infiltration models. Based on this rare opportunity to accurately measure infiltration, it would appear that estimation of infiltration, at least in high altitude settings, is not reliable using accepted proportions of precipitation, and accepted computational methods.

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