ESTIMATING RECHARGE AND DISCHARGE WITHIN A RIPARIAN, GLACIAL-OUTWASH AQUIFER

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ABSTRACT: Data obtained from boreholes, streamflow measurement, modeling, and soil maps provide a basis for characterizing surface water–groundwater interaction. Up to 15 m of outwash and alluvium deposited along the North Branch Forest River comprise the 100 km² Fordville aquifer in northeastern North Dakota, where demand for rural and municipal water continues to increase. Field data, GIS, and MODFLOW simulations were used to estimate water-budget components. Direct precipitation to the aquifer and runoff from tills that underlie an area more than four times larger than the aquifer provide recharge. Streamflow, groundwater levels, and MODFLOW results indicate that recharge occurs seasonally along the channeled, losing reaches of the river and tributaries, which occupies former floodplain. Discharge from the aquifer maintains the gaining, perennial lower reaches of the river, and contributes water to evapotranspiration and wells. Leakage and seepage occur through a geologically older part of the aquifer confined by a clay-till moraine.

KEY TERMS: recharge, glacial sediments, groundwater-surface water interaction, MODFLOW

INTRODUCTION

Many areas of the northern Midwest and Plains region of the U.S. and Canada rely on small, shallow riparian and glacial outwash aquifers as a water source. These aquifers often have a close relationship to surface water because surface water processes control one or more components of the aquifer's water budget. Examples include recharge and discharge to wetlands (glacial terrains often have poorly integrated drainage) or recharge and discharge to streams that flow on and directly connect to unconfined aquifers.

The natural hydrological processes and patterns in many of these areas have been greatly altered. For example, the channels of streams have been modified to reduce meandering on unconfined aquifers. Wetlands have been drained, lowering the water table and increasing near-surface hydraulic gradients. Production wells have greatly increased the discharge of groundwater from aquifers.

This paper presents a case study of the Fordville aquifer in northeastern North Dakota. Glacial outwash sediments and recent alluvium comprise the aquifer, which covers about 100 km². The water budget of the aquifer is closely connected to precipitation, evapotranspiration, and surface water dynamics of the intermittent North Branch Forest River. This interconnection is described and analyzed using numerical modeling and GIS. Results show the effect that agricultural development and rural water use have had on the water budget.

HYDROGEOLOGICAL SETTING

The Fordville aquifer lies between the western margin of the Late Pleistocene Lake Agassiz, present in what is now the Red River of the North Valley, and Late Wisconsinan till plains farther to the west. The highest and earliest known beach ridges of Lake Agassiz lie at the southeastern corner of the aquifer. Depth to Cretaceous shale bedrock varies from 50 to 100 m below the surface (Bluemle, 1973). Except for the upper 0-15 m of glacial outwash and alluvium, all the underlying glacial sediment consists of clay till.

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Glacial Geology

The Fordville aquifer records two late advances of ice in the Red River Valley: an early advance from the northwest, and a later advance from the northeast that led to the development of the prominent Edinburg moraine, which overlies and confines the older, lower portion of the aquifer on the east (Fig. 1). The lower portion of the aquifer developed from shale-rich sediments transported from the west (left). Coarser sediments with a greater crystalline fraction were derived from the later westward advance (center). The aquifer was confined by clay till of the Edinburg moraine (center). Downcutting into the underlying till by the Middle Branch and North Branch Forest River in the southern part of the aquifer has exposed the older sediments (right).

![Fig. 1. Sequence of Aquifer Development.](image)

Recharge

There are at least four possible sources of recharge to the Fordville aquifer: direct precipitation, overland runoff from nearby till slopes, streams that flow onto the unconfined portions of the aquifer, and groundwater leakage through the base. Drilling logs from deep boreholes in and around the aquifer suggest that only thin (less than 0.5 m), discontinuous layers of sand and gravel occur in the tills that underlie the aquifer. Shale of the Cretaceous Greenhorn and Carlile Formations underlie the tills and has low permeability. Groundwater leakage into the aquifer through its base is therefore unlikely to constitute more than a few percent of the total water budget.

Within this region, glacial till generally has low permeability because of its high clay content. Although fractures occur in till, these are often restricted to shallow depth and are discontinuous (e.g. Bauer and Mastin, 1997; Taylor, 1994). Therefore, only a small fraction of the precipitation that falls on the till infiltrates. This is especially true when the ground is frozen and during periods when vegetation is senescent. Therefore, a large fraction of the water that recharges the Fordville aquifer is likely derived from drainage basins that extend up to 25 km to the west (Fig. 2). The North Branch Forest River constitutes the largest and most prominent of these watersheds and may have been a meltwater channel during the inception and after development of the Edinburg moraine. Figure 2 reveals that the North Branch's basin and drainage system is better defined and integrated than that of adjacent basins, suggesting a more mature stage of development. Much of the area covered by the other basins has poorly integrated drainage, with most runoff lost to closed prairie potholes.

