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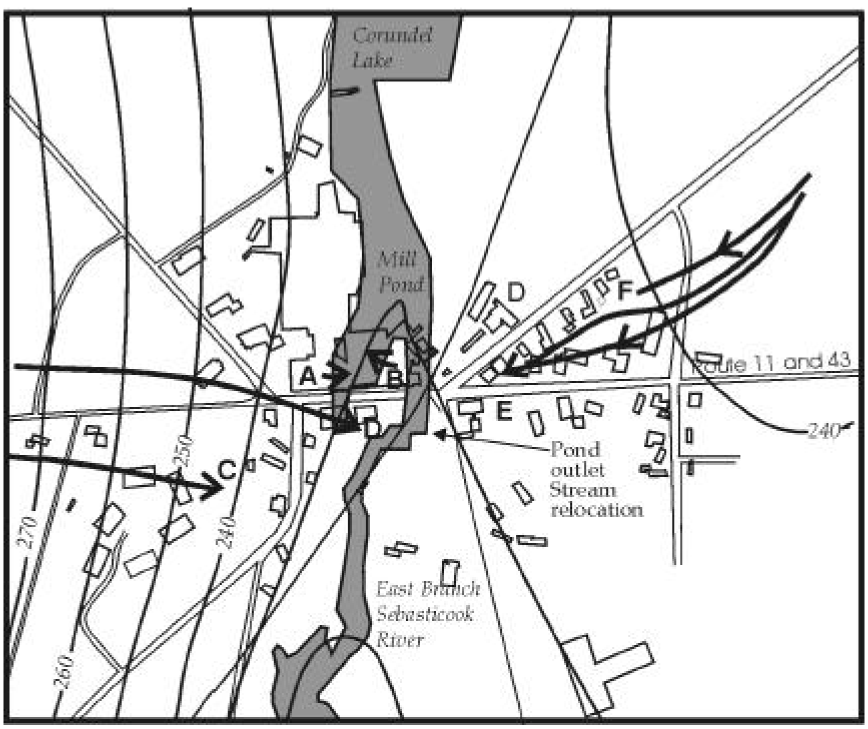
Simulated Ground-Water-Flow Responses to Geohydrologic Characteristics, Corinna, Maine

Water-Resources Investigations Report - WRIR 01-4079



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U.S. Geological Survey

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by Thomas J. Mack, and Robert W. Dudley

U.S. GEOLOGICAL SURVEY

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Augusta, Maine
2001

U.S. DEPARTMENT OF THE INTERIOR
GALE A. NORTON, Secretary

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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
cubic foot (ft^3)	0.02832	cubic meter
gallon (gal)	3.785	liter
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
gallons per day (gal/d)	0.06309	liter per second
	Hydraulic Conductivity	
foot per day (ft/d)	3.797×10^{-6}	centimeter per second

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

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ABSTRACT

Ground-water-flow simulations of an idealization of surficial and bedrock aquifers of the East Branch Sebasticook River Valley, in Corinna, Maine, were done to test the effects of known or hypothesized geohydrologic characteristics on the local and regional ground-water-flow system. The purpose of the simulations was to develop a better understanding of the aquifer system to aid in planning for the eventual removal of contaminants.

The effects of eight individual geohydrologic characteristics on simulated ground-water flow were compared with a base simulation. The eight geohydrologic characteristics simulated were (1) a northeast-southwest transmissive bedding-plane fracture system, (2) a northwest-southeast valley floor transmissive fracture zone, (3) an upper weathered bedrock transmissive zone, (4) river- and pond-stage changes, (5) river- and pond-bottom conductivity changes, (6) multiple withdrawals, (7) a combination of some of these characteristics, and (8) relocation of a pond-outlet stream.

The effects of many of the analyzed characteristics are slight or relatively minor with respect to a simulated bedrock aquifer. The simulated ground-water flow through the bedrock aquifer is a small percentage (about 1 percent) of the total flow to the system; therefore, the effects of most geohydrologic characteristics simulated are minimal in the aquifer. Some characteristics, for example, anisotropy imparted on the bedrock system by a northeast-southwest transmissive bedding-plane fracture system, strongly affect flow patterns in the bedrock aquifer but not in the surficial aquifer. Individually, most of the geohydrologic characteristics evaluated only slightly affect the ground-water flow in the bedrock; however, in combination, these characteristics significantly affected the entire simulated ground-water-flow system. Domestic or remedial withdrawal wells generally had little effect on the regional ground-water-flow system but did affect the local ground-water-flow patterns, which could affect the extent and movement of contaminants.

INTRODUCTION

Surficial- and bedrock-aquifers underlie a former woolen mill, and the surrounding area, in Corinna, Maine. The mill used a variety of dense non-aqueous phase liquids (chlorinated solvents, primarily chlorobenzenes) that were disposed of, or stored, at the mill site and surrounding locations and have migrated through surficial sediments and into fractured bedrock, contaminating the ground water. The U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), developed generalized numerical models of the ground-water-flow system to test hypothesized geohydrologic characteristics and improve understanding of their effects on ground-water flow and, thus, contaminant flowpaths in this system. The study area includes the former Eastland Woolen Mill (EWM), adjacent downtown Corinna, and the East Branch Sebasticook River valley (fig. 1).

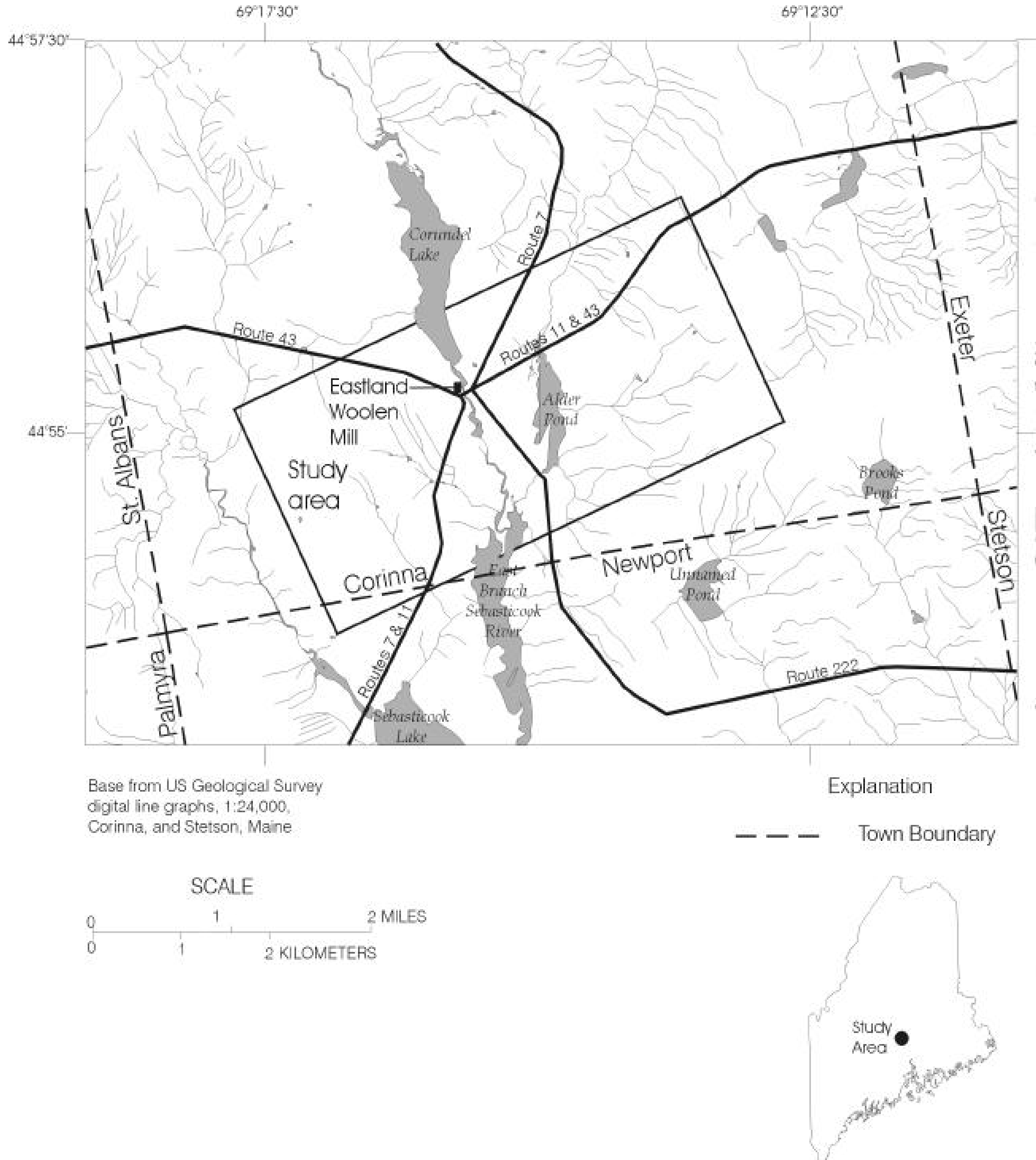


Figure 1. Location of study area, in Corinna, Maine.

Purpose and Scope

The purpose of this report is to describe ground-water-flow simulations that were designed to test the effects of known and hypothesized geohydrologic characteristics and boundary conditions on ground-water flow at the former Eastland Woolen Mill in Corinna, Maine.

The study area includes the regional ground-water-flow system in the river valley surrounding the former mill and is bounded by hillsides to the west and east, Corundel Lake to the north, and a broad area of the East Branch Sebasticook River at about the Corinna town line to the south (fig. 1). The models described in this study were used to qualitatively evaluate the effect of known and potential geohydrologic characteristics on ground-water flow. The simulated results represent ground-water heads, flowpaths, and water budgets that have not been calibrated to measured field conditions.

Description of the Study Area

The town of Corinna, in central Maine, is in a valley formed by the East Branch of the Sebasticook River (fig. 1). The river is dammed in places to form a number of ponded areas including Corundel Lake and Mill Pond. The town center and most commercial and residential buildings are in the valley lowlands (fig. 2a). The former EWM, built directly over the river in the center of the town (fig. 2b), operated during 1909-96 and is believed to be the primary source of contamination to the bedrock aquifer adjacent to the river (Harding Lawson Associates, 1999).

The East Branch Sebasticook River valley (fig. 2a) is characterized by a 355-ft high gently sloping hill to the west and a more extensive and steeper ridge line to the east with a maximum altitude of 583 ft above sea level. Corundel Lake (altitude 229 ft) fills the valley floor upstream to the north, and the East Branch Sebasticook River opens to Sebasticook Lake (altitude 200 ft) to the south. A small lake, Alder Pond (altitude 218 ft), is one-half mile east of Corinna at the base of the eastern valley wall.

Methods of Assessment

An assessment was done of the effects of eight hypothesis concerning geohydrologic characteristics using three-dimensional finite-difference, steady-state models of a generalized valley-fill and bedrock aquifer system. The USGS finite-difference model MODFLOW (Harbaugh and McDonald, 1996a, b) was used to simulate alternative conceptual models of the aquifer system. Ground-water flowpaths were generated through particle-tracking techniques based on MODPATH (Pollock, 1994). Model data-set preprocessing and visualization postprocessing were done using MODFLOW-Graphic User Interface (GUI) (Shapiro and others, 1997; Winston, 1999).

A bedrock aquifer can be treated as an equivalent porous medium when applied to fractured rock on a large scale in MODFLOW simulations. On a regional scale such as the Corinna river-valley setting this assumption is valid (Dominico and Schwartz, 1990), particularly where bedrock fracturing is relatively systematic throughout the study area.

Simulation results include comparisons of head distributions, ground-water flowpaths, and ground-water budgets. Geohydrologic characteristics were incorporated individually into an idealized, base simulation, ground-water-flow model and tested. Each simulation result was compared to the base simulation. To facilitate comparisons, the most simplified representation of the aquifer system was used for the base simulation. Because the purpose of this study is to test geohydrologic hypotheses regarding the aquifer system, and the aquifer system is generalized, simulation results are qualitatively compared and are not to be considered calibrated simulations of ground-water flow.

GEOHYDROLOGIC CHARACTERISTICS

Surficial Aquifer

The surficial aquifer is comprised of glacial till sediments deposited in the river valley, about 20 ft thick in most places (Harding Lawson Associates, 1999). The till is believed to be composed of an upper ablation till, consisting of dense silty sand and sandy silt, and a lower basal till that may be coarse grained and contain some gravel (Harding Lawson Associates, 1999). Till covers both hillsides and generally is present throughout the study area. Throughout most of the area the water table is in the surficial aquifer, probably within 10 ft of the land surface. In some parts of the study area, particularly in the uplands, the water table may be below the base of the till seasonally or throughout the year.

A summary of till hydraulic conductivities compiled for southern New England (Melvin and others, 1992) indicated that for tills derived from sedimentary rocks, horizontal hydraulic conductivities ranged from about 8 x 10^{-4} to 3.4 ft/d. For this study, hydraulic conductivity of the till was assumed to be about 1 ft/d. Vertical hydraulic conductivities essentially were similar to horizontal conductivities indicating that anisotropy generally is not present in the tills. Till derived from sedimentary rocks was found to have porosities that ranged from 18 to 40 percent.

No mapped sand and gravel aquifers are present in the area. Broad, relatively flat-lying areas, such as the area about 0.5 mi south of Corinna, are indicative of stratified sediments. If stratified sediments are present, they are within the extent of the Presumpscott unit and are likely to be marine silts or clays overlying till. The hydraulic conductivities of marine sediments are likely to be about the same order of magnitude as the upper till layer in the surficial aquifer (about 1 ft/d).

