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WEST SIBERIAN BASIN HYDROGEOLOGY - REGIONAL FRAMEWORK FOR CONTAMINANT MIGRATION FROM INJECTED WASTES

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ABSTRACT

Nuclear fuel cycle activities of the former Soviet Union (FSU) have resulted in massive contamination of the environment in western Siberia. We are developing three-dimensional numerical models of the hydrogeology and potential contaminant migration in the West Siberian Basin. Our long-term goal at Pacific Northwest Laboratory is to help determine future environmental and human impacts given the releases that have occurred to date and the current waste management practices. In FY 1993, our objectives were to 1) refine and implement the hydrogeologic conceptual models of the regional hydrogeology of western Siberia developed in FY 1992 and develop the detailed, spatially registered digital geologic and hydrologic databases to test them, 2) calibrate the computer implementation of the conceptual models developed in FY 1992, and 3) develop general geologic and hydrologic information and preliminary hydrogeologic conceptual models relevant to the more detailed models of contaminated site hydrogeology.

Calibration studies of the regional hydrogeologic computer model suggest that most precipitation entering the ground-water system moves in the near-surface part of the system and discharges to surface waters relatively near its point of infiltration. This means that wastes discharged to the surface and near-surface may not be isolated as well as previously thought, since the wastes may be carried to the surface by gradually rising ground waters.

From our FY 1992 geologic and hydrologic characterization work, we knew ground-water flow in the West Siberian Basin was topographically driven, with recharge to the basin occurring in the highlands on the west, east, and south, and internal discharge localized in numerous river valleys and lakes that ultimately discharge north to the ocean. In FY 1993, we developed three conceptual models (hypotheses) of ground-water movement within the basin for testing. In the first, recharge would infiltrate vertically into exposed fractured Paleozoic rocks (in the highlands) until coming in contact with onlapping Mesozoic and Cenozoic sediments. This deep recharge would then redistribute itself laterally in response to the topographic gradient, favoring flow paths through more highly permeable strata. Contaminants infiltrating with this water would be associated with slow moving brines and would be relatively isolated from the surface. In the second conceptual model, most recharge would be restricted to the unconfined aquifer, with very little of the incoming precipitation going to deep recharge. Under these conditions, even deeply injected contaminants would return to surface waters relatively close to their points of origin after relatively short travel times. In the third conceptual model, much of the recharge in the highlands surrounding the basin would percolate deep into basement rocks underlying the basin; ground water and associated contaminants in these rocks would have little interaction with the overlying rocks.

To evaluate these hypotheses, we developed a hydrogeologic model of the West Siberian Basin incorporating all known geologic and hydrologic information. This required locating and processing topographic, geologic, hydrostratigraphic, hydrogeologic, and water balance data and constructing a regional water table for the West Siberian Basin. Data processing included digitizing, registration, projection, gridding, and quality control analysis. Constructing the regional water table required combining data from two primary sources and filtering them using a specially developed relaxation method. All data were gridded at spatial resolutions of either 500 m or 1,000 m.

We used the Coupled Fluid, Energy, and Solute Transport (CFEST) program to numerically model the regional hydrogeology. Calibrating the basin's moisture balance (i.e., recharge and discharge) to the derived water table determined plausible input parameter values for unknowns such as hydraulic conductivities. We found that achieving a water balance using realistic values for water table elevation and rock properties required that most ground-water flow in the unconfined, near-surface part of the system. This finding supports our second conceptual model, suggesting that contaminant migration pathways and travel times from waste injection site to surface waters are relatively short. Details of surface-water/ground-water interactions will be important to our local contaminant migration models. Because preliminary results suggest that assumed interactions between surface water and ground water are more critical to the modeled water balance than we initially thought, in FY 1994 it will be important to properly account for recharge partitioning between the upper and intermediate/regional flow systems while adjusting model parameters to achieve a water balance. For this reason, it may be necessary to model the surface-water and unconfined aquifer zone (upper flow system) separately from the intermediate and lower zones in the regional and local models.

Local, higher resolution models of ground water and associated contaminant movement nested within the regional hydrogeologic model will be used to provide a more detailed assessment of the potential environmental impacts within the West Siberian Basin. Numerical hydrogeologic models will be used to quantify local ground-water flow and to evaluate potential contamination release scenarios and migration pathways from injection sites. We used higher resolution (100 m) topography, published hydrogeologic information, and direct interactions with individual Russian scientists and engineers to gain better insight on the hydrogeology of the local model areas and to design boundaries within the regional model. Our conceptual ground-water flow models for these areas mimic those of the regional hydrogeologic system.

INTRODUCTION

The former Soviet Union (FSU) has extensive defense-related nuclear production industries. Over the past four decades, wastes from these industries have massively contaminated the environment by airborne, surface-water, and ground-water releases of hazardous and radioactive materials. Of most concern, with the exception of the waste management activities subsequent to the Chernobyl accident, is the radioactive contamination of the environment in western Siberia. Little information has been reported on radioactive releases from Russian defense facilities. However, a detailed picture is emerging of the situation at the Mayak site near Kyshtym, due to recent visits by Western scientists and publications by FSU scientists of that site's history (Drozhko et al. 1989, 1993; Bradley 1991; Chukanov et al. 1991; Kossenko 1992).

The radioactive releases from the Mayak site are the largest known in the world; at least 130 million curies have been discharged to the environment, with profound environmental effects. Immediate impacts in terms of human health effects were apparently severe (Chukanov et al. 1991). About 18,000 people have been relocated at various times to reduce ongoing exposure from relatively long half-life radionuclides, and about 500,000 people have been exposed to increased radiation levels (Chukanov et al. 1991; Bol'shakov et al. 1991). Harmful environmental impacts include the death of vegetation from wind dispersal of nitrates or phosphates, as well as severely contaminated surface and ground waters. Radionuclides in the surface traces of contamination events have been plowed under in an attempt to prevent their spread, and areas with $^{90}Sr > 4\ Ci/km^2$ have been sequestered from use for forest game hunting. Selected lakes have been declared off-limits for fishing and waterfowl hunting (Chukanov et al. 1991).

Clearly, releases to date have already had severe environmental and human impacts. The FSU will likely require Western assistance in mitigating these regional impacts, which may escalate to a global level in the future (Chukanov et al. 1991). Therefore, it is critical to determine how to remediate both nonnuclear hazardous chemical and radionuclide contamination at these sites and the fate and transport of contaminants away from the sites. This paper provides the status of efforts by Pacific Northwest Laboratory[a] to quantify the regional hydrogeologic context for potential contaminant migration from areas in western Siberia.

OBJECTIVES

Our long-term goal for this research is to quantify the regional hydrogeology of western Siberia to provide the boundary conditions for determining the hydrology and long-term contaminant migration pathways. Our objectives for FY 1993 were to document:

- the detailed, spatially registered digital geologic and hydrologic databases that implement the hydrogeologic conceptual model of the regional hydrogeology of western Siberia we described in Foley et al. (1993),
- calibration of the computer implementation of this conceptual model, which will be the tool for satisfying our long-term objective (above), and
- general geologic and hydrologic information relevant to potential detailed models of site-specific contamination and contaminant migration.

REGIONAL GEOLOGIC AND HYDROLOGIC SETTING

PHYSIOGRAPHY

The West Siberian Basin (Figure 1) is the largest platformal basin and region of low relief on earth (Peterson and Clarke 1991). The basin is a broad downwarp within folded and metamorphosed Precambrian and Paleozoic cratonal rocks filled with relatively undeformed Mesozoic and younger sediments. With an area of about 3.5 million km^2, the West Siberian Basin is larger than the combined drainage basins of the Missouri, Mississippi, and Ohio rivers, stretching from the Ural Mountains on the west to the Yenisey River on the east and from the Kazakh Uplands on the south to the Arctic Ocean on the north (Figure 2). Nudner (1970) described the basin as a combination of individual basins and uplands with up to about 175 to 285 m of relief on the interfluvial uplands between the Ob' and Yenisey rivers. This relief is too low to prevent flooding of vast areas during spring, when the frozen headwaters of north-flowing rivers begin to melt (Peterson and Clarke 1991).

Located in the center of Eurasia, the West Siberian Basin has a distinct continental climate with a prolonged cold winter and a short, comparatively warm summer (Nudner 1970). Moisture

(a) Pacific Northwest Laboratory is operated by Battelle Memorial Institute for the Department of Energy under Contract DE-AC06-76RLO 1830.

comes almost entirely from the Atlantic in repeated continental anticyclonic weather and in an exchange of air masses during summer and winter. Most of the precipitation occurs from July (south) to August (north). The period from the second half of winter to early spring is driest. Precipitation in the West Siberian Basin is affected somewhat by the Ural Mountains, especially in the south. The Altai Mountains (south of Tomsk) receive up to 800 mm of precipitation per year and feed the rivers of this region such as the Ob'. In the West Siberian lowland, the yearly total increases from 250 mm on the shores of the Kara Sea in the north to 400 to 500 mm in the central basin, falling to 250 mm in the southern regions. The annual total varies up to 200 to 250 mm from these means. Ground waters are fed mainly by melting snow and cold autumn rains. During the last 30 to 40 years, global warming has resulted in the retreat of glaciers by 15 to 16 m/yr, which has caused the appearance of small islands of rock due to melting ice. Permafrost is ubiquitous in the northern regions. The frost depth of clayey and black soils reaches 1 to 1.5 m as a rule. In severe dry winters, the frost depth exceeds 2 to 3 m in bare ground.

From north to south, ecological zones change successively from tundra to taiga, forest, forest steppe, and steppe. The soil zones change accordingly—tundra and arctic soils give way to podzols [spodusols], gray forest soils and basic black soils [Chesnut soils], black soils [chernozems], and brown soils [brunizems]. The flora change from mosses, lichens, dwarf birch, and certain sedges and grasses (cereals) in the tundra of the north to spruce-deciduous forests and cedar with intrusions of pine, fir, and birch characteristic of the taiga zone. Aspen-birch forests, pine forests, and tall grass meadows and marshes predominate farther south in the forest steppe zone. Grasses dominate the steppe.