Average annual precipitation for the aquifer is slightly less than 0.5 m. Most of this falls as rain during the summer, with about 0.1 m occurring from October through March (NOAA, National Climatic Data Center). Much of the runoff from the basins underlain by till to the west flows onto the aquifer and contributes to recharge. Areas along the margin of the aquifer, especially on the north where the North Branch Forest River enters the aquifer, show a large rise in the water table during the spring (Fig. 3).

Discharge

Discharge from the aquifer occurs through evapotranspiration, wells, leakage through the confined portion of the aquifer on the east, and springs and seeps along the Forest River (Fig. 4). Well discharge has averaged about 1940 m$^3$ day$^{-1}$ during the last five years (unpublished data, North Dakota State Water Commission).
MODFLOW MODEL

Sources of Data and Model Discretization

A steady-state MODFLOW (McDonald and Harbaugh, 1988) groundwater flow model of the aquifer was developed on the basis of stratigraphic data recorded for 108 borings and water levels in 32 observation wells placed in and near the aquifer during the last 35 years (Downey, 1973b and ND State Water Commission, unpublished data). Pump test analysis (Downey, 1973a) and stream flow measurements (Fig. 4) were used.
Three layers containing a total of 4900 active flow cells (each 200 m square) were used in the model discretization. Intermittent streams were modeled as drains and, for this part of the modeling effort, constant heads were used for perennial streams lying within the aquifer.

Parameterization and Calibration

Based on pump test analysis and the texture of aquifer sediments, 30 m$^3$ day$^{-1}$ was used as an average hydraulic conductivity. Recharge was set at 5.5 x 10$^5$ m day$^{-1}$ (2 cm yr$^{-1}$) over most of the aquifer, with greater recharge (44 cm yr$^{-1}$) along the course of the upper North Branch Forest River and much lower recharge over the confined portion of the aquifer. All the water level calibration points were less than ±1.5 m from observed values, which is within the average seasonal range for most of the wells. Steady-state heads, as expected, were very sensitive to changes in hydraulic conductivity and recharge; a 20% or more increase in hydraulic conductivity or a 20% or more decrease in recharge forced most cells of the model to go dry. The lowest layer included a general head boundary to account for leakage to the east through the deeper confined portion of the aquifer.

Water Budget

The overall water budget for the aquifer indicates that recharge and constant head cells along the middle reach of the North Branch Forest River constituted 80% (7012 m$^3$ day$^{-1}$) and 20% (1781 m$^3$ day$^{-1}$) of the input, respectively. Output of water was to drain cells (32% - 2827 m$^3$ day$^{-1}$), constant head cells (28% - 2428 m$^3$ day$^{-1}$), wells (22% - 1940 m$^3$ day$^{-1}$), and general-head boundary cells (18%, 1607 m$^3$ day$^{-1}$).

Changes in Recharge Potential Since Drainage and Channelization

Significant changes in the channel of the North Branch Forest River have occurred since the development of agriculture in the area, which began about 1880. The north central portion of the aquifer has a gentle slope and maintained a large floodplain prior to drainage. This area also received fine-grained sediment from the surrounding till slopes and basins. The effect of wetland drainage and channelization on stream runoff and recharge are a strongly debated issue in the region. The section examines the effect that channeling the North Branch may have had on the potential for recharge.

Methods

The original natural channel of the river was based on information taken from old planimetric maps and air photos, the distribution of prominent oxbows now cut off by drainage channels, and from the distribution of flood plain soils, most notably the LaPrairie, Bearden, and Walsh series (Hetzler and others, 1971). Although the accuracy of the map in showing the original active channel of the river (Fig. 4) cannot be thoroughly evaluated, the most important aspect of this modeling effort is to determine a reasonable estimate of sinuosity for the original channel. Both the approximate former and the present channel were digitized (Fig. 4) and incorporated as data layers in the groundwater flow model.