Bedrock Aquifer

Bedrock in the Corinna area consists of the Waterville Formation, which is a shaley metasediment and siltstone (Osberg and others, 1985). The areal extent of the Waterville Formation trends North 40 to 50 degrees East (N40E to N50E) and is in the Kearsarge Synclinorium in this area. Few outcrops are present in the study area. An outcrop adjacent to the EWM building is characterized by nearly vertical bedded shale that is highly fractured on bedding planes. The strike of fracture and bedding planes is predominantly N50E and the dip is about 60 degrees South. Because the shale is highly fractured in a somewhat systematic nature, the hydraulic conductivities probably are consistent regionally in the study area, with the exception of local fracture zones. Preliminary investigations, including pumping drawdowns and contaminant distribution (Harding Lawson Associates, 1999), and topographic features, indicate a regional NE trending bedrock-fracture pattern. A regional-fracture pattern likely would create an anisotropy to the bedrock aquifer where the transmissivity is greatest in the NE direction.

Horizontal hydraulic conductivities of the shale may be about 1 ft/d (Peter Thompson, Harding Lawson Association, oral commun., 1999). Locally, the bedrock surface could be broken apart with excavation equipment revealing a weathered and friable upper bedrock surface. The upper bedrock surface probably is less than 20 ft thick and may be more transmissive than bedrock at depth; however, little is known about the extent of this surface.

The East Branch Sebasticook River roughly follows a North-South (N10W) photo-linear feature that may represent a fault zone (Harding Lawson Associates, 1999). This fault zone, which forms the river valley, could represent an area of increased bedrock conductivity.

Ground-Water Recharge and Discharge

Sources and sinks acting on the ground-water-flow system include surface-water bodies, ground-water inflows and outflows, recharge from precipitation, and ground-water withdrawals. Recharge to the upland area flows through the surficial and bedrock aquifers and discharges at the surface-water bodies in the valley floor.

Corundel Lake, Mill Pond, the East Branch Sebasticook River, above the former Moosehead Mill, and Alder Pond are kept at relatively constant altitudes by artificial controls. In addition, the East Branch Sebasticook River, 1 mi downstream of the town center, also is ponded. These water bodies are relatively large, likely dominate the ground-water-flow system, and act as constant-head sources or sinks in the ground-water-flow system.

Long-term average precipitation in the area is about 40 in/yr. Ground-water recharge from precipitation in a till-covered watershed in northern New England, with a similar precipitation rate, was calculated to be about 13 in/yr (William Nichols, U.S. Geological Survey, written commun., 1999). Mau and Winter (1997) estimated recharge to be between 16 and 45 percent of long-term average precipitation, or about 8 to 24 in/yr, at an upland watershed in northern New Hampshire. Tiedeman and others (1997) estimated recharge to be about 11 in/yr for a ground-water-flow simulation of that same watershed. Recharge rates for Corinna, Maine, are assumed to be about 13 in/yr for all model scenarios presented in this report. Seasonal variations in recharge, or annual departures from normal, will have short-term affects on flow and contributing areas to wells; however, such variations probably do not affect long-term simulations (Reilly and Pollock, 1996).

Historically, ground water was pumped from individual or shared wells in the bedrock aquifer to supply homes and businesses in the area. Late in 1995, when some wells were found to be contaminated, a town water system was installed to supply some homes and businesses near the EWM. A ground-water-withdrawal system, well R-2 (point D in fig. 2b), 106 ft deep, was installed to recover contaminated ground water. Ground-water pumpage is controlled by head in the well and, therefore, the withdrawal rate is not precisely known. Domestic bedrock wells in the area generally are about 100 to 300 ft deep, and all but the top 20 to 40 ft of the well is open hole. If an average per-person water use is 70 gal/d, a typical domestic well in the study area might withdraw about 200 gal/d. Withdrawn water is discharged to leachfields where it recharges the surficial aquifer.

NUMERICAL MODELS

Numerical models were developed to represent various geohydrologic characteristics. The models use realistic, or known, input values or characteristics where possible; however, the models are generalized and are not considered calibrated simulation models. The sensitivity of the aquifer system to various boundary conditions is not assessed because the nature of this study was to assess hypothesized geohydrologic characteristics. As a result, the simulations shown are likely to be different when using characteristics other than the ones selected.

A base simulation was developed by creating a simple model with layering designed to approximate the aquifer system underlying the study area. An idealized, simplified model provides a basis for comparing the effects of alternative geohydrologic characteristics of a ground-water-flow system against common criteria. For the base conditions, hydraulic conductivities are considered isotropic and homogenous for all simulated aquifers. Each additional simulation presents the results of one modification from the base simulation. Simulation 7 is an exception where more than one geohydrologic characteristic is modified. As geohydrologic characteristics are modified, the ground-water fluxes and flowpaths of the resulting ground-water-flow simulation are compared against the base simulation.

Discretization and Layer Characteristics

The horizontal extent of the local river valley area simulated by a ground-water-flow model is shown in figure 2a. The model grid extends west and east to the top of the valley walls and north and south from the lower half of Corundel Lake to the point where East Branch Sebasticook River broadens near the southern town line. The model columns were oriented parallel to the river because the waterbody represents a hydrologic boundary and possibly is an indicator of a bedrock-fracture zone. The model rows are parallel to the bedding plane in the shale, a probable dominant fracture orientation. This grid alignment facilitates the numerical representation of these approximately orthogonal geohydrologic features.

The model area (6.3 mi^2) was discretized into various cell sizes (fig. 2a). Cells are approximately 200 by 200 ft on the valley sides and outer parts of the model. At the EWM and downtown area (fig. 2a,b), where more detailed flow calculations are warranted, the grid is 50 by 50 ft.

The simulated area was discretized vertically to simulate surficial materials and bedrock, and ground-water flow within these units. Five layers, shown in figure 3, were used in the model; two to represent the surficial materials (1-2), and three to represent bedrock (3-5). Model-layer altitudes parallel the land-surface altitude. The land surface used for model-layer calculations was a “smoothed” representation of the actual surface to simplify model development. Horizontal (x and y directions) and vertical (z direction) hydraulic conductivities were specified in MODFLOW-Graphic User Interface (GUI) data sets; vertical hydraulic conductance (Harbaugh and McDonald, 1996a) between model layers was calculated using MODFLOW-GUI (Shapiro and others, 1997).

Surficial materials were separated into two layers to represent an upper and lower glacial till (fig. 3). The first model layer (layer 1) represents the upper till, which is assumed to extend from zero to 20 ft below the landsurface. Layer 1 may be unsaturated in some areas, particularly in the upper sides of the valley as in nature, and includes water bodies and possibly areas of stratified sediments. Use of a relatively thin uppermost model layer allows the numerical model to realistically represent surface-water bodies, which are necessarily simulated within the entire topmost model layer. A horizontal and vertical hydraulic conductivity of 1 ft/d was assigned to layer 1. The second model layer (layer 2) represents a lower, more hydraulically conductive till.

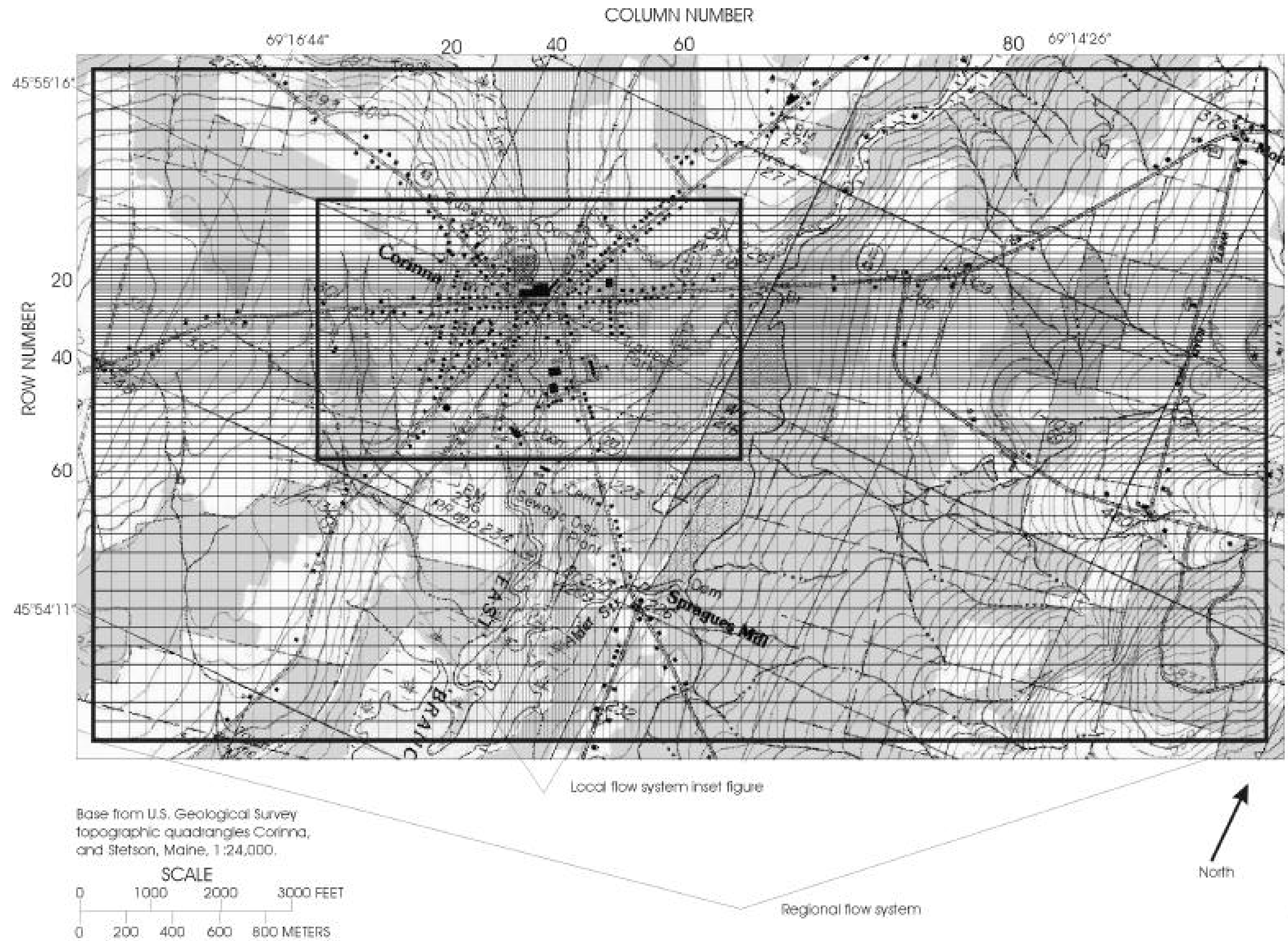


Figure 2a. Regional plan view of conceptual ground-water model discretization, Corinna, Maine.

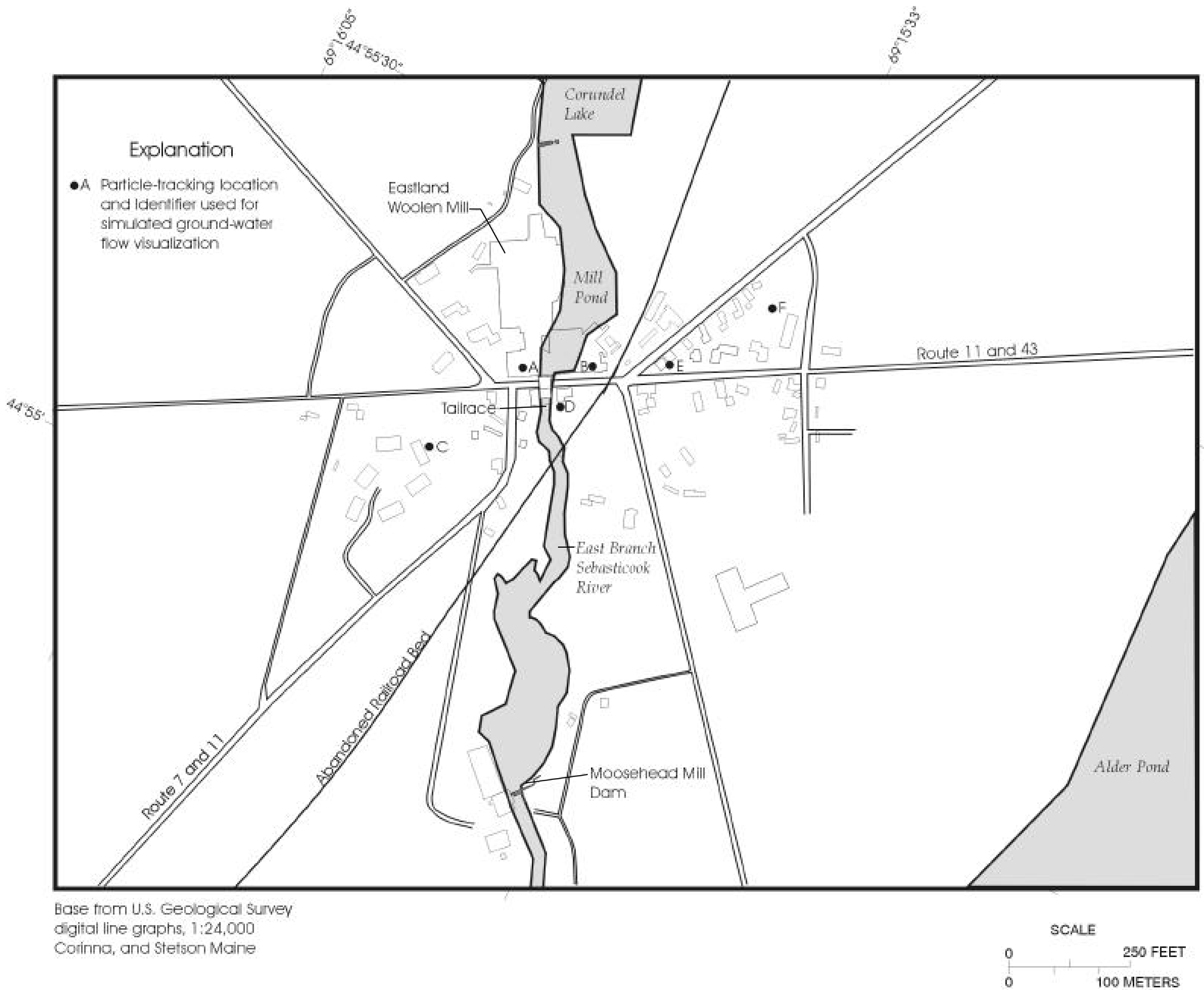


Figure 2b. Local plan view (inset from figure 2a)