Because of the northern latitude of the West Siberian Basin, permafrost is a phenomenon to be considered in hydrogeologic reconstructions. Current limits of discontinuous permafrost are approximately 61°N (Figure 3) except at higher elevations of the Ural, Sayan, and Altai/Salair mountains (Grave 1984). However, relict Late Pleistocene permafrost buried to depths ranging from 50 to 160 m up to 200 to 400 m (Baulin and Danilova 1984) is reported to occur as far south as 55°N (Baulin et al. 1984). These authors divided the basin into three zones; in each zone or study area, the structure of the permafrost differs with depth. The first zone, extending from the Arctic to a southern boundary approximately along the Arctic circle and coinciding with the northern boundary of the forest, consists of primarily monolithic structure (although not continuous). A second zone south of the first consists of primarily two-layered structure. The surficial frozen layer in this zone is 30 to 80 m thick near the Arctic Circle, thins significantly to the south, and disappears south of 64°N. A thawed layer extends 50 to 150 m below the surficial frozen layer, with a relict Pleistocene frozen layer below. In some wells, three or more frozen layers have been observed. The third zone contains only relict Pleistocene permafrost, the top of which lies at depths 150 to 230 m, and the base extends down 400 to 500 m or more.

The thickness of the permafrost is apparently related to the structure of the Mesozoic-Cenozoic layer and the tectonic region. As a rule, the depth to the bottom and the thickness of the permafrost are much less over the Triassic rifts than on their edges (Nudner 1970). This thinning may be related to heat flow that correlates with these structures. The thickness of the zone of seasonal melting (the permafrost active layer) increases from north to south and varies depending on lithologic composition of the deposits, continuity of relief and elevation above sea level, thickness of snow cover, temperature, exposure, water saturation and thermal conductivity of the deposits, and plant cover. The permafrost ice consists of fine crystals, accumulations, veins, pockets, interlayers, large lenses, and infrequent wedges, depending mainly on the mechanical composition of the rock. Treeless tundra and peaty deposits offer the most favorable conditions for formation of ice wedges and patterned ground, and for surficial permafrost manifestations that might affect contaminant migration and introduction into the ground-water system. Buried relict permafrost will have a substantial effect on spatial variability of the basin's artesian aquifers.

GEOLOGY

The West Siberian Basin consists of an inner region deformed by mega-anticlines and megasynclines along basement graben faults surrounded by a monoclinal outer belt that is otherwise relatively undeformed (Peterson and Clarke 1991). Structures of pre-Triassic basement rocks beneath the West Siberian Basin consist of several fold systems separating platformal blocks that may be microplates caught between the fold systems. Geosynclinal sedimentary piles and older rocks were caught up in the deformation and metamorphism of these fold systems.

Beginning in the Triassic, the West Siberian Basin was formed by vertical movements along faults defining aulacogen-like grabens (Aleinikov et al. 1980) in the Paleozoic basement (Figure 4) and by differential compaction of clay-rich and sand-rich Mesozoic and Cenozoic sediments (Zonenshain et al. 1990; Peterson and Clarke 1991). These grabens, which are bounded by faults with as much as 3 to 5 km of displacement, are filled with basic intrusive rocks overlain by volcanic and sedimentary rocks in the upper portions. The grabens are geothermal anomalies, producing temperatures 3° to 4°C above background at a depth of 1 km (Peterson and Clarke 1991).

Underlying structures, particularly fracturing related to the bounding faults of Triassic grabens, disappear upsection in the Mesozoic-Cenozoic sedimentary cover of the West Siberian Basin (Aleinikov et al. 1980; Peterson and Clarke 1991), although Glavinskaya (1990) reported a 200-km-long, 15- to 40-km-wide graben of recent origin on the Ob' River east of Surgut that is visible in satellite imagery. Principal structural elements of the post-Triassic cover are the inner region and outer belt, with an indistinct boundary between the two where the dip of the basement surface is steepest. Post-Triassic basin sediments lap onto this outer zone, which has a thinner sedimentary section than the inner region and weak or no manifestation of basement structures other than the generally monoclinal nature of the basin-bounding zone.

Zonenshain et al. (1990) hypothesized on the basis of paired linear magnetic anomalies in the West Siberian Basin (Aplonov 1988) that substantial rifting (270 km in the north) produced the Ob' Paleo Ocean, which underlies Triassic and younger sediments of the basin. However, Peterson and Clarke (1991) suggested that rifting was a short-lived (17 MYBP) event in the Triassic. They further suggested that the "paired magnetic anomalies" are serendipitous relicts of the accretion of microplates that accompanied the late Paleozoic collision of the Russian and Siberian platforms, which produced the Ural orogenic belt (Hamilton 1970; Kirschvink and Rozanov 1984).

The Phanerozoic sedimentary cover of the West Siberian Basin ranges in thickness from 3 to 5 km near the center of the basin and from 8 to 12 km in the north and northeast (Peterson and Clarke 1991). Similarly, the Mesozoic-Cenozoic sedimentary section that contains most of the hydrologic system (see below) is 3 to 4 km thick near the center of the basin and 8 to 10 km thick in the north.

Basement rocks of the basin consist of Precambrian- and Paleozoic-age granitic rocks in the south and central parts, igneous and metamorphic rocks of Proterozoic age in the central part, and Late Proterozoic greenschist and other metamorphic rocks in the southwest. Carbonate and clastic rocks of upper Proterozoic and lower Paleozoic age are widespread in the basin and are metamorphosed strongly enough in most areas to be considered basement (Peterson and Clarke 1991). Where slightly to moderately metamorphosed, the Paleozoic rocks retain some hydrocarbon source and reservoir characteristics.

Post-Triassic-rifting Mesozoic-Cenozoic sediments of the West Siberian Basin were deposited in a broad, shallow inland sea and have undergone only mild tectonic disturbance since deposition. The rocks are almost entirely clastic sediments (sandstones, siltstones, and shales) and were deposited in three major and several minor transgressive-regressive sedimentary cycles, each of which is separated by an unconformity of variable magnitude. The megacycles recognized are Triassic-Aptian, Aptian-Oligocene, and Oligocene-Quaternary. Predominantly continental sediments occur at the base of each megacycle, grading to largely marine or nearshore sediments at the top (Peterson and Clarke 1991, p. 25).

QUATERNARY HISTORY

Quaternary deposits are distributed throughout the entire West Siberian Basin (Nudner 1970). Marine and fluvial-glacial deposits consisting of silt, sand, and gravel are found in the north. The Ob'-Yenisey watershed also contains glacial-marine and marine deposits of sandy silt and silt with lenses of sands and inclusions of boulder-gravel materials. Quaternary deposits in the central and southern basin (south of the glaciated region) are silt and sand of lake-alluvial and eolian origin. These deposits are usually less than 50 m thick; in the Barabinskii and Kulundinskii steppes, thickness ranges from 100 to 150 m.

Except in the Ural Mountains, the late-stage Wisconsin-Weichselian ice sheets (Figure 5) did not extend beyond about 66°N (Denton and Hughes 1981, Figure 8-11; Late Zyryanka stage, Arkhipov 1984) to 64°N (Early Zyryanka stage, Arkhipov 1984). However, these ice sheets dammed the north-flowing Irtysh, Ob', and Yenisey rivers to form vast proglacial lakes (Denton and Hughes 1981; Astakhov 1987) that inundated most of the basin (Figure 5). Astakhov (1987) defined the predominant Pleistocene environments of the West Siberian Basin as a succession of 1) fluvial landscapes with peat bogs in interglacial epochs, 2) ice-dammed lakes during glacial advances, and 3) arid steppes accompanying deglaciation.

Widespread Quaternary lacustrine deposits have tended to further reduce the relatively low relief of the basin and set the stage for development of low-gradient Holocene drainages with low divides and abundant lakes and marshy/swampy areas. The major drainages reflect this history by exhibiting broadly meandering/anastomosing patterns with abundant bars and islands. Major terrace systems have been developed along these rivers (Feniksova 1977), reflecting the complex Quaternary history of ice damming and isostatic adjustment of both base levels and northern basin elevations.

HYDROLOGY

The surface hydrology of the West Siberian Basin is characterized by an extensive system of rivers, lakes, and marshes (Figure 6). Approximately 10% of the total land surface is covered by surface water in one form or another. The linear and subparallel courses of many of the large and small river valleys, as well as their sharp bends, are ascribed to control by geologic structures of the basement rock and the Mesozoic-Cenozoic sedimentary mantle of the West Siberian plate (Nudner 1970). Most of the rivers in West Siberia are fed by melting snow in the highlands on the west, east, and south, and flow north to the Arctic Ocean. In mountainous regions, the rivers have a comparatively short high-water period in the spring and a brief summer low-water period interrupted by flash floods. The lowest flow rate generally occurs in the winter. The high-water period shifts to the summer for rivers that originate farther north. Rivers of the forest and forest-tundra zones have a long spring high-water period and elevated levels and flows during the summer and fall. In the southern portion of the basin, rivers tend to freeze at the end of October and thaw in April and May; in the tundra, rivers freeze slightly earlier and thaw slightly later in the year. Ice remains on steppe rivers for about 155 days, on forest-steppe rivers for 160 days, and on northern rivers for 222 days out of the year. The average yearly flows of some of the larger rivers in Western Siberia are shown in Table 1.

The West Siberian lowland contains a large number of lakes (subsequent discussion follows Astakhov 1987). Areas of the largest lakes are up to 1,500 km^2; most of the lakes are much smaller, and few of the lakes are more than 10 m deep. The arctic belt, within the limits of continuous modern permafrost, contains innumerable small lakes and several large lakes, up to 20 to 27 km across. The larger lakes are the deepest in the West Siberian Basin—60 to 120 m deep—and their bottoms are often below sea level. The lakes are associated with arcuate ice-pushed ridges and probably represent glacially scoured hollows that were once filled with dead ice. South of the arctic belt, the numerous lakes of the taiga zone are located on the interfluves or in river valleys as oxbow lakes. These lakes differ markedly from the arctic lakes; taiga lakes are up to 17 km across, are extremely shallow (1 to 3 m deep), and occur preferentially in large clusters. Their origin is ascribed to excessive Holocene precipitation. Located farther south is a region described as the "world's greatest area of expanding peat bogs" (Astakhov 1987, p. 151). The peat mantle is up to 10 m thick, with innumerable buried sinkholes and blow-outs. Occasional lakes consist of excessive water stored in the spongy peat bodies. The existence of these deposits is probably the result of poor drainage over nearly impermeable loess-like silt and clay. Large lakes occur south of the peat deposits, contained within river-fed depressions overlying Tertiary clay deposits. The river-fed lakes are the largest in West Siberia, up to 90 km long. Many of the southern lakes are much smaller than the depressions they inhabit, and those in the extreme south are salty. This suggests that these lakes are relicts from an earlier, much wetter period. In the highlands rimming the basin, there are more than 1,500 small lakes associated with ancient and modern glaciation.

