the mine workings. As in previous simulations, the relatively small movement of the degraded water during the simulation period is due to the small ground-water velocities in the aquifer. The model-simulated effects of hydrodynamic mixing (dispersion) cause simulated changes in concentration upgradient and downgradient from the mine.

SUMMARY AND CONCLUSIONS

The bedrock geohydrologic system in the upper part of the Mesaverde group of northwestern Colorado consists of two regional aquifers separated by three principal confining layers. The confining layers, consisting primarily of marine shale, underlie the Trout Creek Sandstone Member of the Iles Formation (the deepest regional), separate the Trout Creel Member from the younger Twentymile Sandstine Member of the Williams Fork Formation (the second regional aquifer), and overlie the Twentymile Sandstone Member. Numerous aquifers of local extent are present in sandstone beds and coal seams of the middle confining layer in dandier lithology of the western part of the study area. In the eastern part of the study area, the only local aquifer (the basal Williams Fork aquifer) consists of sandstone and coal within the basal part of the Williams Fork Formation.

The basal Williams Fork aquifer has greater water-yielding potential that either of the two regional aquifers in the eastern area. Sandstones in the Trout Creek and Twentymile aquifers are similar in appearance, composition, grain size, sorting, and thickness (about 10 to 150 ft) but differ in average hydraulic conductivity; the hydraulic conductivity of the Trout Creek aquifer is about one-third that of the Twentymile aquifer. The basal Williams Fork aquifer generally contains more sandstone (100 to 200 ft) and has an average hydraulic conductivity about eight times larger than that of the Twentymile aquifer. The resulting mean transmissivity is about 20 ft^2/d for the basal Williams Fork aquifer, 4 ft^2/d for the Twentymile aquifer, and 0.0 ft^2/d for the Trout Creek aquifer. Fractured coal seams may contribute to the larger average hydraulic conductivity of the basal Williams Fork aquifer.

Infiltration of precipitation is the principal source of recharge to bedrock aquifers in the study area. Precipitation generally increase with altitude because of orographic effects associated with up-valley and cross-valley movement of storms. The upper reaches of the Yampa River valley is an exception in that lesser mean annual precipitation occurs at higher altitudes upstream from Steamboat Springs because of rain-shadow effects of cross-valley tracking storms. The mean annual precipitation of 14 to 25 in. in the study area is much less than potential evaporation, which exceeds 40 in/yr. As a result, excess surface water is available to recharge the aquifers only during periods of snowmelt or intense rainfall. Of approximately 150 ft^3/s of mean annual precipitations that falls on the eastern part of the study area, only about 2 percent recharges the bedrock aquifers,

Geologic structure and the resulting topography of the formations have an important bearing on the ground-water recharge, discharge, and flow system in the aquifers. Structure in the study area has marked similar eastern and western tectonic forms. In the eastern part of the area, complex deformation associated with the Laramide orogeny has produced a series of four plunging synclinal and anticlinal features that resulted in structural basins southeast of Hayden and in Twentymile Park. Structurally high areas occur at outcrops of the formations in the mountainous areas surrounding Twentymile Park and on the elevated flanks of the Sage Creek, Fish Creek, and Tow Creek anticlines. In the western part of the area, the predominant structure is the southern limb of the Sand Wash basin, which has been only slightly deformed and dips northward. Structurally high areas occur along the crest of the Williams Fork Mountains at the southern margin of the western area.

Exposed outcrops of the aquifer units allow infiltration of water from precipitation and snowmelt. This water may become part of a local ground-water flow system and discharge at local stream valleys crossing the outcrop, or the water may become part of a larger regional ground-water flow system and move to depth in the aquifer. Modeling indicates that recharge to the three aquifers in the eastern part of the study area totals only about 2.8 ft^3/s. Rates of discharge are similar under the steady-flow conditions in the area and occur by upward leakage through leaky confining layers, by lateral flow to stream valleys that cross low-lying outcrops, or by evapotranspiration.

In the eastern part of the study area, ground water generally moves from recharge areas along the elevated margins of the aquifers toward discharge areas in the central low-lying parts of Twentymile Park and the valleys of Grassy, Fish, Foidel, Middle, and Trout Creeks. Lateral ground-water velocities generally range from 0.5 to 30 ft/yr. Head gradients between the shallow and deeper aquifers enable downward movement of water in the recharge areas and upward movement of water in Twentymile Park and near Grassy Creek and the Yampa River. Calculated traveltimes for a particle of water to move vertically through the slightly leaky confining layers separating the aquifers average about 8,000 years. Heads in all the aquifers are above land surface in much of the low-lying area in Twentymile Park.