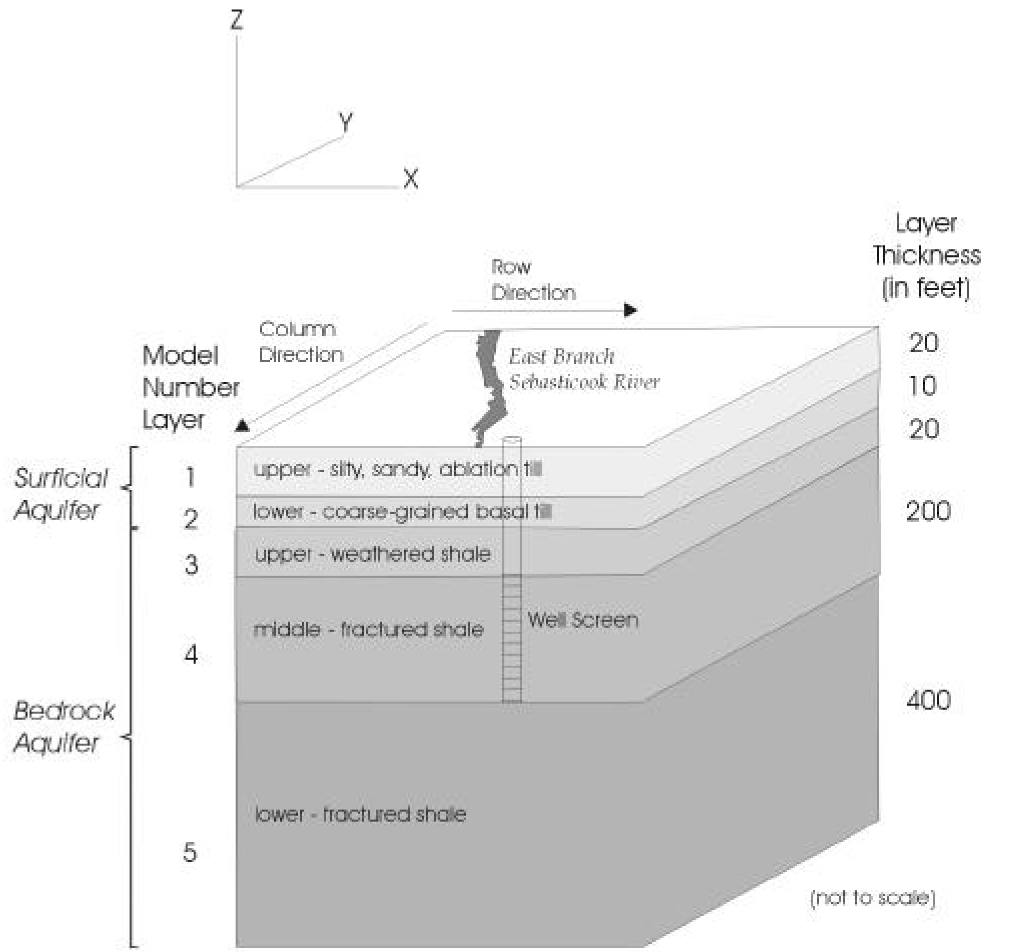


Figure 3. Model design of generalized surficial (1 and 2) and bedrock (3, 4, and 5) aquifers, Corinna, Maine.

This layer was assumed to be 10 ft thick, extending from 20 to 30 ft below the land surface. A horizontal and vertical hydraulic conductivity of 10 ft/d was assigned to layer 2.

Bedrock was subdivided into three model layers—20, 200, and 400 ft thick (layers 3, 4, and 5, fig. 3). This subdivision was done to allow testing of a weathered bedrock surface (layer 3), representation of the length of open hole of most wells in the study area (layer 4), and to calculate flow at depth (layer 5). The horizontal and vertical hydraulic conductivity for the base simulation for all bedrock model layers was 0.1 ft/d. To represent an upper 20-ft-thick weathered bedrock surface in some simulations, layer 3 vertical and horizontal (isotropic) hydraulic conductivities were increased by an order of magnitude to 1ft/d. Model layer 4, which is 200 ft thick (50 to 250 ft below land surface), represents the bedrock interval where most of the domestic wells are screened based on available well information. Model layer 5 allows the model to simulate an extensive bedrock layer 400 ft thick at a depth of 250 to 650 ft below land surface.

The effect of anisotropy in the bedrock, for example a pervasive east-west fracture pattern, was evaluated by increasing the hydraulic conductivity in the x (row) direction by an order of magnitude (1 ft/d) relative to that in the y (column) direction (0.1 ft/d). The effect of an extensive fracture zone following the valley floor was simulated by creating a zone (model columns 22 to 63) where the hydraulic conductivity in all directions (x, y, and z) in layers 3, 4, and 5 was increased an order of magnitude (1 ft/d) relative to that in the rest of the study area (0.1 ft/d).

Boundary Conditions and Stresses

Boundary conditions include recharge from precipitation, the flux of ground water moving in or out of the model at model boundaries, recharge or discharge to the model from surface-water bodies, and withdrawals from the aquifer system. Recharge from precipitation was assigned to the topmost active model layer at a uniform rate of 13 in/yr. The outermost model cells (fig. 2a) in layers 2-5 were simulated as constant-head cells, where the head was specified as 10 ft below land surface to simulate ground-water flow in and out of the modeled area. Simulation of this flow was necessary to produce a realistic head surface, one that roughly approximates landsurface. Without perimeter head cells the aquifer head would be relatively flat and no ground-water flux would occur at the upgradient and downgradient valley ends. The bottom of layer 5 was simulated as a no-flow boundary.

Most surface-water bodies in the model area are ponded and were simulated by use of constant-head cells in layer 1. Constant heads, set at topographic map or surveyed elevations, were placed at the East Branch Sebasticook River, Mill Pond, Corundel Lake, and Alder Pond. Changes to the hydraulic conductance of the bottom of surface-water bodies were approximated by increasing or decreasing the vertical hydraulic conductivity of layer 1, at constant-head cell locations, by an order of magnitude. Stage changes were simulated by adding or subtracting 2 ft to all constant-head values.

Withdrawal wells were simulated along a transect at four sites (points C, D, E, and F, fig. 2b) in all model simulations, at locations where bedrock wells are known to be contaminated. The intention of simulating wells at C-F was not to represent all withdrawals but to stress the simulated aquifer so that the effects of changes to a geohydrologic characteristic could be viewed more readily in areas of interest. The wells were assigned to model layer 4 with a pumping rate of 200 gal/d, to represent a typical domestic withdrawal rate. A return flow of 132 gal/d (66 percent) was placed in layer 1 at that same location to simulate recharge from leach fields. By simulating wells in layer 4, an effective open-hole length of 200 ft is used, which is the entire thickness of that layer. Model simulation 6 incorporated a number of known withdrawals in downtown Corinna to simulate a more heavily stressed condition.

Known locations of contamination in the lower surficial aquifer are shown in figure 2b (points A and B). Points A and B are used as starting points for forward-tracking particle transport in an effort to observe ground-water flow directions in the vicinity of EWM.

SIMULATIONS OF GEOHYDROLOGIC CHARACTERISTICS AND GROUND-WATER FLOW

Eight model simulations, shown in table 1, were compared with a base simulation to test the effects of geohydrologic characteristics on simulations of ground-water flow. The simulations were (1) a northeast-southwest fracture pattern, (2) a northwest-southeast valley floor fracture zone, (3) an upper weathered bedrock zone, (4) high and low surface-water body stage, (5) increased and decreased bottom sediment conductivity, (6) increased pumping stresses, (7) a combination of selected characteristics previously simulated, and (8) relocation of Mill Pond outlet.

Base simulation

Simulated ground-water heads and flowpaths (fig. 4a, b) in the East Branch Sebasticook River valley are largely controlled by dominant landforms (fig. 2a) and surface-water bodies. Simulated ground-water-head surfaces are slightly below land surface (generally 10 to 20 ft) and follow the general topography, as expected. Ground-water flow in the bedrock and surficial aquifers is from the upland areas towards the river and ponds in the valley bottom. The valley surface-water bodies are the dominant drains for the ground-water-flow system. In the valley bottom, simulated ground-water-head gradients are upwards, and on the hillsides the gradients are downwards.

Reverse-tracking of ground-water particle flowpaths from selected cells in the model to the point of recharge are shown in figure 5. Particles were placed in the layers at 3 locations, column 34, 54, and 67 in model row 34 (fig. 5). These locations were selected to best illustrate the selected flowpaths in cross section. At each location, one particle was placed in layers 1, 2, and 3, and two particles were placed in each of layers 4 and 5 (because these layers are thicker than 1-3). Flow-

Table 1. Ground-water-flow simulations, geohydrologic characteristics, and model characteristics for aquifer systems in Corinna, Maine

[Kx, hydraulic conductivity in the x-direction (row); Ky, hydraulic conductivity in the y-direction (column); Kz, hydraulic conductivity in the z-direction (vertical); ft, foot; ft^3/d, cubic foot per day; gal, gallon; gal/d, gallon per day]

Simulation	Geohydrologic characteristic	Model characteristic
Base	Base geohydrology: nominal surface-water stage, isotropy, no pumping stresses	Base model simulation
1	Northeast-southwest fracture pattern throughout entire bedrock thickness	Horizontal anisotropy in the horizontal hydraulic conductivity of model layers 3, 4, and 5 with Kx:Ky = 10:1
2	Increased fracturing in the valley floor throughout the entire bedrock thickness	Increased Kx, Ky, and Kz by a factor of 10 in a region of cells corresponding to the valley floor, column 22 through 63, of model layers 3, 4, and 5
3	Increased hydraulic conductivity of an upper weathered bedrock zone	Increased Kx, Ky, Kz by a factor of 10 in all cells of model of layer 3
4	High (4a) and low (4b) stages in all surface-water bodies	Higher and lower constant boundary head of all simulated surface water bodies by 2 ft
5	Increased (5a) and decreased (5b) permeability of bottom sediments of all surface-water bodies	Increased or decreased vertical hydraulic conductivity, in model layer 1, of all simulated surface water bodies by a factor of 10
6	Increased pumping stresses and well interference	Simulated pumpage of 26.7 ft^3/d (200 gal/d) at 38 locations where water has been withdrawn
7	Combination of all characteristics considered in simulations 1, 2, 3, and 6	Simultaneous implementation of all changes listed for simulations 1, 2, 3, and 6
8	Relocation of Mill Pond outlet 150 to 200 ft to the northeast	Changed the location of constant-head cells in layer 1 that represent Mill Pond outlet

paths generally do not travel in one model row or layer representing the surficial and bedrock aquifers; therefore, they are projected back onto row 34 with some paths appearing as if they leave the model boundary.

The general flow pattern of water at greater depths in the bedrock aquifer (layer 5), which originates as recharge at the upland hillsides, is shown in figure 5A. Recharge on the southwest hillside discharges to East Branch Sebasticook River, whereas recharge on the northeast hillside discharges toward Alder Pond. A ground-water-flow divide is in the middle of the section, between the East Branch Sebasticook River and Alder Pond. Ground water in the middle of the model (for example, column 54) flows in a primarily southeasterly direction and, when projected back onto row 34, appear to flow vertically in cross section (fig. 5A).

The total simulated water budget is approximately 5.0 ft^3/s. Components of the water budget, including rates of flow into, out of, and between the model layers, are illustrated in figure 6. Ninety-six percent of the water-budget inflow (4.8 ft^3/s) is precipitation recharge and the remaining 4 percent (0.2 ft^3/s) is from perimeter constant-head cells representing ground-water flow into the system (fig. 6). The use of constant-head cells to maintain heads at the appropriate level at the model perimeter, therefore, does not strongly affect ground-water-flow rates in the interior of the simulated system. Most of the water moving through the system flows through the surficial aquifer. A net flow of 0.35 ft^3/s, or 7 percent of the total water budget, flows from the surficial aquifer to the bedrock aquifer (fig. 6, net flow from model layer 2 to 3). Of the ground-water leaving the model, 54 percent discharges to the simulated surface-water bodies (2.7 ft^3/s) and 46 percent (2.3 ft^3/s) discharges to constant-head cells simulating ground-water flow out of the study area (fig. 6). Eighty-one percent of the ground water flowing out of the system to adjacent aquifers leaves the system through the simulated lower till layer (fig. 6, model layer 2), while the remaining 19 percent leaves through the simulated bedrock (fig. 6, model layers 3-5). Simulated ground-water withdrawals represent less than 1 percent of ground water leaving the system.