Marshes and swamps cover a significant portion of the West Siberian Basin land surface and form an important interface between surface water and ground water. In the northern half of the basin, marshes compose up to 6% of the total land area. Marshes represent the intersection of the water table with the ground surface. Contrary to the concept of marshes as large bodies of stagnant water, flow through marshes can be substantial. Depending on the climatic regime and the topography of the land surface, runoff from marshes varies from a few $L/s/km^2$ to > 100 $L/s/km^2$ of marsh (Ivanov 1953). Flow generally occurs in the same direction as the movement of ground water.

Ground water in the West Siberian Basin is contained in a single geologic structure (i.e., a single basin, Nudner 1970) but varies considerably in flow rates and degree of mineralization both vertically and laterally within the basin. As used here, the term ground water refers to water contained in both the unconfined aquifer (composed of Oligocene to Quaternary deposits) and confined aquifers and aquitards in Jurassic to Oligocene-age rocks. Approximately 8% (i.e., 288 km^3/yr) of the total precipitation that falls within the West Siberian Basin enters the unconfined aquifer and is returned to the rivers as baseflow. Because of changes in precipitation and evapotranspiration from north to south, the values of underground flow rates (in the unconfined aquifer) decrease from 2.5 to 3 $L/s/km^2$ in the region of the Ob' River inlet and Yenisey Ridge to 0.3 to 0.5 $L/s/km^2$ in Northern Kazahkstan and the Kulunda steppes (Kudelin, Zekster, and Popov 1970). Russian hydrologists believe that only a very small fraction of the total precipitation enters the deeper confined aquifer system (L'vovich et al. 1961). The confined and unconfined systems generally flow from the highlands on the west, south, and east northward to the Kara Sea (Nudner 1970). Ground-water mineralization patterns reflect both the general flow pattern and the fact that a significant portion of the precipitation recharges the unconfined aquifer. Hydrogeologic cross sections (Nudner 1970) indicate that freshwater wedges are present in both unconfined and confined aquifers (as well as in Paleozoic rocks) in the highland regions that rim the basin (Figure 7). Toward the center of the basin, fresh water persists in the unconfined aquifer, but water in the confined aquifer becomes highly mineralized (generally saline) with depth.

REGIONAL CONCEPTUAL MODEL AND HYPOTHESES

The West Siberian Basin has been described by Russian hydrogeologists as a single basin with a pervasive artesian character (Nudner 1970), suggesting that ground-water flow through post-Triassic sedimentary rocks is topographically driven. Recharge to the basin occurs in the highlands on the west, east, and south. Internal discharge is localized in numerous river valleys and lakes that ultimately discharge north to the Kara Sea and Arctic Ocean. In our conceptual flow model, the principal driving force of flow is supplied by the elevation of the water table across the region. Recharge to the water table, a function of regional water balance, provides the gradient that drives the flow mass balance.

We had originally envisioned that ground water moved through the West Siberian Basin in a series of five hydrostratigraphic aquifer/aquitard complexes comprising Jurassic and younger rocks and sediments (Foley et al. 1991; Figure 10). We anticipated that system recharge would initially infiltrate vertically into fractured Paleozoic rocks exposed in the recharge areas (highlands) until it came in contact with onlapping Mesozoic and Cenozoic sedimentary facies. This deep recharge would then redistribute itself laterally (Figure 8a) in response to the topographic gradient, favoring flow paths through more highly permeable strata (aquifers). We hypothesized that the most likely discharge scenario would include a widely distributed system of discrete discharge zones, possibly along fracture zones, in the central part of the basin south of the active permafrost area.

Our review of Russian hydrologic and hydrogeologic literature conducted during FY 1993 indicated that this conceptual model may not be entirely correct. Based on water balance studies, the Russians have concluded that most, if not all, recharge is restricted to the unconfined aquifer, with very little of the incoming precipitation partitioned into deep recharge (L'vovich et al. 1961; Kudelin et al. 1970). In the Russian view, any precipitation that infiltrates the ground surface in a highland valley essentially ends up alimenting rivers at lower elevations. Consequently, contaminants discharged to ground water may surface relatively rapidly in rivers and streams down gradient (Figure 8b). Independent support for this hypothesis is available from Russian hydrogeologic studies, which depict highly mineralized brine waters in deep confined aquifers in the center of the basin (Nudner 1970). Reports in Russian water resources publications, for example, *The Waters of Russia*, also indicate that ground water from deep wells is too highly mineralized for industrial or domestic use. Flow in confined aquifers that is topographically driven with meteoric precipitation should be fresh at depth, through the mechanisms of dilution and replacement (Deming and Nunn 1991). The fact that deep ground water in the West Siberian Basin is very highly mineralized suggests that it is stagnant or slow moving (Toth 1963; Freeze and Witherspoon 1967) and undiluted by fresh meteoric water, thereby indicating that most recharge is restricted to the unconfined aquifer.

An alternative hypothesis is that deep recharge occurs in highland areas, but is confined solely to fractured Paleozoic rocks. In this scenario, fresh water deeply infiltrates weathered Paleozoic rocks, and there is little or no interconnectivity with overlying and onlapping sedimentary complexes. Because the Paleozoic rocks extend for long distances outside the West Siberian Basin, water and associated contaminants are essentially lost to the basin system. Depending on flow properties within the Paleozoic rocks, contaminants in these recharge waters may be contained for geologically long periods of time. The evidence to support this hypothesis is largely negative. Deep recharge is notoriously difficult to measure in water balance studies, and as a water balance element, it is usually lumped with evapotranspiration as a leftover quantity. It is difficult to determine the amount of water (and associated contaminants) actually partitioned between recharge to the unconfined aquifer and deep recharge to confined aquifers and Paleozoic rocks.

To test these various ground-water flow hypotheses and consequent contaminant distribution scenarios, we are developing a mathematical model of topographically driven ground-water flow in the West Siberian Basin. This model allows us to describe the flow physics within the basin with an equivalent mathematical expression that can be evaluated using numerical techniques. To invoke a mathematical model requires that we characterize the three-dimensional geometry of the basin flow system, including topography as well as the lateral and vertical extent of different rock and sediment types. We must also characterize the spatial distribution of the specific rock hydrogeologic properties that control the flow of water, such as transmissivity, porosity, and specific storage of the rock units. The mass balance of water in and out of the system and the rate of fluid movement are also functions of the amount of 1) regional recharge to the ground water (i.e., the vertical flux of fluid into the system), and 2) the position of the regional water table, which provides the distribution of hydraulic heads driving the flow in the absence of temperature, pressure, or density gradients. Within confined aquifers, fluid pressure, temperature, and density gradients may become important flow drivers; these attributes must also be characterized. In conjunction with regional characterization, we must specify flow conditions around the regional boundaries and the proper equation of flow within the region. The regional characterization activities we completed during FY 1993 are described in the next section; boundary conditions, and the selection and implementation of the flow equation used to test our hypotheses are discussed in a subsequent numerical modeling section.

REGIONAL CHARACTERIZATION

Regional characterization activities performed to support mathematical modeling during FY 1993 included locating and processing topographic, geologic, hydrostratigraphic, hydrogeologic, and water balance data, and constructing a regional water table for the West Siberian Basin. The data were derived from a number of sources, including U.S. and Russian geologic and hydrologic literature and maps. Data processing activities included digitizing parameter value contours and geologic contacts from maps, back projection of map control points to determine the original map projection, forward projection into our West Siberian Plane Coordinate System, interpolation of digitized contour values to a regular grid (gridding), and quality control analysis of the resulting data sets. Constructing the regional water table required combining data from two primary sources, filtering the data using a specially developed relaxation method, and critically interpreting the results. All the data sets were gridded at spatial resolutions of either 500 m or 1,000 m. For use in the numerical model, data values were automatically extracted at the location of the nodes of the finite element grid and stored in a file format suitable for inclusion in the model.

GEOMETRY

To characterize the three-dimensional geometry of the basin flow system, we constructed a digital model of topography and created rock-facies data sets in a geographic information system (GIS). Digital topographic data were originally received from the Defense Mapping Agency in their Digital Terrain Elevation Data (DTED) format in 1° by 1° cells tied to geographic (latitude-longitude) coordinates, and thus required extensive processing before they could be used in the numerical model. Because the West Siberian Basin crosses more than 30° of latitude into the polar region, the original DTED data sets changed in angular resolution to maintain a resolution of approximately 100 m on the ground as the longitude lines converged at the North Pole. This change in resolution required that we merge three data sets representing three angular resolutions; the southern set covered an area from 45°N to 50°N latitude, the central set ranged from 50°N to 70°N latitude, and the northern set comprised the area from 70°N to 75°N latitude. In the interest of computational ease and computer storage requirements, the original elevation data at approximately 100-m resolution were resampled prior to merging by averaging five-by-five cells of data points to create three merged data sets (45° to 50°N, 50° to 70°N, and 70° to 75°N latitude; 59°E to 100°E longitude) with approximately 500-m resolution. As described below, these three data sets were merged into the final digital elevation model (DEM) for the West Siberian Basin (Figure 6).

The three-dimensional extent of Mesozoic (post-Triassic) and Cenozoic rocks and sediments in the West Siberian Basin was characterized from rock facies thickness maps presented in Peterson and Clarke (1991) and from ground-water maps produced by the Russian Ministry of Geology (Ministerstvo Geologii SSSR 1972). Subsurface rock types and thickness were determined primarily from oil, gas, and water well data. Rock thickness maps (isopachs) presented in Peterson and Clarke (1991) were modified from maps originally published in Russian sources. The isopachs from Peterson and Clarke (1991) comprised eleven chronostratigraphic layers ranging in age from the Lower Jurassic to the early Oligocene (about 208 MYBP to 30 MYBP). An isopach map depicting the total thickness of post-Triassic deposits was also presented. Late Oligocene to Holocene (Recent) rocks and sediments and the rimming and underlying Paleozoic rocks were characterized from Russian ground-water maps.