MODFLOW's stream-routing package (Prudic, 1989) was used to simulate the flow down the original and present channels, given a fixed rate of spring runoff entering the river. Many parameters are necessary for the stream package. Some can be obtained with reasonable confidence, such as cell stream length, channel width, top of the streambed, and channel slope. Parameters that are more uncertain include the Manning roughness coefficient (Barnes, 1967), streambed thickness, and streambed permeability. Ranges of these parameters (Table 1), however, can be obtained from borehole data, published and unpublished maps, air photos, and other documents. These data were used in a Monte Carlo simulation to establish an expected range in recharge, discharge, and surface water flow in the North Branch Forest River following spring runoff.

The stream was discretized into 148 cells (100 m square) for the new channel and 218 for the old channel in the area where the river has direct hydraulic connection to the aquifer. Parameters were assigned a single value, or given randomly chosen values for more uncertain parameters. The range of Manning roughness coefficient was assumed normally distributed with a standard deviation equivalent to the average variation observed in similar channels (Arcement and Schnieder, 1989). With additional information lacking, a uniform distribution was assumed for both streambed permeability and thickness. Randomized values for these three parameters were obtained using the methods described by Morgan and Herion (1990).
Table 1. Input Parameters for MODFLOW’s Stream-Routing Module.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>stream length</td>
<td>estimated from 1:24,000 topographic map</td>
</tr>
<tr>
<td>channel slope</td>
<td>linear estimate between 1:24,000 topographic contours</td>
</tr>
<tr>
<td>channel width</td>
<td>constant – 5 m</td>
</tr>
<tr>
<td>elevation – top of streambed</td>
<td>linear estimate between 1:24,000 topographic contours</td>
</tr>
<tr>
<td>streambed thickness</td>
<td>uniform distribution - 1 to 4 m (original channel), 0 to 2 m (new channel)</td>
</tr>
<tr>
<td>streambed conductivity</td>
<td>uniform distribution – 0.12 to 1.2 m day</td>
</tr>
<tr>
<td>roughness coefficient (original channel)</td>
<td>minimum 0.036, maximum 0.066, mean 0.051, standard deviation 0.011</td>
</tr>
<tr>
<td>roughness coefficient (new channel)</td>
<td>minimum 0.031, maximum 0.053, mean 0.042, standard deviation 0.010</td>
</tr>
</tbody>
</table>

Fig. 4. Map of the Fordville Aquifer. Dashed contours - hydraulic head (m), solid line - present channel of the North Branch Forest River, solid gray line - approximate original channel, short dashed lines - river reaches that have cut into underlying till. Italicized numbers indicate surface water discharge on 29 August 2001.

Each realization provided input for a MODFLOW model of the stream-aquifer system. Initial heads were created by allowing the model to reach a steady state with areal recharge, but without any surface water input to the channel. To simulate spring season runoff, water was allowed to flow into the first cell of the reach at 12,063 m³/d for thirty days, followed by a second stress period of ninety days without channel input. Baseflow, recharge, and discharge conditions were recorded at the end of 12.5 and 90 days following the 30-day spring flow.
Results

In this reach of the North Branch Forest River, two parameters were derived from the output: groundwater discharge to the stream and channel length without flow at 12.5 and 90 days (Table 2). Using 23 realizations for the old and new channels, results indicate that the new channel probably maintains only a slightly smaller recharge potential than the old channel, although the new channel is only about one-half of the original length. The likely reason for this similarity is that the new channel was excavated to about one-half the depth to the coarse sediments, thereby approximately offsetting the 50% decrease in the length of the original channel. Incorporation of spatial autocorrelation among variable parameters, which was not estimated, would likely increase the variability of the results.

Table 2. Summary of results for spring runoff models.

<table>
<thead>
<tr>
<th></th>
<th>estimated total length (km)</th>
<th>discharge to stream (m&lt;sup&gt;3&lt;/sup&gt; s&lt;sup&gt;-1&lt;/sup&gt;) after 12.5 days</th>
<th>discharge to stream (m&lt;sup&gt;3&lt;/sup&gt; s&lt;sup&gt;-1&lt;/sup&gt;) after 90 days</th>
<th>channel length (m) without any flow</th>
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<tbody>
<tr>
<td></td>
<td>average S.D.</td>
<td>average S.D.</td>
<td>average S.D.</td>
<td>12.5 days</td>
</tr>
<tr>
<td>natural channel</td>
<td>24.3 ± 20</td>
<td>594 ± 20</td>
<td>116 ± 3.3</td>
<td>1,525</td>
</tr>
<tr>
<td>ditched channel</td>
<td>13.8 ± 16</td>
<td>482 ± 16</td>
<td>96 ± 4.3</td>
<td>1,030</td>
</tr>
</tbody>
</table>

REFERENCES