Two locations at the EWM (A and B, fig. 2b) were selected for forward tracking of ground-water flowpaths from layer 2, the lower suficial aquifer just above the simulated bedrock surface (fig. 3). These locations were selected to provide reference points to observe the local effects of various geohydrologic characteristics close to the mill, which straddled the river. At each point or model grid cell, four particles were distributed evenly over the thickness of the cell in layer 2. In the base simulation (table 1), flowpaths from

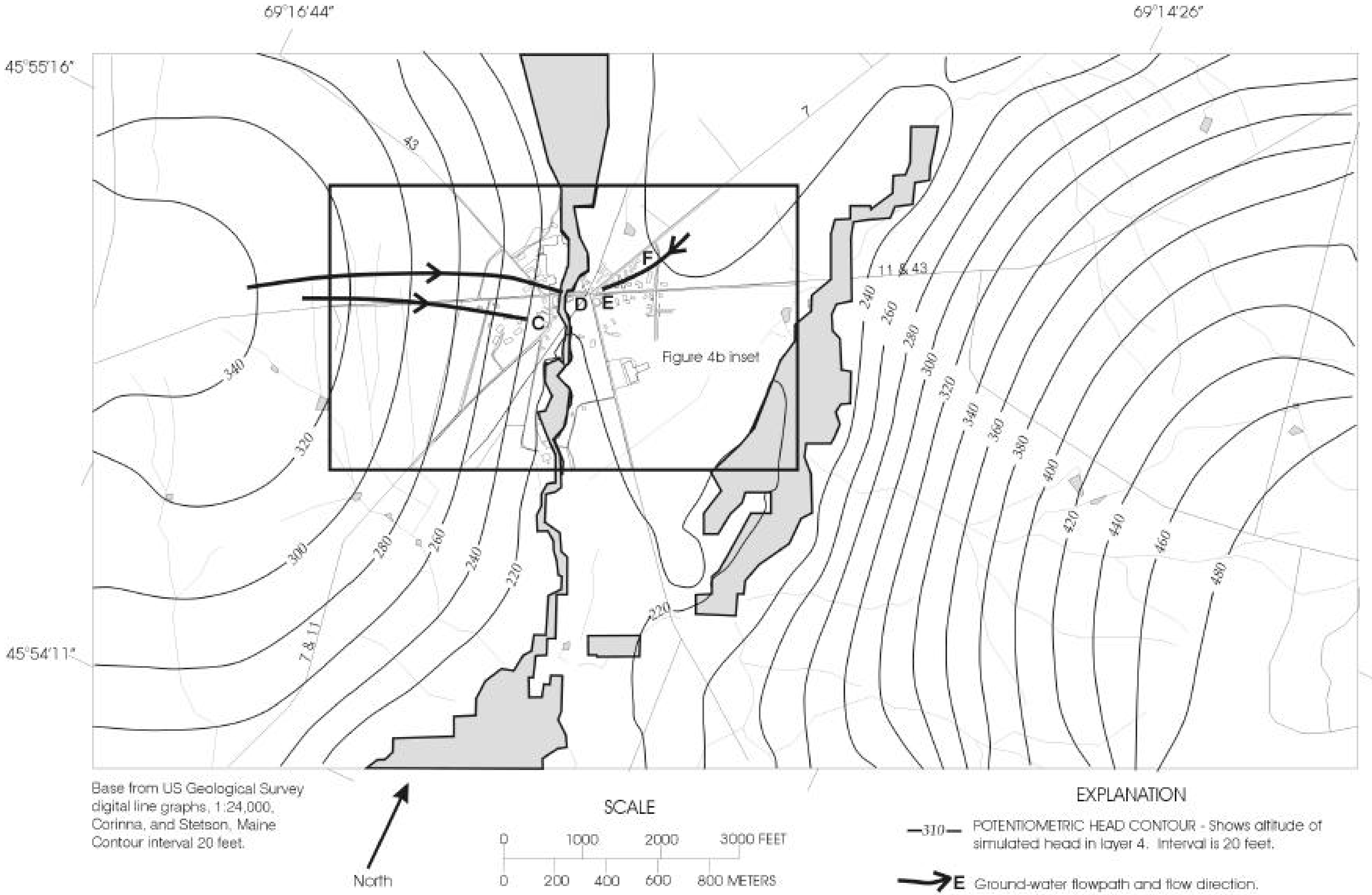


Figure 4a. Simulated ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine for the base model simulation.

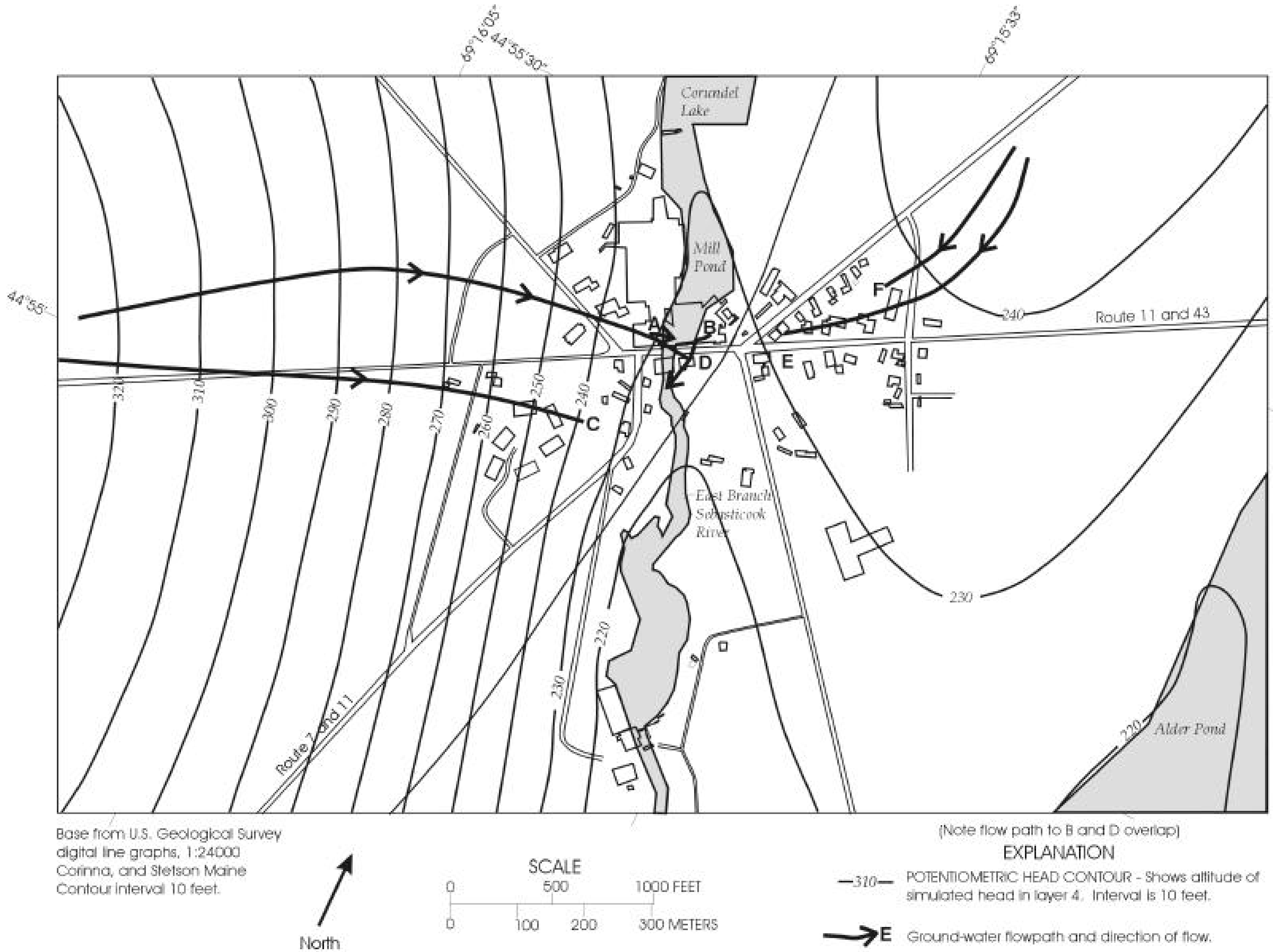


Figure 4b. Simulated ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine for the base model simulation.

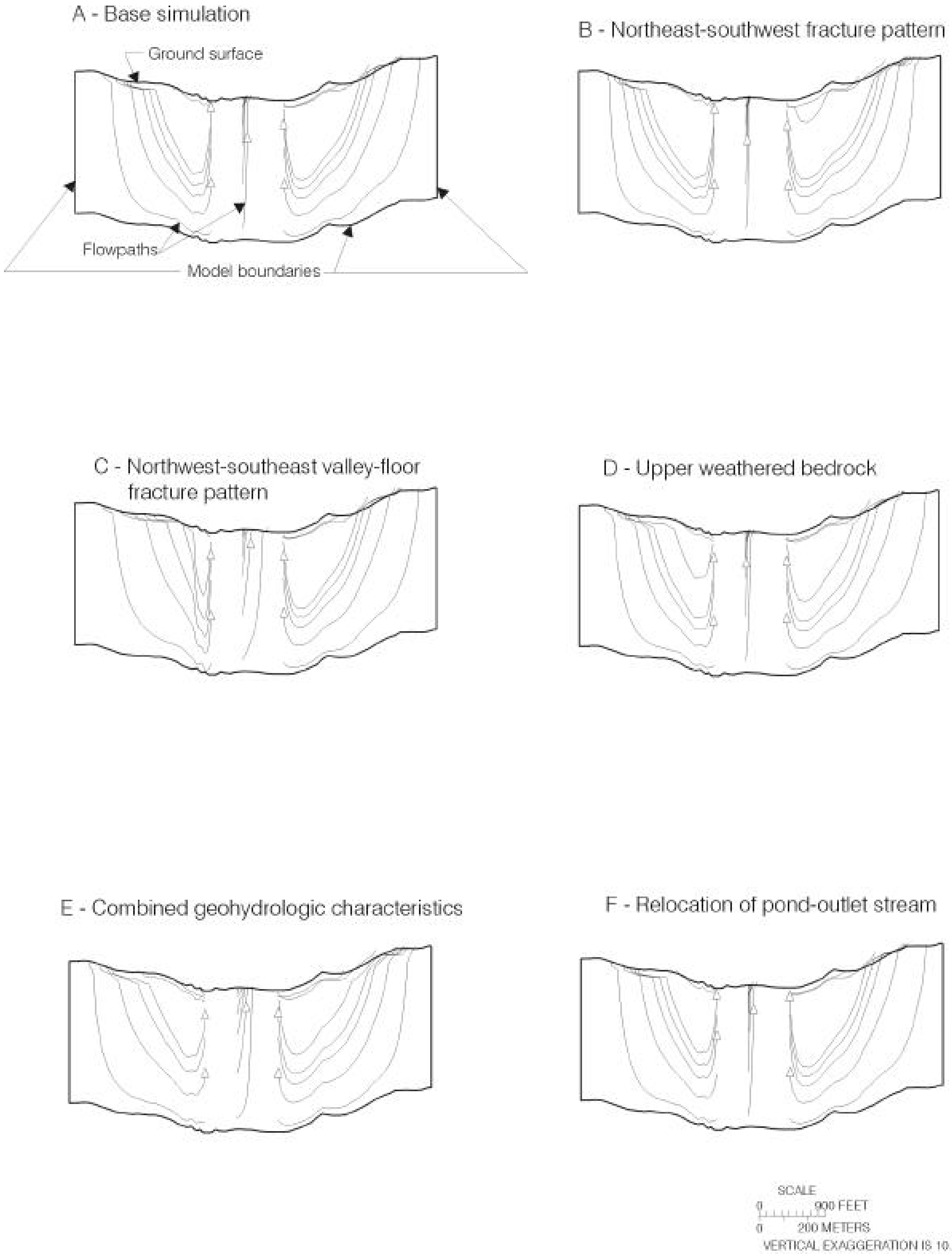


Figure 5. Cross section along row 34 of the models showing ground-water flowpaths to recharge locations in model simulations, Corinna, Maine. (see fig. 2a for row location)

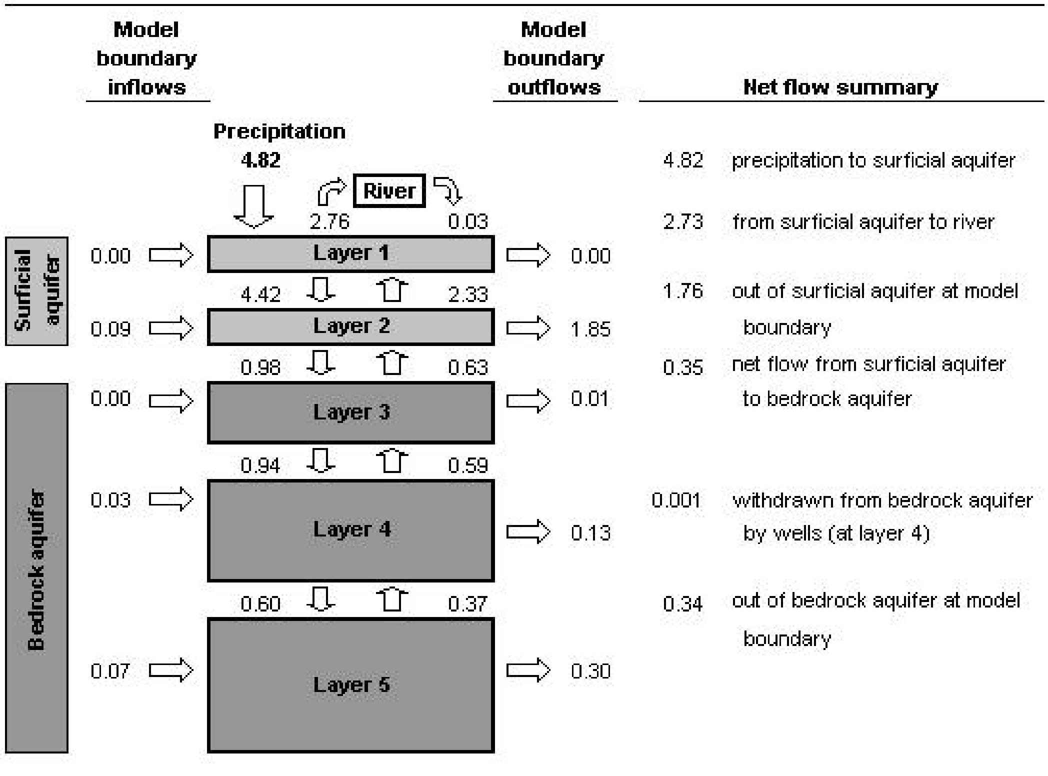


Figure 6 Water budget for the base model simulation, Corinna, Maine (all units in cubic feet per second).