MAP DATA PREPARATION AND MANIPULATION

Processing and manipulating the data derived from numerous, diverse sources was an important part of our FY 1993 activities. Data such as rock facies and thickness contours were first digitized into the Geographic Resources Analysis Support System (GRASS) GIS. Data were digitized from several different map and report sources; the maps varied in scale from 1:1,000,000 to 1:20,000,000 and contained linear, polygonal, and contour information. After digitizing, the data were spatially rectified so that properties associated with an area on the earth's surface were correctly represented in our digitized versions. Rectification was complicated by several factors, most notably the lack of information concerning the type of projection of the original map. In addition, data sources other than atlases were often lacking registration control points, such as a longitude-latitude grid.

To overcome these difficulties, we digitized the map data in an arbitrary rectilinear grid system (inches on the map page) and digitized any discernible control points (e.g., towns, river confluences) for which longitude and latitude could be determined. We used these control points to determine the best projection equation for each map for translating the rectilinear coordinates to longitude-latitude coordinates (back projection). The control points and their corresponding longitude-latitude coordinates were back projected for each map with a PNL-developed code that used projection algorithms presented in Snyder (1987). A "best guess" projection type and projection parameters were entered by the analyst, and the two sets of X-Y coordinates (i.e., those digitized from the map and their projected longitude-latitude coordinates) were compared using a least squares fit. Iteratively incrementing the projection parameters and comparing the relative root mean square errors allowed optimization of the fit within the projection. For maps from Peterson and Clarke (1991), the root mean square error between the two sets of coordinates was 15 km. For the Russian ground-water maps, the root mean square error was 9 km. Using the best projection parameters and scale factors for the control points, we "unprojected" the digitized data into a longitude-latitude coordinate system. The accuracy of the best-fit projection determined in this manner was verified by separately digitizing the rivers visible on each original map, unprojecting their coordinates into the longitude-latitude coordinate system, and comparing them to digitized rivers (Figure 9).

After verifying accuracy of the "best-fit" projection for each map, we "reprojected" all map data (including digitized topography) into our West Siberian Plane Coordinate System (forward projection). Projection into a plane coordinate system was necessary because our ground-water model required cartesian rather than latitude-longitude coordinates. We centered a Lambert Conformal Conic map projection on the West Siberian Basin for model data, providing a plane coordinate system with less than 2% distortion at the extreme limits of the model.

After projection into our plane coordinate system, data that had been originally contoured were gridded to create a continuous distribution of the contoured property across the study area. The gridding algorithm we used was included in the commercial geologic analysis software package, PV-WAVE. The gridded data were then automatically contoured, and the results were compared to the original contoured data source to ensure the data were not distorted during the gridding process. Gridding the data allowed us to extract properties, such as rock layer thickness, at any point in the West Siberian Basin. Most data were gridded at 1,000-m resolution.

HYDROGEOLOGY

From the raw, digitized map data, we derived our hydrostratigraphic interpretation (i.e., the sequence of aquifers and aquitards) from the Russian hydrogeologic interpretation presented in Nudner (1970) and the Russian ground-water maps (Ministerstvo Geologii SSSR 1972). Nudner's (1970) cross sections (Figure 10) define the hydrogeologic character of the post-Triassic deposits as a five-layer system with four confined layers. We found good correlation between confining layers depicted in Nudner (1970) and fine-grained marine shales and clays in Peterson and Clarke's (1991) isopachs. Accordingly, we collapsed the eleven layers from Peterson and Clarke (1991) into Nudner's hydrostratigraphic layers two through five. The uppermost or unconfined aquifer, as well as the rimming and underlying Paleozoic layer, were derived from the Russian ground-water surface geology maps. Because thickness information was unavailable for the uppermost layer, we approximated its thickness by subtracting the total thickness of the four hydrostratigraphic layers from the total thickness of post-Triassic deposits. The thickness of the basement layer (Triassic and older rocks) was set arbitrarily at 1,000 m; we expect to add successive 1,000-m layers of basement rocks if our model produces substantial flow in this layer. Structure contour maps depicting the actual elevation of the top of each unit for the resulting six layers were created by subtracting subsequent thicknesses from the digital topography.

Hydrostratigraphic interpretation was used to assign characteristic hydrogeologic parameters to the aquifer-aquitard system and to build the hydrogeologic geometry of the West Siberian Basin. For our initial model simulations, book value hydraulic conductivities (Freeze and Cherry 1979) were assigned to the different rock and sediment types (facies) as they occurred in the maps from Peterson and Clarke (1991) and the Russian Ministry (1972). These hydraulic conductivity facies were then joined with the gridded isopachs to produce transmissivity layers (transmissivity is the layer's hydraulic conductivity multiplied by its thickness). The transmissivity layers created in this fashion were combined to produce the six-layer aquifer-aquitard system presented in Nudner (1970). The hydrogeologic feasibility of creating aquifer-aquitard geometries, which are essentially lithostratigraphic properties, from chronostratigraphic facies isopachs is still being assessed.

WATER BALANCE

Characterization of the regional water balance of the West Siberian Basin was necessary to estimate the fraction of the total regional precipitation recharging the ground water, thus providing the vertical flux of water into the system. Regional water balance data were derived almost exclusively from the Russian hydrological literature and Russian atlases. Russian hydrologists have a long history of gauging and mapping the distributions of precipitation, total runoff, the surface and baseflow components of total runoff, evapotranspiration, and soil moisture, not only for Russian territories, but for world land surfaces as well. In general, distributions are for yearly, and, in some cases, monthly averages of these hydrologic parameters. Despite the diversity of sources for these data (see Appendix), the distributions appear very similar, probably because the personnel involved in development have been relatively constant.

During FY 1993 we processed all available water balance data to allow ourselves a certain amount of flexibility in partitioning that percentage of the total annual precipitation contributing to recharge in the West Siberian Basin. Original maps exhibiting the distributions of precipitation, runoff, evapotranspiration, and soil moisture content were created under the Russian paradigm of the annual moisture balance. Manuscripts published during the 1960s and early 1970s (L'vovich et al. 1961) presented the water balance as

$$P = U + S + N + T \quad (1)$$

where P = total precipitation, U = underground runoff (i.e., baseflow), S = surface runoff, N = evaporation, and T = transpiration. Under these conditions, the total soil moisture (W), defined as the volume of water absorbed by the soil in a year, is given as

$$W = P - S, \text{ or} \quad (2)$$

$$W = N + T + U \quad (3)$$

Note that in these equations there is no mention of recharge to ground water. The Russians assume that most of the renewable ground-water reserves are discharged into streams as baseflow. Below the drainage horizon, according to L'vovich et al. (1961), there is a very small volume of renewable ground-water reserves. This view is reflected in the Russian idea of vertical zonality in ground-water movement expressed by Noratov and Popov (1961). They recognize three vertical zones of ground-water flow, including an upper zone of active flow (its lower boundary is the local base level of rivers), an intermediate zone of delayed flow (the lower boundary is the base level of large rivers), and a lower zone of relatively stagnant water lying below the base level of large streams (Figure 11a). Flow partitioning between the zones is dependent on relative surficial relief, with most flow in the intermediate and regional zones in areas of low relief (Figure 11b) and in the upper zone where relief is significant (Figure 11c). In a later manuscript, Kudelin, Zekster, and Popov (1970) recognize the existence of deep percolation into the lower zone (i.e., not drained by the hydrographic network), although they do not quantify its contribution to the overall moisture balance. Instead, deep percolation is lumped with evapotranspiration in water balance calculations and represents the unknown residual after measured surface runoff and baseflow have been subtracted from total measured precipitation.

WATER TABLE

A principal activity for FY 1993 regional characterization was to create a regional water table for the West Siberian Basin. In the absence of fluid pressure and temperature or density gradients, ground-water flow responds to a gradient in hydraulic head. The hydraulic head at any point on the water table is equal to the elevation of the water table at that point, indicating that elevation differences in the water table provide the head gradient for topographically driven flow. For steady-state flow, the flux of water delivered from the surface to the water table through the unsaturated zone is exactly equal to the ground-water discharge, and the water table maintains the same position throughout the year. The water table thus provides a convenient calibration target of hydraulic heads for topographically driven, steady-state flow of the type we are modeling for the West Siberian Basin.

The water-table configuration in the West Siberian Basin is relatively unknown. In topographically driven flow, the configuration depends on the hydraulic conductivities of the rock types present and on the amount of recharge available. However, exact relationships between hydraulic conductivities, recharge, and water-table configurations have not been developed. Additionally, our knowledge of hydraulic conductivities and rates of recharge for the West Siberian Basin is relatively poor. We have, therefore, resorted to more empirical means to estimate the position of the water table below the land surface. It has been noted that the water table in up-land regions rather closely follows the form of the topography. We also know that rivers, lakes, marshes, seeps, and springs represent the surface expression of the water table, except where surface water is perched over relatively impermeable, discontinuous strata. We have used these two observations to create a method for estimating the position of the water table within the West Siberian Basin.

Our method of deriving a continental-scale water table from topographic and surface-water data consisted of filtering the topographic data (i.e., "flattening" the topography) while holding the water table elevation fixed at known surface water elevations. The gridded, digital topographic data were filtered using a technique in which a square box with sides of a specified (odd) number of nodes was passed sequentially over each node in the data set. At each location, all the values within the box were averaged, and the average value was assigned to the node at the center of the box. The filter box was passed over the image a maximum of five times. Elevations at surface-water nodes, whose locations were extracted from the Digital Chart of the World database using the ARC/INFO GIS, were held fixed during passage of the box filter so that the resulting water table at a node could not rise above the surface elevation during elevation averaging. Away from these surface-water nodes, no calculated water table elevations were allowed to exceed topographic elevations. To force the water table below the land surface in regions of the basin where the topography is extremely flat, the initial topographic land surface file used for filtering consisted of elevations 1 m lower than their actual elevations, except where surface water was present. In these ways, we ensured that the derived water table was always below the land surface except in areas of surficial water.