In the western part of the study area, ground water generally moves in a northeasterly direction from the recharge areas along the upper parts of the Williams Fork Mountains toward discharge areas, or outflow areas, along the study area boundary at the Yampa River. This larger flow system contains smaller flow systems associated with local recharge in upland areas and discharges in nearby outcrops of water-yielding units in stream valleys. Downward head gradients in the recharge areas and upward head gradients in the discharge areas likely occur as they do in the eastern part of the area.

Most streamflow is the result of snowmelt and precipitation runoff and is little affected by ground-water recharge or discharge in the study area. Subparallel streams that drain cuesta dip slopes formed by the Williams Fork Formation or Lewis Shale in the western part of the area generally are ephemeral; snowmelt runoff occurs from March to July. Discontinuous perennial reaches are produced by ground-water discharge at seeps and springs. Larger streams in the eastern part of the area commonly cross structural trends, have perennial flow, and may have drainage areas extending well beyond the study area. Gain-loss measurements in Fish Creek and its unnamed tributaries draining Twentymile Park indicate small gains in streamflow at the points where the streams cross the mountain-front outcrop of the aquifer units. Minimal gain in streamflow occurs downstream from these outcrops even though heads in the aquifers may be above land surface. Surface-water quality is strongly affected by the geology of the drainage area. Older, crystalline-rock drainage areas upstream from the study area generally yield calcium bicarbonate streamflow of excellent quality (100 to 400 mg/L of dissolved solids). Sedimentary rocks of mixed continental and marine origins, such as the Williams Fork Formation, commonly yield streamflow of either calcium magnesium bicarbonate or calcium magnesium sulfate composition; dissolved-solids concentrations range from 300 to 800 mg/L. Marine terrain yields streamflow of magnesium sodium sulfate composition that has dissolved-solids concentrations of about 1,000 to about 8,000 mg/L.

The chemical composition of ground water in the study area is the result of geochemical processes that include dissolution, cation exchange, and precipitation. These processes may differ depending on the aquifer sampled and the location of the sample point in the ground-water flow path in the aquifer. Carbonate dissolution near the margins of the basal Williams Fork aquifer produces the calcium bicarbonate water that predominates within about 1 mi of the outcrop. As the water moves farther into the aquifer, cation exchange naturally softens the water and produces a sodium bicarbonate water type, and dissolved-solids concentrations range from 300 to 1,400 mg/L. Oxidation of pyritic minerals associated with coal and dissolution of gypsum contribute dissolved sulfate to ground water downgradient from spoils and coal outcrops. Sulfate concentrations decrease at greater distance along the ground-water flow path, possibly in response to sulfate reduction.

Solute-transport models that simulate dissolved-solids concentrations in the basal Williams Fork aquifer and in the Twentymile aquifer were constructed. These models were used to evaluate the potential effect on the aquifers of movement of poor quality water away from spoil aquifers and flooded underground mines. Simulation results indicate that ground-water velocities in these aquifers are commonly so small that degraded water does not move a significant distance from its source within the 30- to 100-year modeling timeframe. Thus, mining effects on bedrock water quality are small even when worst-case concentrations are simulated in the spoil aquifers.

The short distance between ground-water discharge areas at streams and the spoil aquifers at open-pit mines may decrease or halt further movement of degraded ground water. Ground-water discharge areas at streams commonly receive inflow from the bedrock aquifer underlying both sides of the stream valley. If degraded water moves toward the discharge area from a spoil aquifer on one side of the valley, the convergent ground-water flow field may prevent the movement of the degraded water beyond the valley. Spoil aquifers at each of the three large open-pit mines, and several of the smaller mines, in the eastern part of the study area are located on dip slopes above the stream valleys of Trout Creek, Foidel Creek, Fish Creek, and a tributary to Grassy Creek. Each of these stream valleys function as ground-water discharge areas and tend to retard movement of degraded water beyond the valley.

Movement of degraded water away from spoil aquifers primarily will affect the chemical quality of the ground water discharging to the nearby stream valley. However, the most rapid and direct effect on surface-water quality is produced by the direct discharge of degraded water to the streams from spoil seeps and springs. The effect on stream quality attributable to movement of degraded water through the bedrock aquifer will be delayed, because of small rates of ground-water movement, and also will be decreased because the small rates of affected ground-water discharge (generally less than 0.3 ft^3/s) will be diluted by the relatively large rates of streamflow (generally 1 to 20 ft^3/s).

Minimal differences in model simulation results were obtained by changing the head configuration in a simulated underground mine to represent hydrologic conditions associated with open mine voids or collapsed mine voids.

Sensitivity analyses of model dispersivity and porosity indicated that simulation results are insensitive to dispersivity but more sensitive to porosity. Porosity variations of 33 percent produced a 13-percent change in the dissolved-solids concentrations of ground water discharging to a stream downgradient from a spoil aquifer.

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