A and B, near the upper bedrock surface, discharge directly toward Mill Pond (fig. 4b). Four locations (C, D, E, and F, fig. 2b) were selected for reverse particle tracking of ground-water flowpaths. For the reverse particle tracking, four particles were distributed evenly over the thickness of each cell at C, D, E, and F in model layer 4. In the base simulation, flowpaths to hypothetical wells located at points C and D is from the uplands to the west (fig. 4a). Flowpaths to well D, cross under the river and the EWM to their source on the western valley hillside. Flowpaths to hypothetical wells E and F is from an area in the center of the valley, at a ground-water high, or local divide, between the East Branch Sebasticook River network and Alder Pond. The flowpaths described in the following sections are advective flowpaths, which represent the general direction of flow and do not take into consideration the effects of variable fluid densities, dispersion, diffusion, absorption on flow.

Recharge from the simulated leachfields represents a partial return to the aquifer system of the ground water withdrawn from wells. Because the hydraulic conductivity of the bedrock is at least an order of magnitude lower than that of the surficial aquifer, this return flow does not readily recharge the bedrock aquifer and does not affect flowpaths, or heads, in the simulated bedrock model layers 3-5.

Simulation 1 -- Northeast-southwest fracture pattern

Simulation 1 conveys the effects of a pervasive northeast-southwest fracture pattern (an x:y anisotropy of 10:1). This simulation yields a pattern of more linear northeast-southwest bedrock ground-water flowpaths (fig. 7). Ground-water flowpaths diverge from the linear pattern when they are tracked back into the surficial aquifer where the materials are isotropic. A northeast-southwest fracture pattern causes changes in discharge of ground-water flowpaths from A and B. Discharge from A flows directly to Mill Pond whereas water from B now discharges west to Mill Pond. Examination of the known areas of bedrock ground-water contamination indicates that this is a potential geohydrologic control on the ground-water-flow system. Such a fracture pattern may accelerate advective distribution of water and transported contaminants in the direction of the fractures, as indicated by flowpaths in section (fig. 5B), which extend slightly further out from the center of the model in the row direction. Regional ground-water-head patterns are relatively unchanged. The simulated net ground-water flow to the river, however, is about one third less than that of the base simulation (table 1). Presumably, a northeast-southwest fracture pattern would decrease the effect of the river as a ground-water drain.

Simulation 2 -- Northwest-southeast valley-floor fracture zone

Simulation of a northwest-southeast valley-floor fracture zone, with an increased hydraulic conductivity (table 1), causes changes in the quantity and directions of flows in the ground-water system (fig. 8). Heads beneath the East Branch Sebasticook River system are lower than heads beneath Alder Pond area, which remain relatively unchanged. Bedrock with high transmissivity, caused by a northwest-southeast trending fracture zone underlying the valley, more effectively drains the valley-aquifer system. A transmissive-fracture zone in the valley bottom, approximately doubles flow through the ground-water system (gains and losses). Ground-water flowpaths from A and B in plan view (fig. 8) are relatively unchanged, whereas flowpaths to wells at C-F have a more northerly flow component in this simulation. Ground-water flowpaths in cross-section (fig. 5C) show the simulated fracture zone to be an area of preferential (increased) flow. Flowpaths can appear to cross as seen in figure 8 where the flowpath associated with B, in the surficial aquifer, overlies the flowpath associated with D, in the bedrock aquifer.

Simulation 3 -- Upper weathered bedrock

Inclusion of highly weathered upper bedrock in the model (layer 3, fig. 3) slightly lowered heads near the East Branch Sebasticook River system and slightly increased ground-water flow to the river (fig. 9). Heads in both aquifers remain relatively unchanged. Increasing the upper bedrock-surface transmissivity allows water to more readily transmit through the upper part of the rock and discharge to the river system. The effect of an upper weathered bedrock zone is small on the flowpaths to wells at locations C-F. Ground-water discharge paths from A and B (fig. 9) are changed because they originate in layer 2, close to the affected model layer. Flowpaths from A and B are slightly longer than flowpaths in the base simulation because they are more easily transmitted in this zone and discharge to the Mill Pond tailrace. The flowpath from A does not discharge directly to the river but crosses under and discharges on the other side of the river in this simulation (fig. 9). A transmissive (highly weathered) bedrock surface would increase advective transport and distribution of contaminants in ground water along that surface from locations A and B.

Simulation 4 -- Surface-water stage

Simulation of stage changes in the East Branch Sebasticook River system causes changes to ground-water head distributions (figs. 10a, b) and slight changes (10 percent) to river fluxes. With an increased stage (fig. 10a), heads are high throughout the valley bottom and net ground-water discharge to the river decreases by about 10 percent. With a low stage, heads correspondingly are low throughout the valley bottom (fig. 10b), while at the same time, net ground-water discharge to the river increases by about 10 percent from the base simulation (fig. 6). Because the river network is the primary sink in the ground-water-flow system, increasing the stage makes the sink less pronounced and lowering the stage makes the sink more pronounced. Raising or lowering the river network stage about 2 ft causes little change in the flowpaths of water recharging wells at C-F (figs. 10a, b). These stage changes, however, affect the flowpaths immediately adjacent to the river. For example, in the high- and low-stage simulations, the flowpaths from A cross under the river to discharge at the Mill Pond tailrace, and the flowpaths from B discharge directly to Mill Pond.

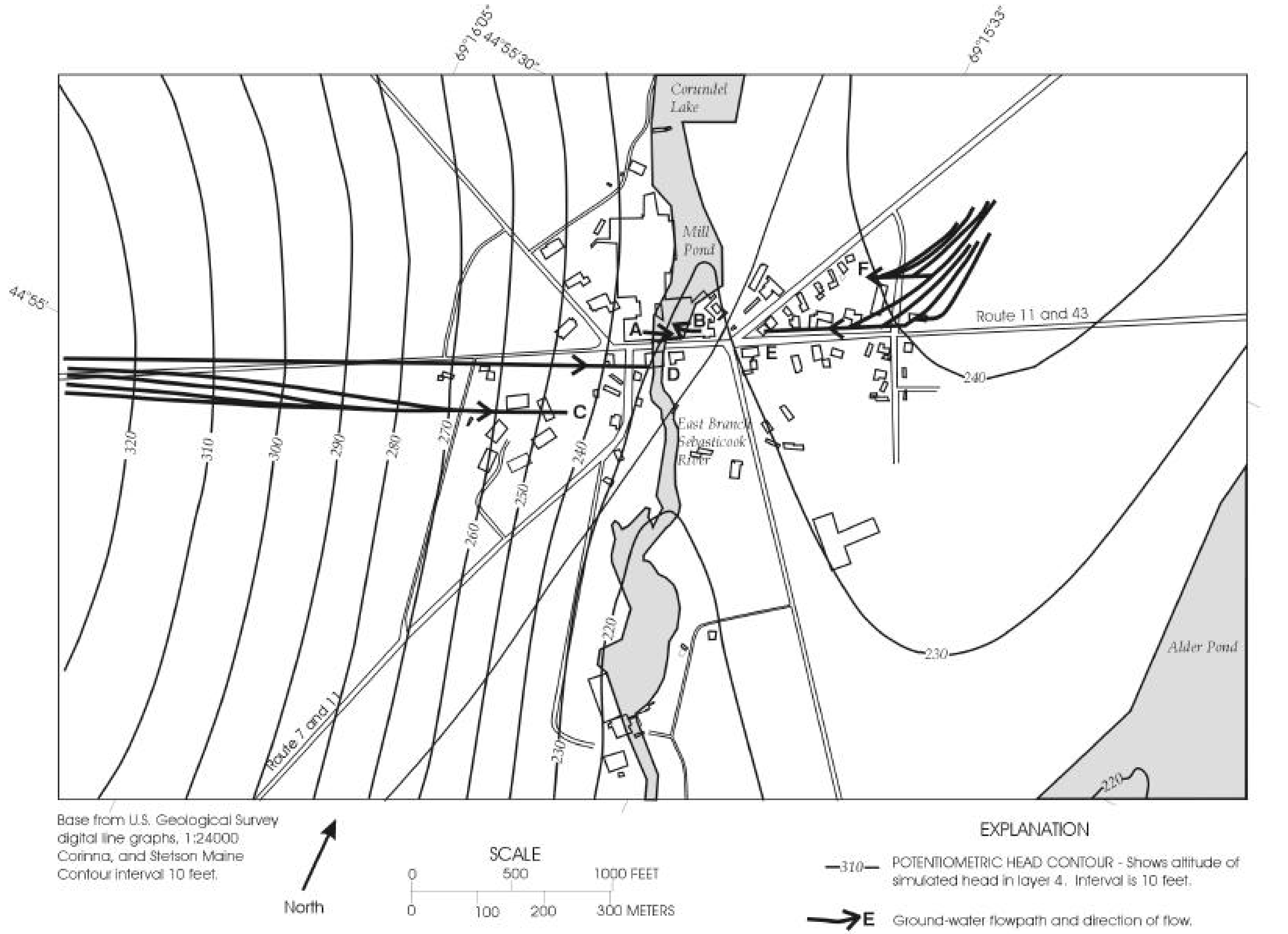
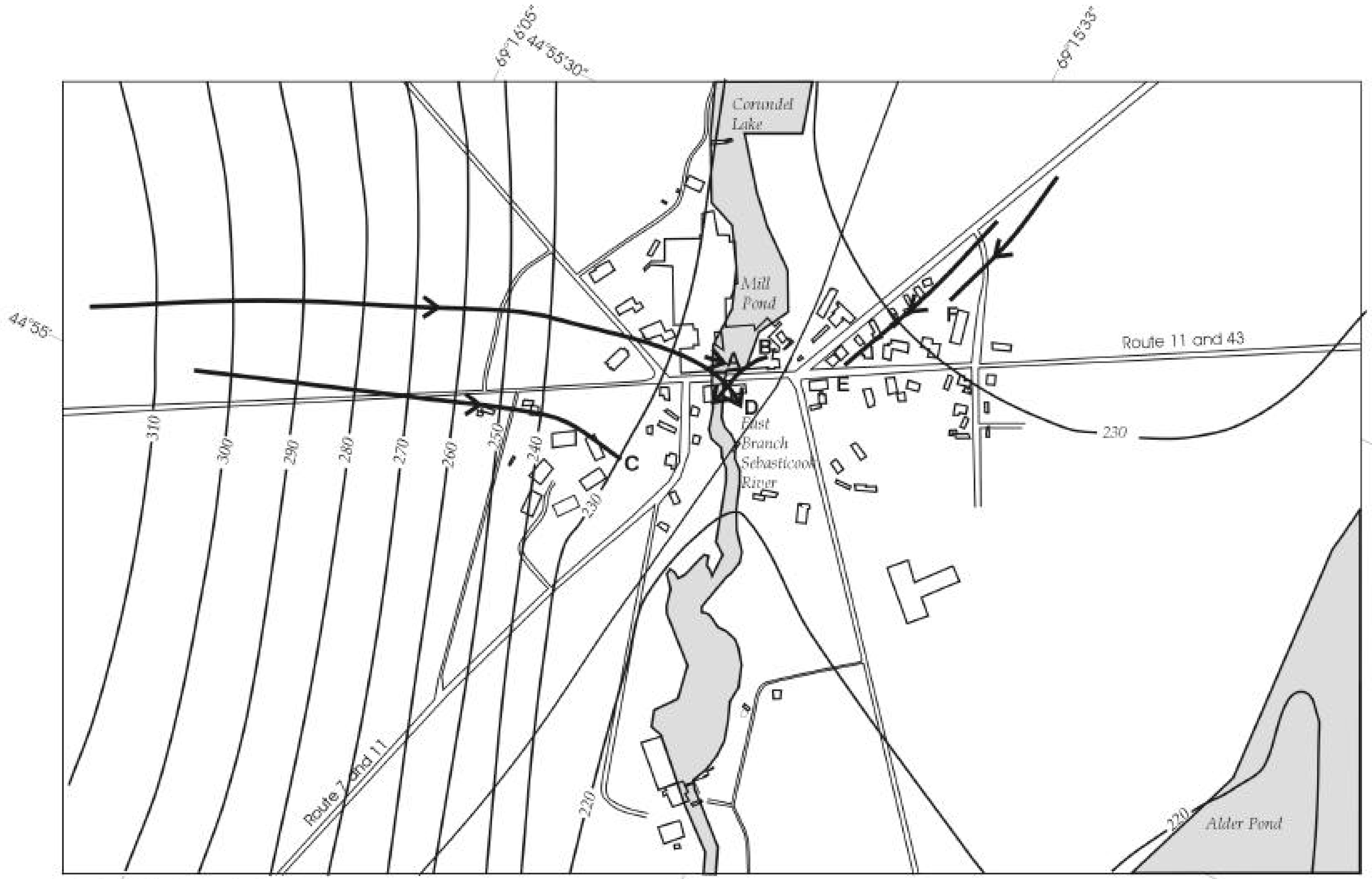


Figure 7. Simulated effects of a northeast-southwest fracture pattern on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 1).