Using a relaxation filter of arbitrary size without a set number of filter passes allowed us to generate a large number of hypothetical water table configurations for the West Siberian Basin. One filter/number-of-passes combination, for example, produced relatively realistic results over the low-relief portions of the basin, while flattening the highland regions excessively; other combinations had the opposite effect. A combination of filter sizes and iterations is necessary to filter the entire range of relief encountered in the West Siberian Basin; a large box filter passed many times over the data would probably work well on the low-relief portions of the basin, while a small filter with few iterations would be suitable for use in the highlands. To evaluate which water table configuration might best represent the West Siberian Basin, we compared the configurations of our derived water tables with known water table configurations from the Mayak site (Drozhko et al. 1993), the Tomsk area (Bradley 1992), and from a water table estimated for a mountainous region of similar geology and northern climate (Jamieson and Freeze 1983). These examples indicated that the water table should be no more than 2 to 6 m below the surface in low-relief areas, but could be as much as 800 m below the peaks in areas of high relief.

Because it is the sole driver for ground-water movement, our derived water table required further refinement before it was in a form suitable for use in calibrating the hydrogeologic model. These refinements were necessary primarily because the water table was derived from relatively noisy digital topographic data that, despite the smoothing that had been done, still contained a considerable amount of noise that particularly affected elevations of surface-water locations. Hydrologic flow equations are uncompromising; surface-water bodies must either be flat (lakes) or have monotonic elevation changes (streams and rivers). We revised surface-water elevations to reflect these requirements and to match elevations posted on the ONC charts wherever they were found. An additional significant problem with water-table river elevations was registration between ground-water model finite-element nodes intended to lie along rivers and the actual position of rivers in the water-table realization. If intended river nodes were not placed exactly on the rivers in the digital water-table (an extremely difficult task), their elevations were not necessarily those of the river but rather elevations of streambanks or terraces or some other nearby fluvial landform. As a result, river node elevations did not always change monotonically in elevation even after we forced the river elevations in the water table to do so. Finally, the 500-m resolution of the water table was much less than that of the ground-water model finite element grid (about 5,000 m), which made extraction of meaningful water-table elevations at finite element nodes difficult and complicated direct comparisons of water-table elevation distributions with hydraulic head distributions calculated for the much coarser finite-element grid.

We resolved these problems with additional smoothing, subsampling, and artificial widening of the rivers within the water table. Smoothing was accomplished by passing a box filter ranging in size from 3-by-3 to 11-by-11 over the water table elevations. At each point, the box filter would average the elevations contained within the box and apply that elevation to the center node. Subsampling was then performed without averaging by selecting every tenth or so node to achieve the desired resolution. The problems of nonmonotonically changing river elevations in the water table and in the finite element grid were solved by forced interpolation and by widening the rivers so they were easier to hit with the finite element nodes. For each major river segment, known elevations were determined from the ONC maps where the river crossed a topographic contour. Elevations for subsequent reaches were interpolated between these segments and overwritten onto the water-table elevation file. Rivers were widened by adjusting the width on either side of the river to which these elevations were applied. The resulting water-table elevation file was overwritten several times to reset the widened river elevations subsequent to resmoothing in case smoothing increased elevatio s in the vicinity of the rivers. Resulting water-table elevations were contoured and compared; the water table shown in Figure 12 appeared the most consistent with our assumptions of likely behavior and modeling needs and was selected for use in calibrating the hydrogeologic model.

SUMMARY

During FY 1993 we assembled and processed a substantial amount of regional geologic, hydrologic, and hydrogeologic characterization data from the West Siberian Basin. We acquired topographic, geologic, hydrostratigraphic, hydrogeologic (i.e., hydraulic conductivity and transmissivity), and water balance data, and have generated a regional water table. From original sources, the data have been digitized, back projected into a longitude/latitude coordinate system, forward projected into a Lambert Conformal Conic projection, and gridded to 1,000-m resolution.

For use in the numerical model, values for these parameters are only needed at the nodes of the finite element grid that was constructed for the West Siberian Basin during FY 1992 (Foley et al. 1993). The grid contains 2,759 elements defined by 2,799 nodes. Distance between the nodes is on the order of 3,000 to 5,000 m. Values for the hydrostratigraphic unit surface elevation, the unit thickness, the transmissivity, the ground-water recharge, and the elevation of the water table and/or the unit piezometric value are automatically extracted at the locations of the finite element nodes and are stored in a form that can be read directly into the numerical model input file. To ensure that significant data are neither lost nor distorted during the transfer from higher to lower resolution, subsequent to extraction each parameter is contoured using the ARC/INFO GIS, and the results are compared with the original maps.

REGIONAL NUMERICAL MODELING

Numerical modeling of the regional flow of ground water through the West Siberian Basin comprises five basic tasks that replace the physical problem with an equivalent mathematical problem. The first task is to select the proper equation for describing ground-water flow within the basin. Different partial differential equations are available depending on whether flow is steady-state or transient, whether sources or sinks for ground water are present within the flow region, whether the flow field is saturated or unsaturated, and whether or not contaminants are being transported. All equations are derived by combining Darcy's law for flow through porous media with an expression for continuity (i.e., mass balance). The second task is to specify the boundary and initial conditions that constrain the results generated through application of the flow equation. Boundary conditions may consist of prescribed hydraulic heads (Dirichlet conditions), prescribed fluxes (Neumann conditions), or mixed (Fourier) conditions. The third task is the identification and use of appropriate numerical techniques to solve the flow equation. A plethora of numerical techniques exists, many based on linearization of the partial differential equations used to describe the flow. In the fourth task, model results are calibrated to known or inferred conditions through modification of model input parameters. Finally, the calibrated model is used to test hypotheses of flow travel paths and travel times through the basin.

MATHEMATICAL MODEL

We are modeling regional ground-water flow through the West Siberian Basin as three-dimensional, steady-state, saturated flow that is recharged from above. The expression that describes this type of flow is the Poisson equation

$$\nabla(K\nabla h) = q \qquad (4)$$

which states that the divergence (∇) of the hydraulic head gradient (∇h) multiplied by the hydraulic conductivity (K) is equal to the recharge per unit area of the aquifer (q). Use of the Poisson equation requires that boundary conditions be specified over a closed boundary. This requirement is met in the generalized boundary condition

$$-K(\nabla h \cdot n) = \alpha(h-H) + \beta(Q) \qquad (5)$$

where n is the unit normal to the boundary, H is the prescribed hydraulic head on the boundary, Q is the prescribed flux on the boundary, and α and β describe the type of boundary condition. As $\alpha \rightarrow +\infty$, the boundary condition becomes a Dirichlet condition. If $\alpha = 0$, the boundary condition is a Neumann condition; otherwise, the generalized boundary condition is mixed.

For the West Siberian Basin, we have specified that the horizontal basin boundary and the arbitrary base of our system are no-flow boundaries, indicating that water cannot leave or enter our basin across these boundaries. Prescribed flux (Neumann) boundary conditions are represented by vertical recharge to the basin flow system; recharge rates are variable but continuous over the entire West Siberian Basin. Rivers, lakes, and the Kara Sea represent constant hydraulic head (Dirichlet) boundary conditions, a result of the assumption that surface-water and ground-water divides coincide in the basin. For nodes that fall within areas of surficial water, values of hydraulic head are held constant at the ground-surface elevation.

NUMERICAL MODEL

We are using the Coupled Fluid, Energy, and Solute Transport (CFEST) computer model (Gupta et al. 1987) to provide the appropriate numerical techniques to solve the flow equation. The CFEST code solves partial differential equations for fluid pressure, temperature, and solute concentration for multilayered, confined hydrologic systems using the finite element method. The algorithm used to solve the system of partial differential equations is based on linearization of the coupled equations. Linearization of the Poisson equation (note that for the FY 1993 numerical modeling effort we are neglecting the temperature and solute-concentration equations) involves rewriting the equation as an operator that is integrated over the region of interest. Integration over the entire region is replaced with a summation of integrations over the elements themselves in a process known as discretization, which results in a matrix equation

$$K h = f \tag{6}$$

In this matrix, K is an n x n global conductance matrix, which contains information on the hydraulic conductivity and the shape of the aquifer(s) being modeled, h is an n x 1 hydraulic head solution vector, and f is an n x 1 vector containing the specified fluxes at Neumann nodes, where n represents the total number of nodes in the finite-element grid. Before solving the system of equations represented by the matrix for hydraulic head values, the global matrix is modified by eliminating equations for those nodes where the hydraulic head is known (i.e., the Dirichlet nodes). This results in an asymmetric matrix requiring numerical modification of the remaining equations to remove those matrix columns corresponding to the rows where equations were deleted. The system of equations is then solved for hydraulic head values using nonstandard matrix solving techniques in which two matrices are generated, one that stores only non-zero coefficients and another that identifies the column associated with the non-zero coefficients. For constant time steps and steady-state flow, the equation solver uses a back substitution scheme to avoid unnecessary matrix decomposition steps.

CALIBRATION APPROACH

Calibration is the process of adjusting material properties and boundary conditions until the model is consistent with our understanding (or hypothesized conceptual models) of ground-water flow through the West Siberia Basin with respect to all available data, and computed values of hydraulic head closely match known head values for those locations. The distribution of hydraulic heads reflected by the water table is an appropriate calibration target for flow in the unconfined aquifer (hydrostratigraphic unit I, see Figure 10), where pressure is atmospheric, but flow in confined aquifers contains a fluid pressure component, and the resulting hydraulic heads are composed of both pressure and elevation heads. The level to which water in a confined layer rises, measured with a piezometer, indicates the value of the hydraulic head at that point. Hydraulic head data contoured from measurements by a number of piezometers in a single confined layer reflect the hydraulic gradient for that layer, and thus can be used to indicate the direction of ground-water movement. Piezometric contours for hydrostratigraphic units III through V (Figure 9) in limited areas of the West Siberian Basin are available in Nudner (1970), and can be used as calibration targets for hydraulic head distributions our confined layers.

We calibrated the CFEST model of the West Siberian Basin in two stages, as a single-layer system and then as a multilayer system. We used a single-layer calibration approach at first because the limited data we had to match during calibration were insufficient to constrain hydrogeologic properties of all the layers. After achieving a water balance and matching the water table distribution by adjusting transmissivities of a single-layer model, we used relative transmissivities of the layers to divide the single-layer model into our five hydrostratigraphic complexes. Transmissivity distributions of confined layers III, IV, and V were then refined to match Nudner's (1970) piezometric contours.