Base from U.S. Geological Survey digital line graphs, 1:24000 Corinna, and Stetson Maine Contour interval 10 feet.

North

SCALE

0 500 1000 FEET

0 100 200 300 METERS

EXPLANATION

—310— POTENTIOMETRIC HEAD CONTOUR - Shows altitude of simulated head in layer 4. Interval is 10 feet.

→ E Ground-water flowpath and direction of flow.

Figure 8. Simulated effects of a northwest-southeast valley-floor fracture zone on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 2).

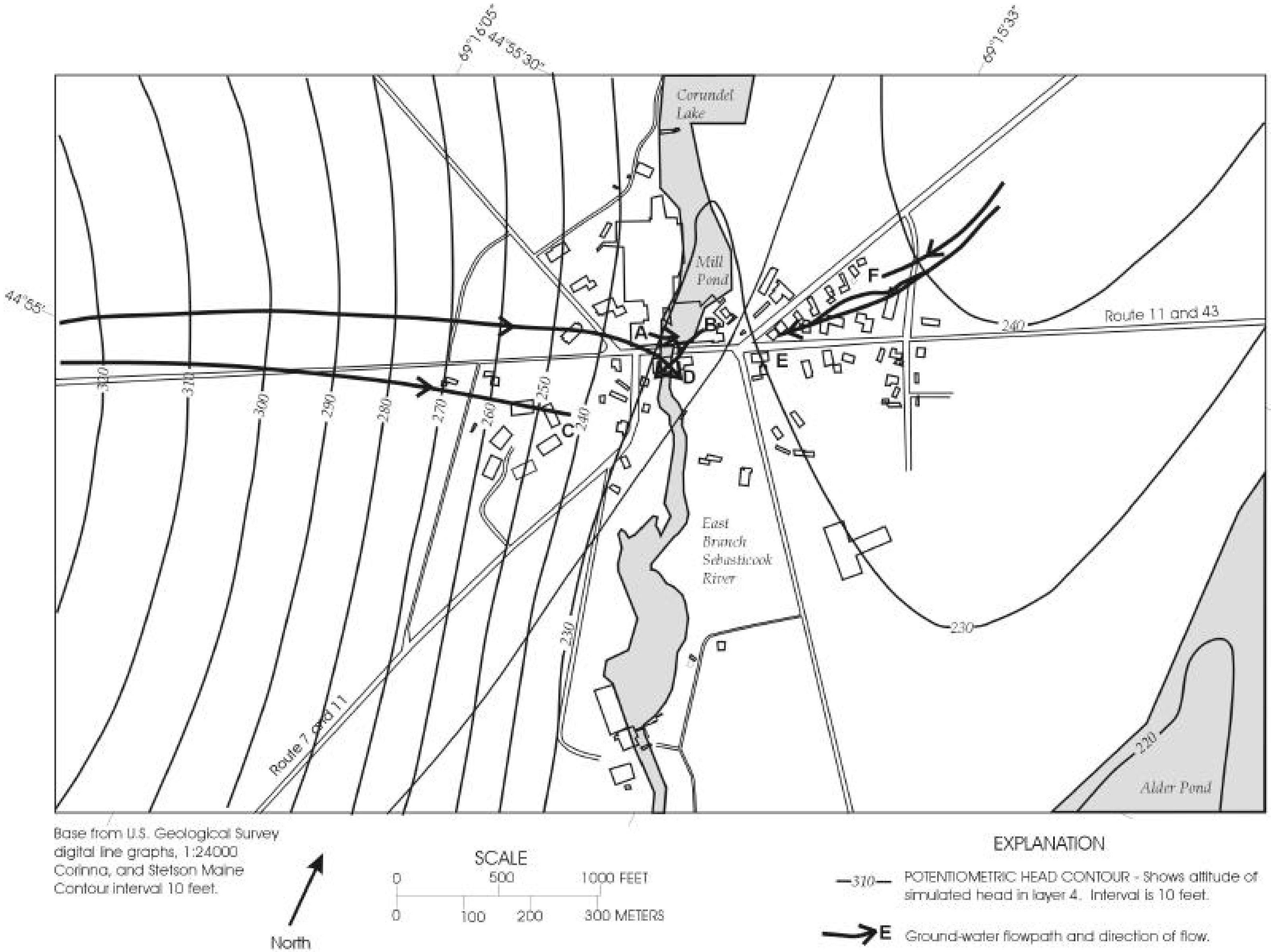


Figure 9. Simulated effects of upper weathered bedrock on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 3).

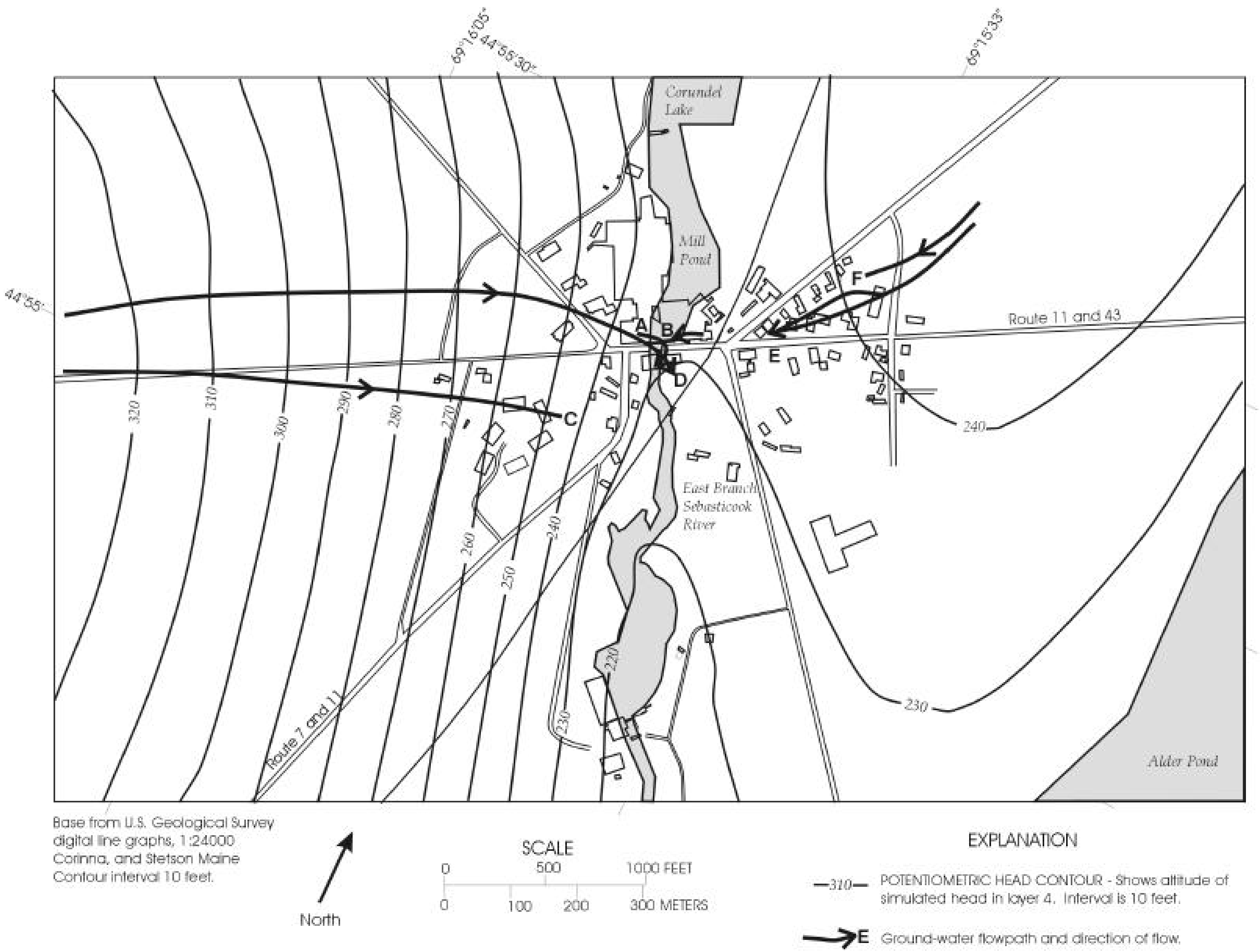


Figure 10a. Simulated effects of high surface-water stage on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 4a).

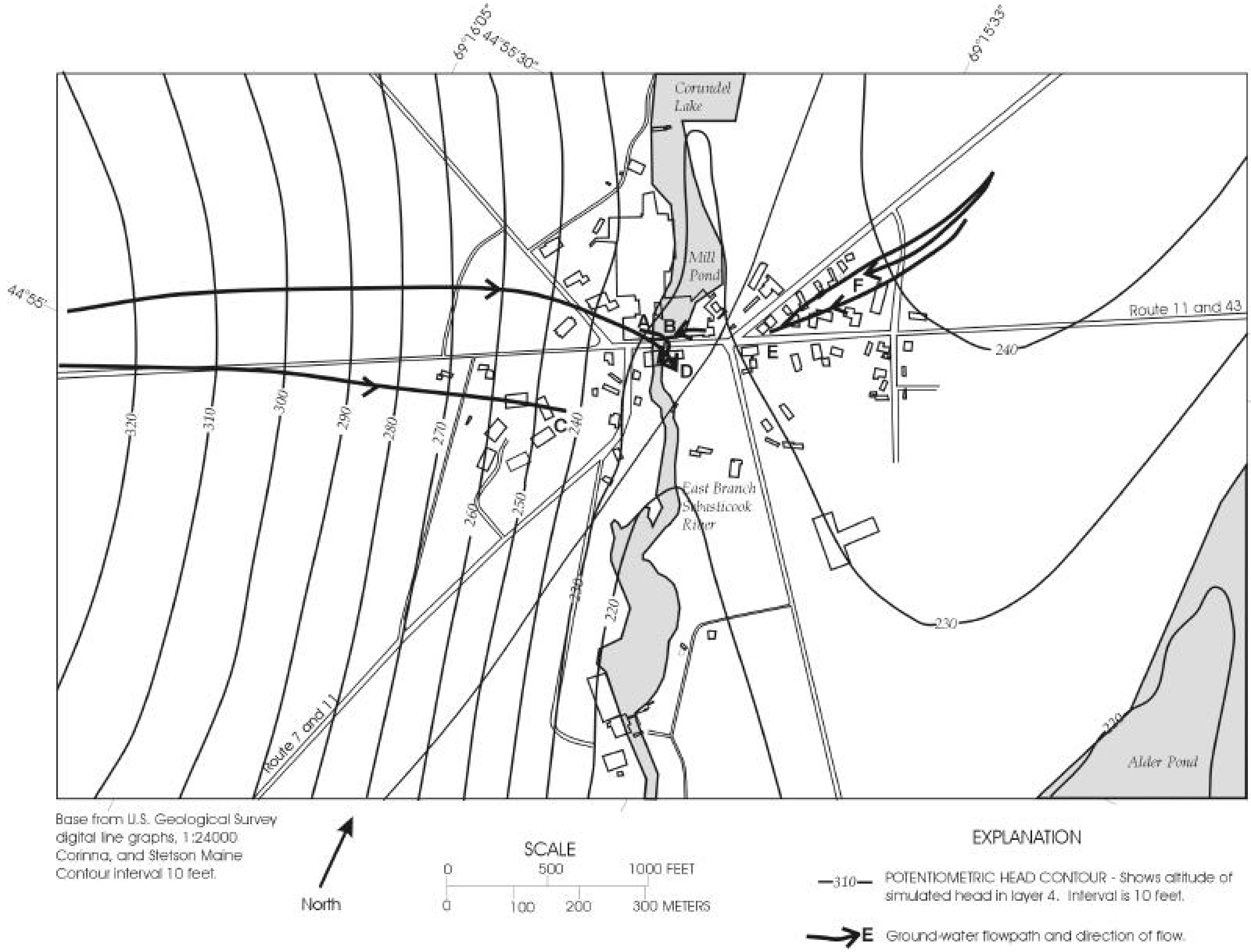


Figure 10b. Simulated effects of low surface-water stage on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 4b).