FY 1993 MODELING RESULTS

Modeling Approach

Because the West Siberian Basin is such a large, complex system, we used a stepwise approach to calibrate the regional hydrogeologic model. First, we assumed a single-layer model (Figure 13a) with constant transmissivity and constant recharge. Once we achieved a good approximation of the system (based on comparison with the smoothed water table), we applied the variable recharge distribution. After calibrating the single-layer model, we redefined the model as a three-layer system (Figure 13b) assuming 1) Layer I (100 meters thick) represents surficial sediments in the center of the basin and basement rocks at the edges of the basin, 2) Layer II combines Nudner's (1970) hydrostratigraphic complexes II through V, and 3) Layer III (representing basement rocks) has a variable thickness that results in a uniform elevation of the base of the system at -10,000 m MSL. Multilayer model calibration completed in FY 1993 is based on this three-layer model; in FY 1994, we will divide Layer II into the four layers coinciding with Nudner's hydrostratigraphic complexes II through V (Figure 13c) to explore implications of our regional conceptual models.

Model Grid and Boundary Conditions

The regional hydrogeologic model is defined by the layering geometry, hydrologic properties, finite element grid, and assumed boundary conditions. The agreement between the head distribution needed to drive an assumed recharge distribution through the modeled system and the regional water table is the measure of the model's internal consistency. Figure 14 shows the finite element grid used to represent the West Siberian Basin. We assumed that the outer boundary and bottom of the model were no-flow boundaries. Although the West Siberian Basin consists of many smaller drainage basins, it is not possible to represent all rivers and streams in a regional scale model. Therefore, we selected the larger rivers as prescribed head boundary conditions for the model. The nodes representing these rivers are shown in Figure 15. Figure 16 shows the surface recharge zonation used in the model.

Single-Layer Simulations

For the first set of simulations, we assumed a unit thickness, single-layer model (Figure 13a) with a constant transmissivity (in a unit thickness case, the hydraulic conductivity is equal to the transmissivity) and a constant recharge. The results of the preliminary simulation (simulation 1) using average estimates for transmissivity and recharge are shown in Figure 17. The resulting water table elevations from this preliminary simulation are much higher than the smoothed water table representing our best estimate of true conditions (Figure 12). Modeling for Test Case 3 of the HYDROCOIN Project (OECD 1992) illustrated the interdependency of flux (recharge) and hydraulic conductivity. It was generally concluded in the HYDROCOIN Project that using only median values of parameter distributions may lead to an incorrect impression of the flow system. Therefore, we scaled model parameters to determine the recharge-to-transmissivity ratio that produced water table elevations closely resembling the smoothed water table. Figure 18 shows the results of the model run (simulation 2) that best approximated the smoothed water table.

Upon closer examination of Simulation 2 results, we discovered that not all the rivers had monotonic elevation changes along their lengths (see water table discussion above). After the water table was refined, we reran this simulation (simulation 3) with the corrected prescribed node values; results are shown in Figure 19. The changes in predicted water table elevations from the previous run are subtle; the most noticeable changes are in the northeast corner of the basin and in the northwest section. In the northeast portion of the basin, the effects of corrected river elevations can be seen in Figure 19 as crenulations in the contours representing river valleys (that can also be seen in the smoothed water table). The effects of the corrections are represented by the lack of mounding caused by erroneously high predicted river elevations in the northwest portion of the basin.

While predicted heads for simulation 3 matched the derived water table well, the constant recharge value used to obtain them was unrealistic. However, once the recharge-to-transmissivity ratio was established, both values could be multiplied by a constant without affecting the water table surface. Simulation 4 (Figure 20) verified that model results were the same after scaling both parameters so that the recharge used in the model run was equal to the total recharge to the basin calculated by integrating the data in Figure 16 over the basin area.

We used the scaled transmissivity value from simulation 4 with the recharge distribution shown in Figure 16 for the final single-layer model run (simulation 5). Results of simulation 5 with variable recharge (Figure 21) show closer agreement with the smoothed water table than previous simulations. This supports the HYDROCOIN conclusion that using median values does not necessarily represent the flow system.

MULTILAYER SIMULATIONS

In upgrading the model from a single-layer system to a multilayer system, it is important to preserve the transmissivity field to maintain the calibration. As discussed above, we assigned book values of hydraulic conductivity to each facies in the stratigraphic layers of the model. With the hydraulic conductivity and thickness known, a transmissivity can be calculated for each facies. We summed these book-value transmissivities for the confined layers of the model (units II through V plus the basement rocks) and subtracted their aggregate transmissivity from the total transmissivity for each model element determined in the single-layer calibration. The difference was assumed to be the transmissivity of layer 1, the layer for which facies information is most uncertain. The resulting model is heterogeneous, but preserves the transmissivity distribution of the calibrated single-layer model. Figures 22 through 25 show the potentiometric surface for each layer resulting from model simulations.

DISCUSSION AND RECOMMENDATIONS

Our long-term goal for this research is to quantify contaminant migration and potential health effects of injected contaminants in western Siberia. Because of the unique character of the West Siberian Basin, the world's largest area of low relief and single ground-water basin, we must quantify the regional hydrogeology of western Siberia to provide the boundary conditions for determining the hydrogeology and contaminant migration at defense sites, as well as long-term contaminant migration pathways. We must also quantify the local hydrogeology of the selected injection sites and evaluate potential contaminant release scenarios and migration pathways into the regional hydrogeologic system. To meet this long-term goal, our FY 1993 objectives were to 1) develop the detailed, spatially registered digital geologic and hydrologic databases that identify and implement the hydrogeologic conceptual models of the regional hydrogeology of western Siberia, 2) calibrate the computer implementation of these conceptual models, 3) develop general geologic and hydrologic information relevant to the more detailed models of injection-site hydrogeology, and 4) develop preliminary hydrogeologic conceptual models for the selected injection sites.

PROGRESS ON FY 1993 OBJECTIVES

Our regional characterization activities included locating and processing topographic, geologic, hydrostratigraphic, hydrogeologic, and water balance data, and constructing a regional water table for the West Siberian Basin. The data were derived from a number of sources, including U.S. and Russian geologic and hydrologic literature and maps. Data processing activities included digitizing parameter value contours and geologic contacts from maps, back projecting map control points to determine the original map projection, forward projecting into our West Siberian Plane Coordinate System, interpolating digitized contour values to a regular grid (gridding), and performing quality control analysis of the resulting data sets. Constructing the regional water table required combining data from two primary sources, filtering the data using a specially developed relaxation method, and critically interpreting the results. All the data sets were gridded at spatial resolutions of either 500 m or 1,000 m. For use in the numerical model, data values were automatically extracted at the location of the nodes of the finite element grid and stored in a file format suitable for inclusion in the model.

We calibrated the finite element ground-water model of the West Siberian Basin as a single-layer system and then as a multilayer system. We used a single-layer calibration approach at first because the limited data we had to match during calibration were insufficient to constrain hydrogeologic properties of all the layers. After achieving a water balance and matching the water table distribution by adjusting transmissivities of a single-layer model, we used relative transmissivities of the layers to divide the single-layer model into our five hydrostratigraphic complexes. Transmissivity distributions of confined layers 3, 4, and 5 were then refined to match Nudner's (1970) piezometric contours.

PRELIMINARY EVALUATION OF REGIONAL HYDROGEOLOGIC CONCEPTUAL MODEL

We developed the regional numerical model during FY 1993 to quantify and test three hypotheses concerning the nature of ground-water flow through the West Siberian Basin. The first hypothesis, based on the Russian understanding of the regional water balance for the area, is that almost all basin recharge is contained in the unconfined aquifer and is eventually discharged to streams. Our second hypothesis is that the layered Mesozoic-Cenozoic basin stratigraphy may contain buried aquifers with higher hydraulic conductivities than the unconfined system. The effects of such aquifers are to intensify the downward flow through the upper layers, and provide a highway for flow that bypasses the upper system. In our third hypothesis, water that percolates into the Paleozoic rocks rimming the West Siberian Basin may have no connectivity with the layered Mesozoic-Cenozoic rocks in the basin proper, and water and associated contaminants may never cycle through the aquifer/aquitard system.

Testing these hypotheses requires that we postulate the conditions that must be implemented in the numerical model (either as boundary conditions or hydrogeologic parameters) to ensure that the specific travel paths are followed, and then to evaluate the reasonableness of the conditions in light of what we know about basin properties. Whether recharge to the basin remains in an unconfined system and is eventually entirely discharged to streams, or whether it is forced downward into more permeable strata that bypasses the upper layers, largely results from the water table configuration and the nature of the geologic heterogeneities. In topographically driven flow, where the water table configuration mimics the topography, highlands serve as recharge areas and lowlands represent discharge areas. In geologically homogeneous media where local relief is pronounced, ground-water flow is dominated by a series of local flow systems having recharge areas at topographic highs and discharge areas at topographic lows located adjacent to one another (see Figure 11c). Travel paths under these conditions may be extremely short. In homogeneous media with negligible relief, the ground-water flow system is generally regional; its recharge area occupies the regional divide, and its discharge area lies at the bottom of the basin (see Figure 11b). Anticipated travel paths and travel times under these conditions are somewhat longer than for local systems.

These patterns are complicated where geologic media are heterogeneous, such as in layered rocks or sediments. The nature of the potential flow field is controlled by the ratios of permeability between the different layers. In aquifer/aquitard systems with large contrasts in permeability, flow patterns are approximately rectilinear, with horizontal flow through the aquifers and vertical flow across aquitards (Freeze and Witherspoon 1967). The conditions causing confinement of a ground-water flow system to the upper layer, with recharge serving as river baseflow (i.e., the Russian paradigm), could include both topographically high- and low-relief areas, but require that low permeability contrasts exist between the hydrostratigraphic complexes. The lack of high permeability contrasts would force the system to operate as one defined by topographically driven flow under relatively homogeneous conditions. To force recharge more deeply into the layered aquifer/aquitard system would require greater permeability contrasts between the layers, with more permeable strata present at depth.

Permeability contrasts may also be expected to govern the nature of the connection between Paleozoic and Mesozoic-Cenozoic ground-water flow systems. Note that testing this scenario represents an attempt to evaluate the assumptions behind the Russian practice of injecting radioactive waste deep into Paleozoic rocks. Waste travel paths and travel times depend on vertical and horizontal hydraulic conductivity ratios within the basement rocks, as well as on permeability contrasts between fractured crystalline rocks and adjacent layered sedimentary units. Higher permeability conduits in the layered rocks may serve to pipe the waste directly into the Mesozoic-

Cenozoic ground-water flow system. The lack of such contrasts, coupled with anisotropy in the fractured crystalline rocks, may induce flow paths that are not intrinsically obvious, although they follow topographically induced gradients to some extent (see Freeze and Witherspoon 1967, Figure 6).

Evaluation of each hypothesis necessarily includes an assessment of whether postulated permeability contrasts are within the levels of uncertainty for our data. Initially, hydraulic conductivities and permeabilities for the hydrostratigraphic layers were assigned using book values available in Freeze and Cherry (1979; p. 29). Within each rock type category, both hydraulic conductivity and permeability values range over three to four orders of magnitude, generating large uncertainties in the absolute values of these parameters for rocks in the West Siberian Basin. In FY 1994, we anticipate running numerical model simulations that will indicate the sensitivity of model results to small changes in these parameters. A model that is relatively insensitive to small variations in conductivity and permeability will be more useful for evaluating whether postulated permeability contrasts are realistic, given the four orders of magnitude of uncertainty.

IMPLICATIONS FOR WORK IN FY 1994

Initial calibrations indicate that interactions between surface water and ground water are more critical to the modeled water balance than we initially thought. While local data (Drozhko et al. 1993) suggest our recharge values digitized from Russian atlases are correct, we find that only a small fraction of that water will flow through the basin rocks with our assumed book value hydraulic conductivities. This suggests that much of the recharge in the high country surrounding the West Siberian Basin is lost to the ground-water system through baseflow to streams relatively close to the recharge point. While using the regional hydrogeologic computer model to explore our competing conceptual models in FY 1994, it will be important to properly account for recharge partitioning between the upper and intermediate/regional flow systems while adjusting model parameters to achieve a water balance. For this reason, it may be necessary to model the surface-water/unconfined aquifer zone (upper flow system) separately from the intermediate and lower zones. In this way, adjustments of hydraulic conductivities *within* the models (evaluation of rock properties) can be kept separate from transfer of recharge *between* the models (evaluation of relative importance of upper, intermediate, and regional flow systems). In this context, we will also evaluate the potential impact of permafrost on near-surface hydrology in the northern part of the model area.

The probable need for a separate model of surface-water/ground-water interactions for the regional model of the West Siberian Basin highlights the very large scale of the problem and the necessity of modeling at a much lower resolution than that of our data or understanding of the physical processes. In part, our difficulties probably arise from a scale effect situation in which most recharge to the ground-water system within one of the large finite elements of our regional model moves as baseflow to surface water within the same element and exits that element as surface water (which is not accounted for in our *ground-water* model). We must thus account for this amount of surface water separately, possibly in a separate model. We expect that a similar approach will probably be necessary for the local models, which are still large-scale models that cannot feasibly include enough topographic and hydrologic detail to properly model surface-water/ground-water interactions. This suggests that our regional model will always be somewhat unconstrained; a unique set of model parameters providing, for example, recharge and hydraulic conductivity distributions explaining a given water table, will not be found during model calibration. Rather, our different conceptual models will yield different sets of consistent distributions of model parameters that must be evaluated by comparison with actual data. Our FY 1994 task for the regional hydrogeologic model will be to quantify our conceptual models and find the comparison points at which differing model predictions may be tested against field data to determine the most valid conceptual model.

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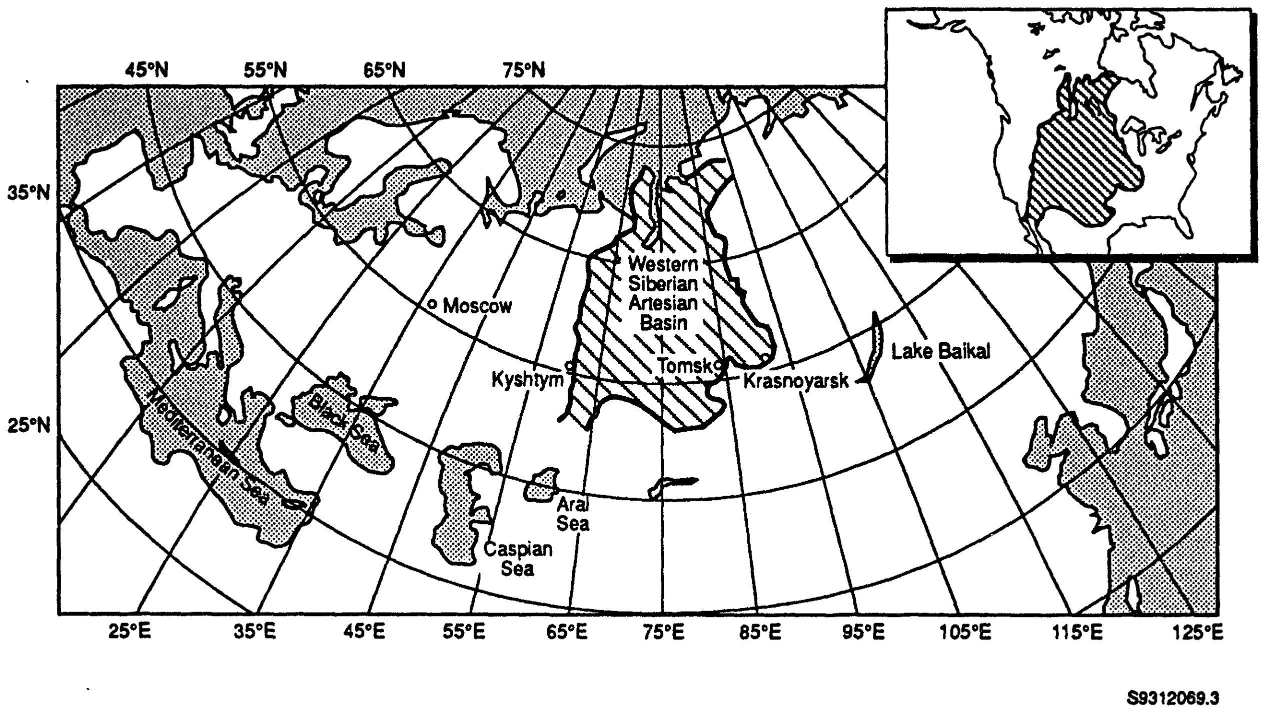

FIGURE 1. Index Map Showing Location of West Siberian Basin and Its Size Relative to North America (inset)

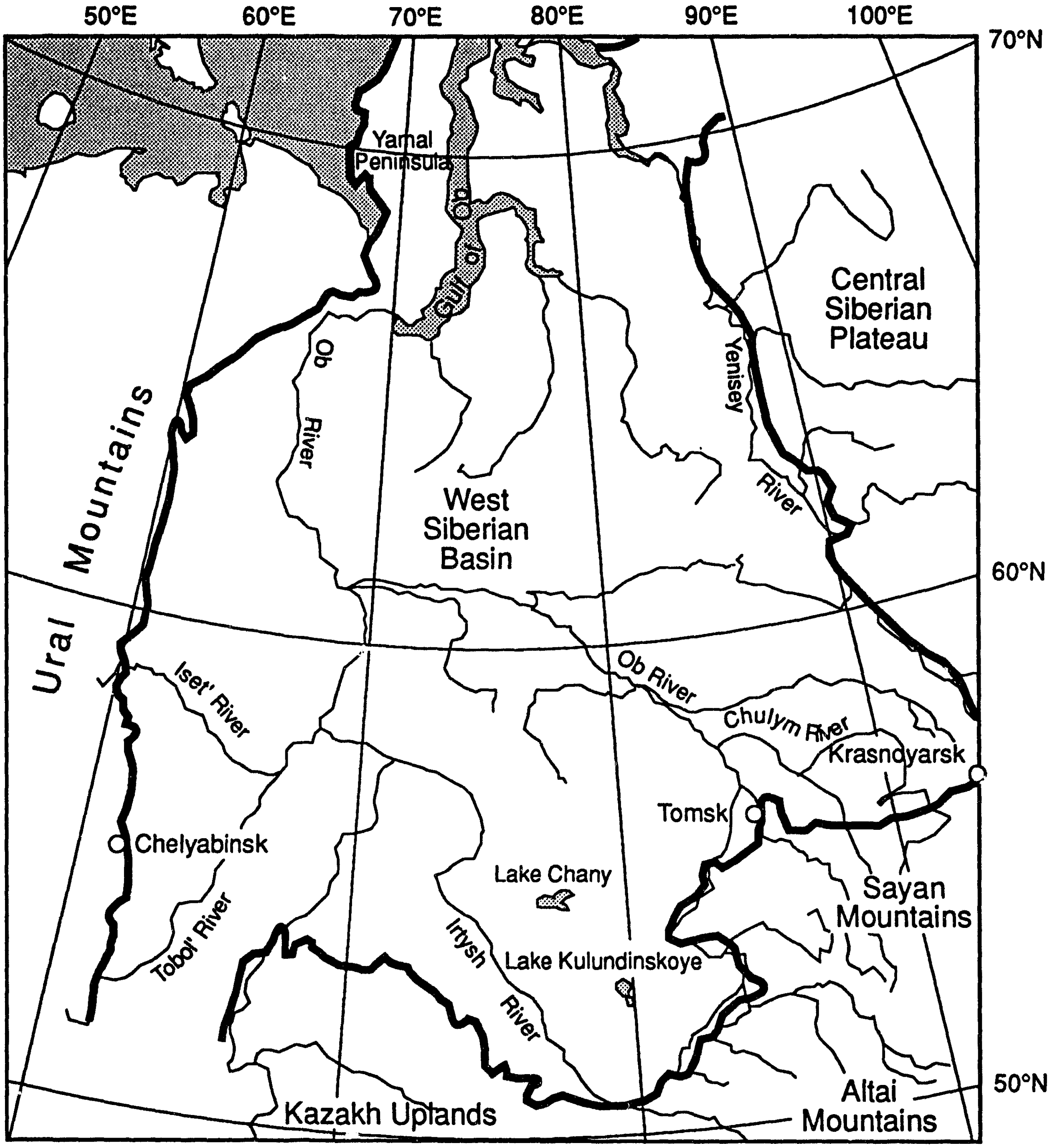

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FIGURE 2. Index Map of West Siberian Basin (after Nudner 1970)