Simulation 5 -- River-bottom conductivity

Changes to the pond- and river-bottom conductance were approximated by changing the vertical hydraulic conductivity of layer 1 immediately beneath surface-water bodies by an order of magnitude. An increase in vertical conductivity only had a slight effect on the regional simulation (fig. 11a), as heads essentially were unchanged. With an increased vertical conductivity, net ground-water discharge to the river increased by only 7 percent from the base simulation. Local flowpaths, however, changed and some paths from B now discharge directly to Mill Pond (fig. 11a). With a decreased vertical conductivity, net ground-water discharge to the river was about 10 percent less than in the base simulation (fig. 6) and heads were lower in the valley bottom (fig. 11b). Decreased vertical conductivity causes discharge flowpaths from A to flow under Mill Pond and discharge to the river (fig. 11b). Vertical conductivity affects local ground-water flowpaths in the surficial aquifer. Anthropogenic changes to pond or riverbed characteristics may affect the path of contaminants from the EWM area in the surficial aquifer.

Simulation 6 -- Selected ground-water withdrawals

The effects of well interference were examined by simulating multiple domestic withdrawals in the bedrock (layer 4) in simulation 6. Budgets and head contours in the regional simulation change little, but locally, bedrock-aquifer, ground-water-flow patterns are changed in the town center (fig. 12). Simulating withdrawals at known historical locations (in addition to locations C, D, E, F) shifts the low point in layer 4 head contours slightly to the east. This change causes the flowpaths from location B to discharge directly to Mill Pond. The flowpaths to wells C and D are essentially unchanged because few of the withdrawals added for simulation 6 are on the west side of the valley. Flowpaths to wells E and F (fig. 12) indicate changes caused by an increased number of withdrawals on the east side of the valley. Current (2000) and historical changes in domestic withdrawals have altered local, and some regional, ground-water flowpaths in the bedrock aquifer. Historical withdrawals likely have affected historical advective flowpaths and the current location of contaminants. In this simulation (6), the flowpaths to domestic wells in the eastern part of town remain to the east. Though contaminants were detected at a well near point E, ground water flowing to wells near E and F in this simulation is not likely to have originated from the EWM area.

Simulation 7 -- Combined geohydrologic characteristics

Simulation 7 combines the effects of a northeast-southwest fracture pattern (simulation 1), a river valley fracture zone (simulation 2), an upper weathered bedrock (simulation 3), and multiple withdrawal wells (simulation 6). This combination of geohydrologic characteristics more likely represents true conditions than the base simulation or the geohydrologic characteristics applied individually (table 1). The simulated heads and flowpaths are shown in figure 13. The combined effect of the simulated characteristics results in appreciable changes to the regional heads and flow directions. Most notable is a low head surface in the center of the valley between the East Branch Sebasticook River network and Alder Pond (fig. 13). In cross section, this combination of geohydrologic characteristics produces flowpaths (fig. 5E) that are more evenly distributed across the section than the base simulation (fig. 5A). The effect of a pervasive northeast-southwest fracture pattern appears to dominate the local flow system on the west side of the river valley, as indicated by the flowpaths to C and D (fig. 13), because the simulated northwest-southeast (river-valley) fracture zone did not extend into the hillsides. In the middle of the valley, the effects of overlapping fracture sets (northeast-southwest and northwest-southeast) appear to have more of a combined effect on the flow system as indicated by flowpaths to E and F (fig. 13) and flowpaths in cross section (fig. 5E). The flowpath to E indicates that flow to this area may originate from both sides of the valley; however, those sources appear to be upgradient of EWM.

Simulation 8 -- Relocation of pond-outlet stream

Simulation 8 examines the effects of relocating the Mill Pond outlet approximately 150 to 200 ft to the east which was proposed as part of the remediation plan. Simulation of a relocated outlet and the resultant heads in the screened interval of the bedrock aquifer (model layer 4) are shown in figure 14. Relative to the

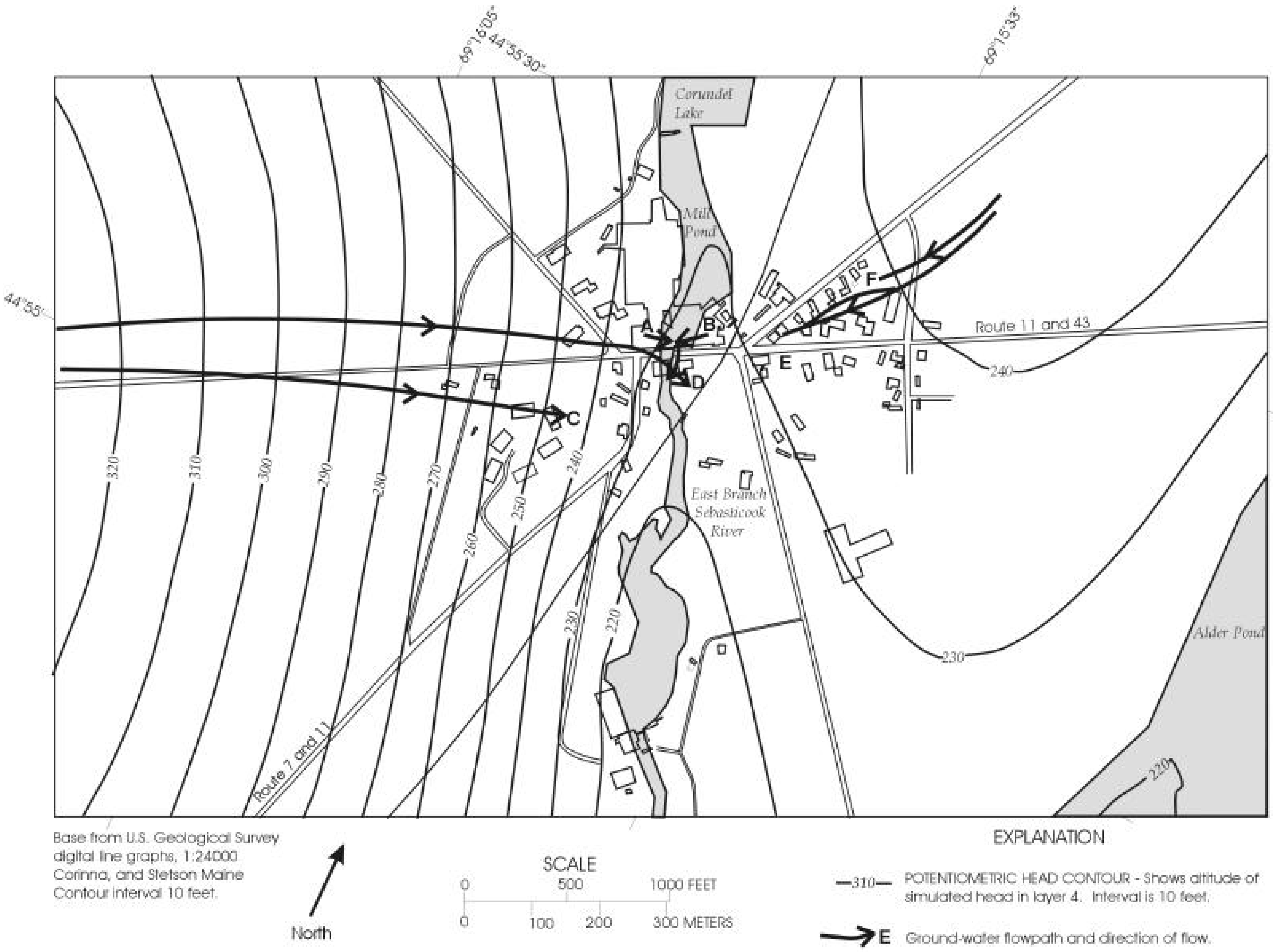


Figure 11a. Simulated effects of increased river-bottom hydraulic conductivity on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 5a).

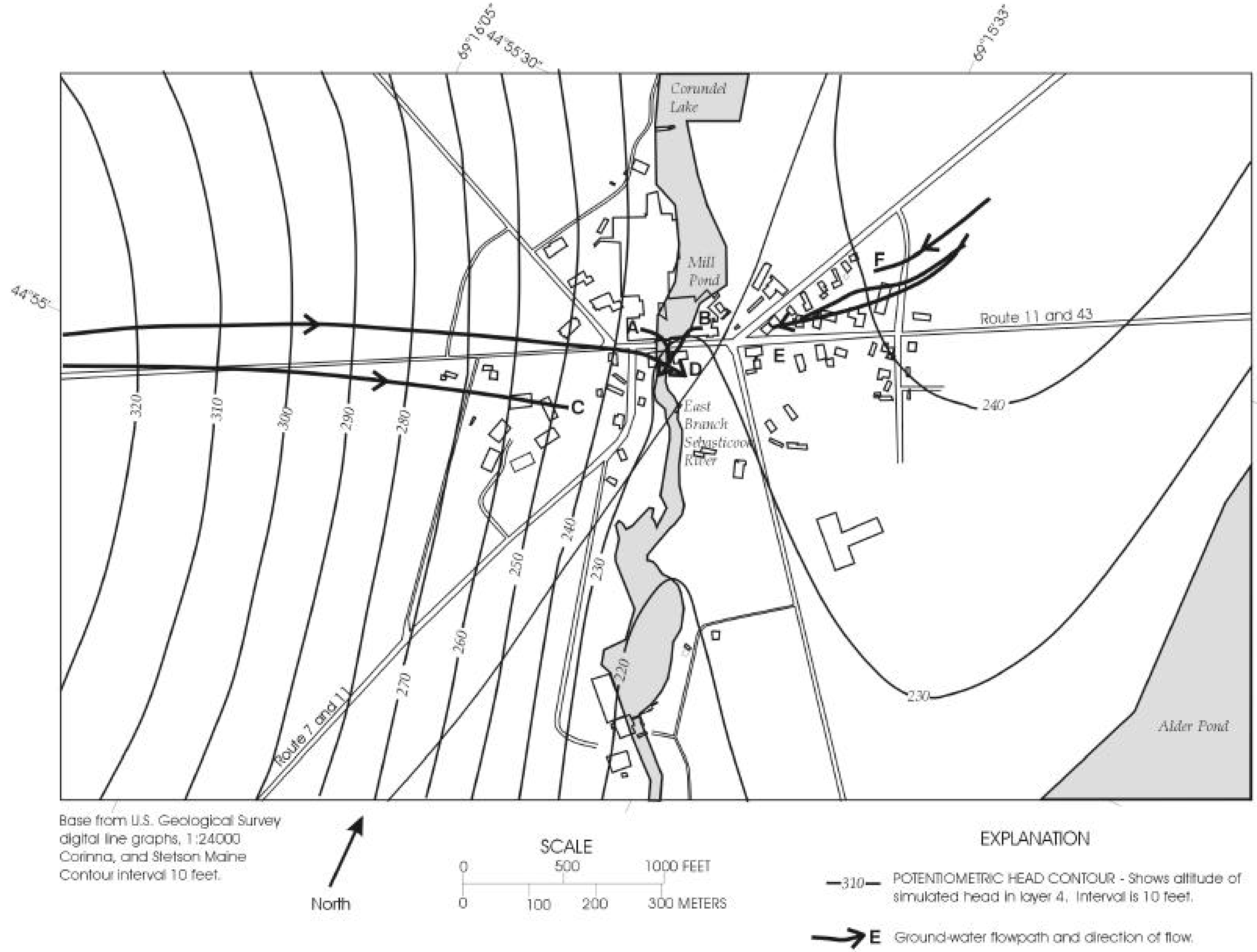


Figure 11b. Simulated effects of decreased river-bottom hydraulic conductivity on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 5b).

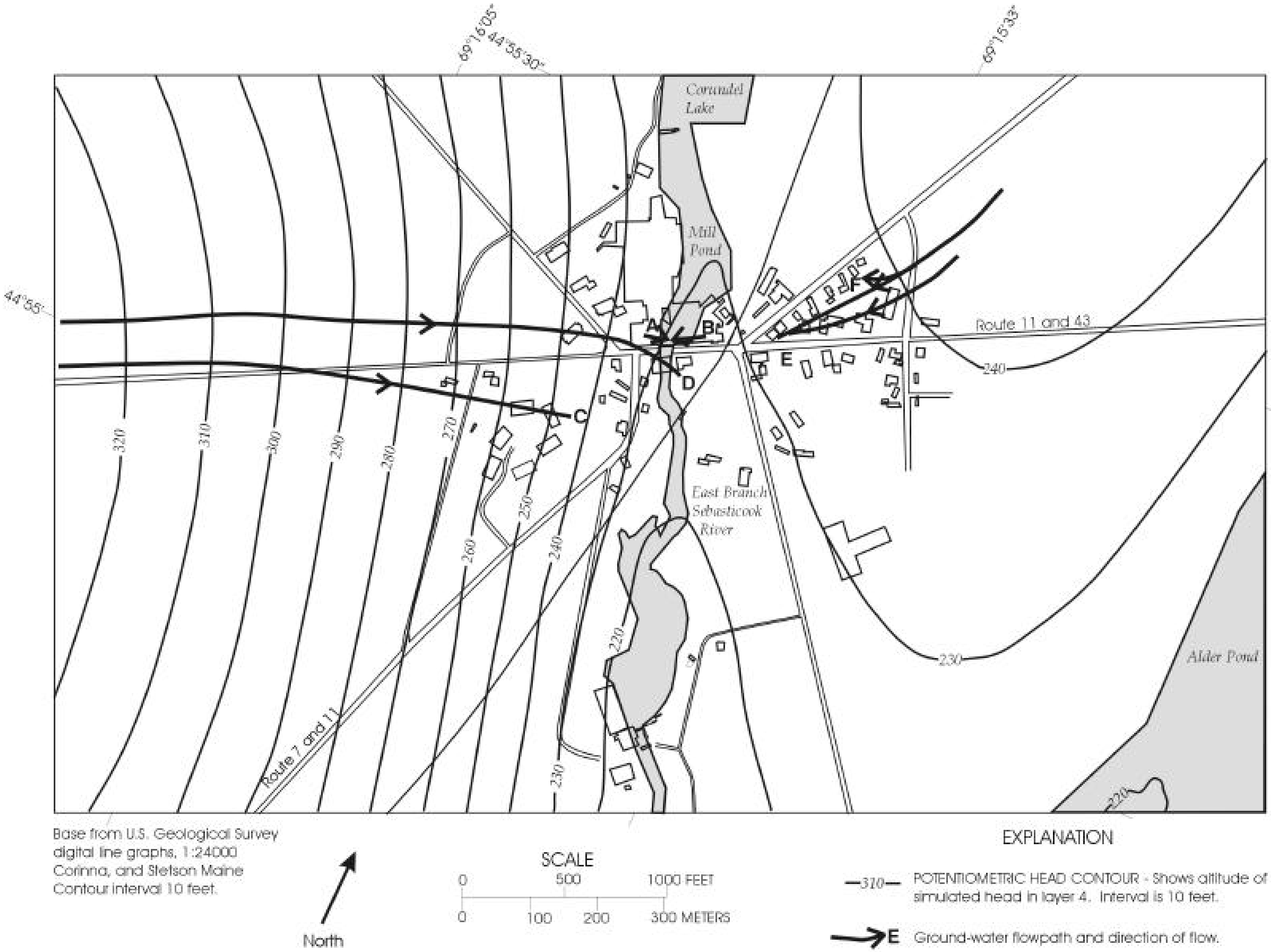


Figure 12. Simulated effects of selected ground-water withdrawals on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 6).

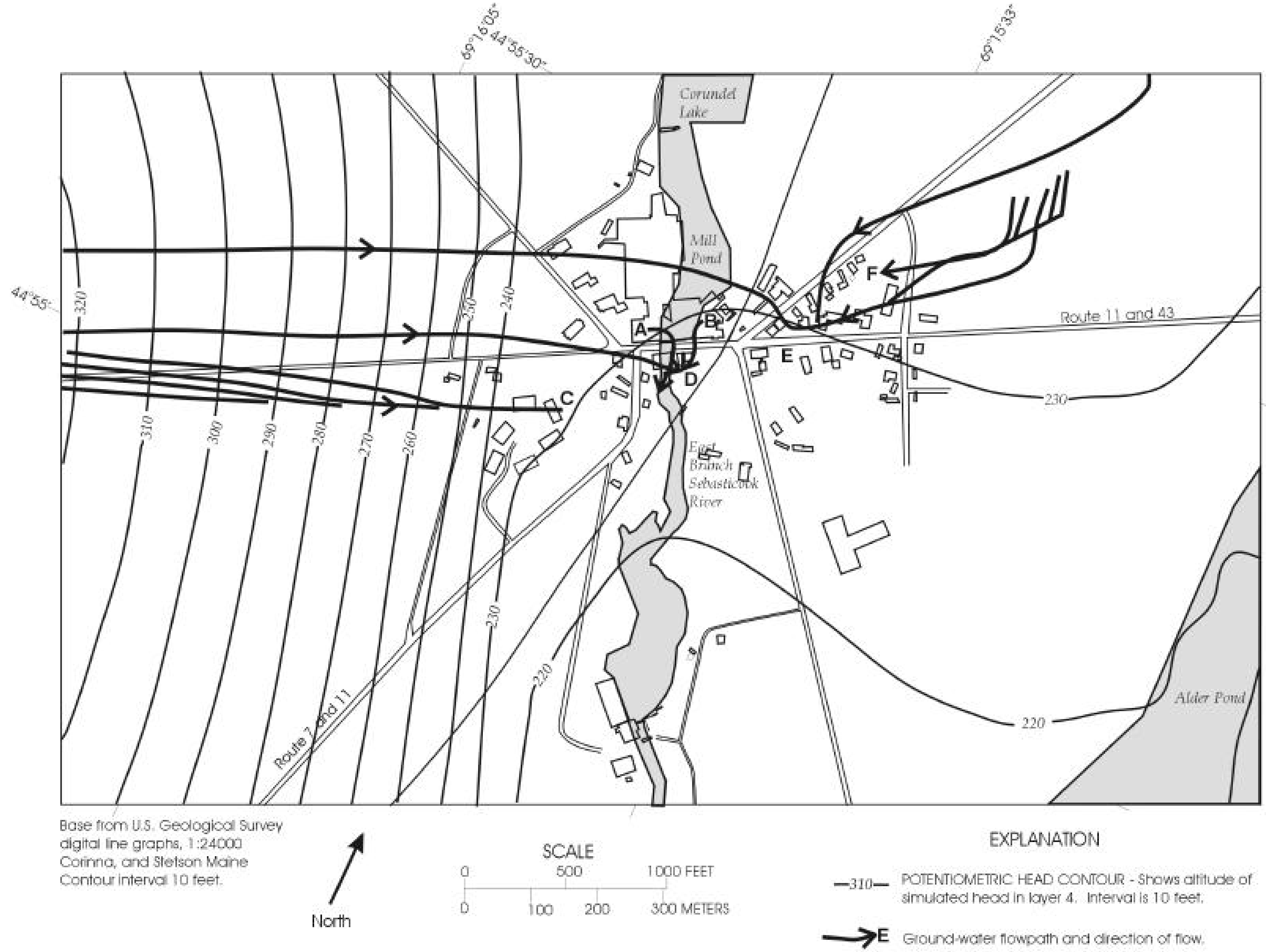


Figure 13. Simulated effects of a combination of geohydrologic characteristics on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 7).

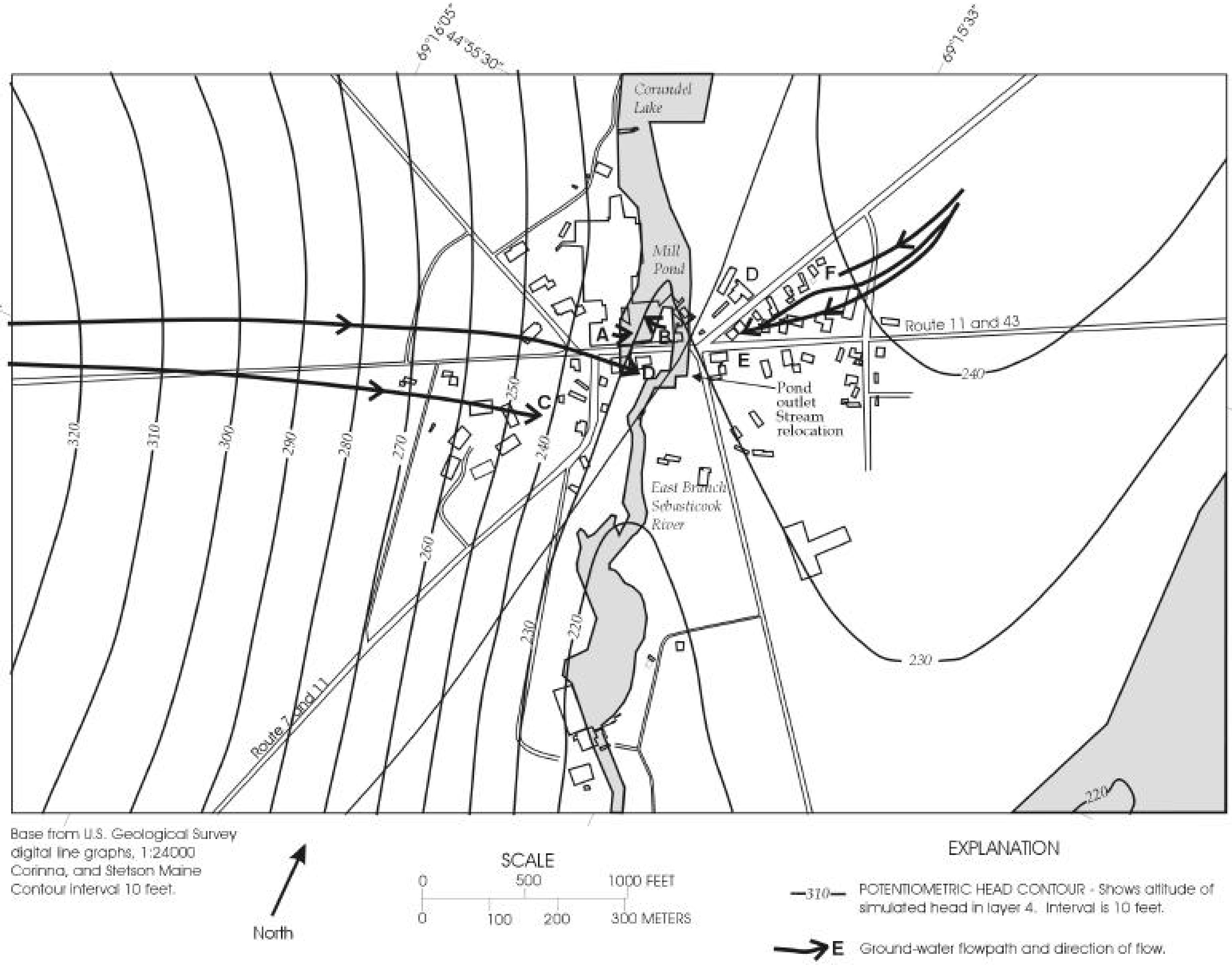


Figure 14. Simulated effects of relocation of the pond-outlet stream on ground-water heads and selected advective flowpaths in the ground-water flow system in Corinna, Maine (simulation 8).

base simulation, the effect of moving the constant heads results in local changes to simulated head contours in the upper model layers (1-2), but the effects are slight in the bedrock model layers (3-5). No changes are observed in ground-water flowpaths in bedrock in cross section (fig. 5F) from relocating the pond outlet. Heads are depressed further to the east, but the effect on the regional system is not noticeable. Simulating the relocation of Mill Pond does not change the magnitude of fluxes to and from the bedrock aquifer (fig. 6).

SUMMARY AND CONCLUSIONS

The Eastland Woolen Mill, in Corinna, Maine, used a variety of DNAPL's (chlorinated solvents, primarily chlorobenzenes) that were disposed of, or stored, at the mill site and surrounding locations and have migrated through surficial sediments and into fractured bedrock, contaminating the ground water. The USGS, in cooperation with the USEPA, developed generalized numerical models of the ground-water-flow system to test hypothesized geohydrologic characteristics and improve understanding of their effects on ground-water flow and, thus, contaminant flowpaths in the surficial- and bedrock-aquifers.The simulated results represent ground-water heads, flowpaths, and water budgets that have not been calibrated to measured field conditions.

The simulated ground-water-flow results for each of the following eight geohydrologic characteristics were compared with a base simulation for evaluation purposes: (1) an east-west transmissive bedding-plane fracture system, (2) a northwest-southeast valley floor transmissive fracture zone, (3) an upper weathered bedrock transmissive zone, (4) river and pond stage changes, (5) river and pond bottom conductivity changes, (6) multiple withdrawals, (7) a combination of some of these characteristics, and (8) relocation of the Mill Pond outlet. Individually, most of the geohydrologic characteristics assessed had minor effects on the regional and local ground-water-flow system. In combination, however, these characteristics can have major effects on directions of ground-water flow and the amount of water moving through the system (water budget).

The effects of many of the geohydrologic characteristics are minor on the flow in the bedrock aquifer at depth (model layer 5). The simulated flux from the surficial aquifer to bedrock is about 20 percent (1.0 ft^3/s) of the total input (recharge, 4.8 ft^3/s; ground-water inflow, 0.2 ft^3/s) to the system. Therefore, the effects of the geohydrologic characteristics are more pronounced in the surficial aquifer where most of the ground water flows through the relatively thin till layer.

Regionally pervasive characteristics, such as anisotropy in the bedrock system or a major valley-bottom fracture zone, affect deep ground-water flow patterns in the bedrock. Such regional bedrock characteristics would affect contaminant distribution in bedrock. Thus, understanding local and regional fracture patterns is important in assessing contaminant movement or in simulating the effects of remedial contaminant actions.

Less than 1 percent of the total simulated water budget is withdrawn from domestic and remedial wells, which has minimal effect on the regional flow of ground water, but affects local flow patterns and contaminant discharge paths near Eastland Woolen Mill and in downtown Corinna. An understanding of historical withdrawal patterns may be necessary to understand previous contaminant paths and sources. A transmissive, highly weathered bedrock surface increases advective transport and alters local flow patterns and contaminant distribution. Vertical conductivity also appears to strongly affect paths of ground-water flow in the upper aquifers, indirectly affecting local flowpaths and contaminant transport.

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