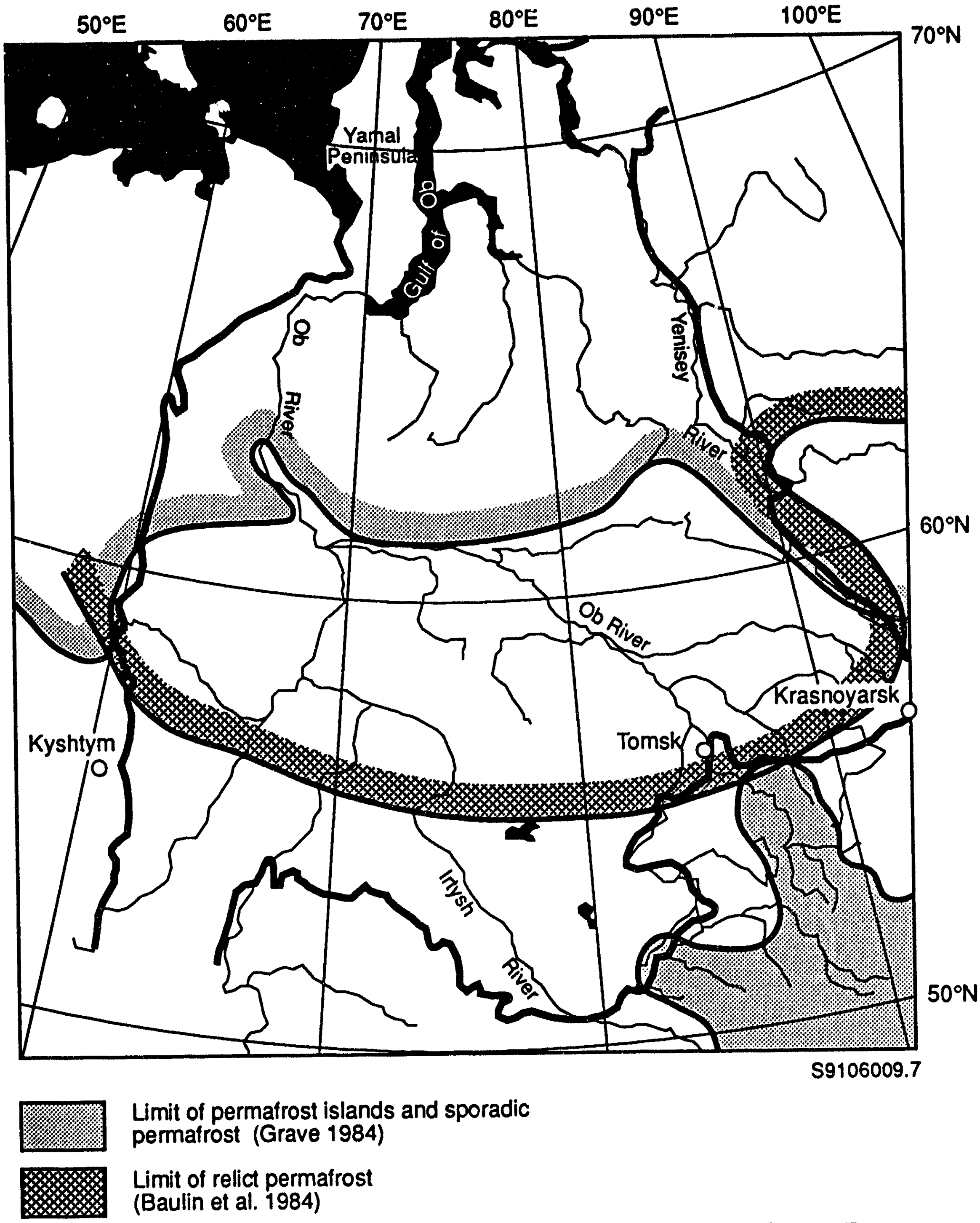


FIGURE 3. Modern and Relict Permafrost Limits of the West Siberian Basin

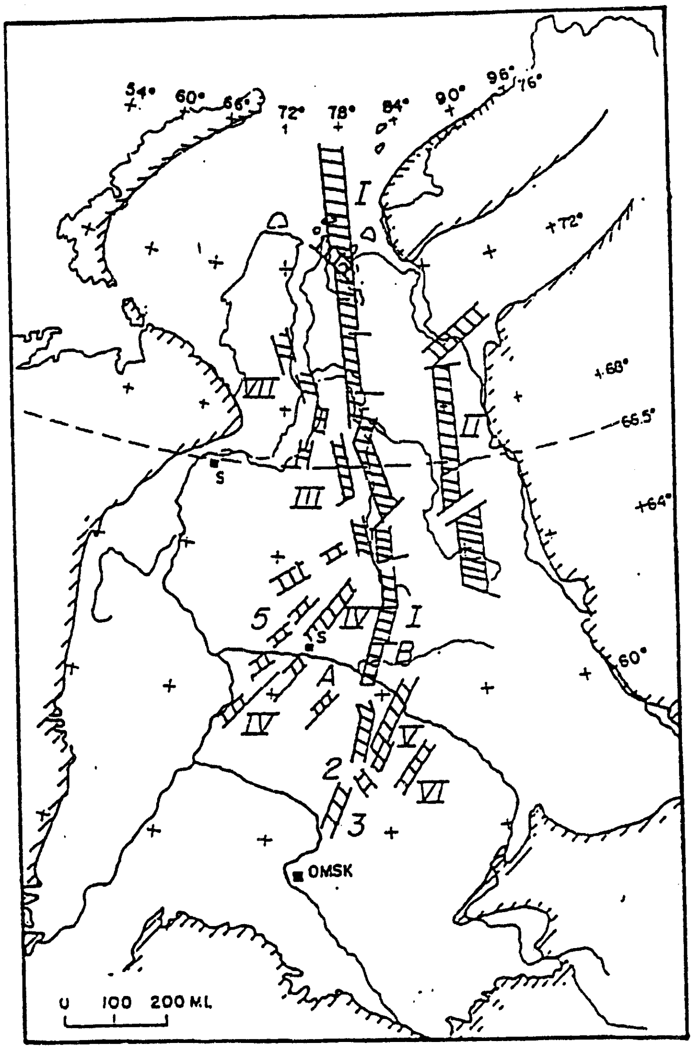


FIGURE 4. Triassic Rift Systems of Basement Rocks of the West Siberian Basin (Peterson and Clarke 1991)

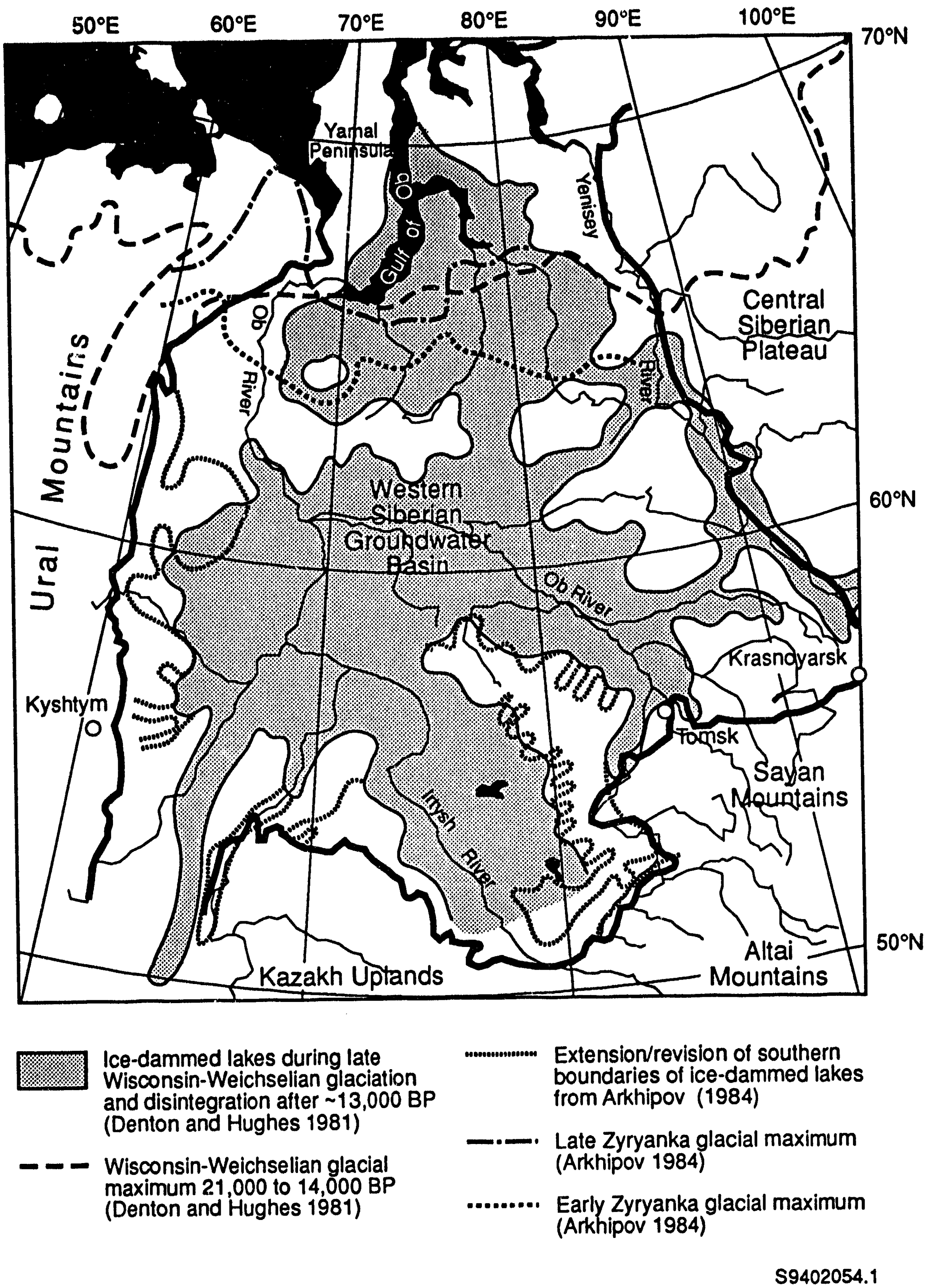


FIGURE 5. Late Pleistocene Glacial Limits and Pro-Glacial Lakes of the West Siberian Basin

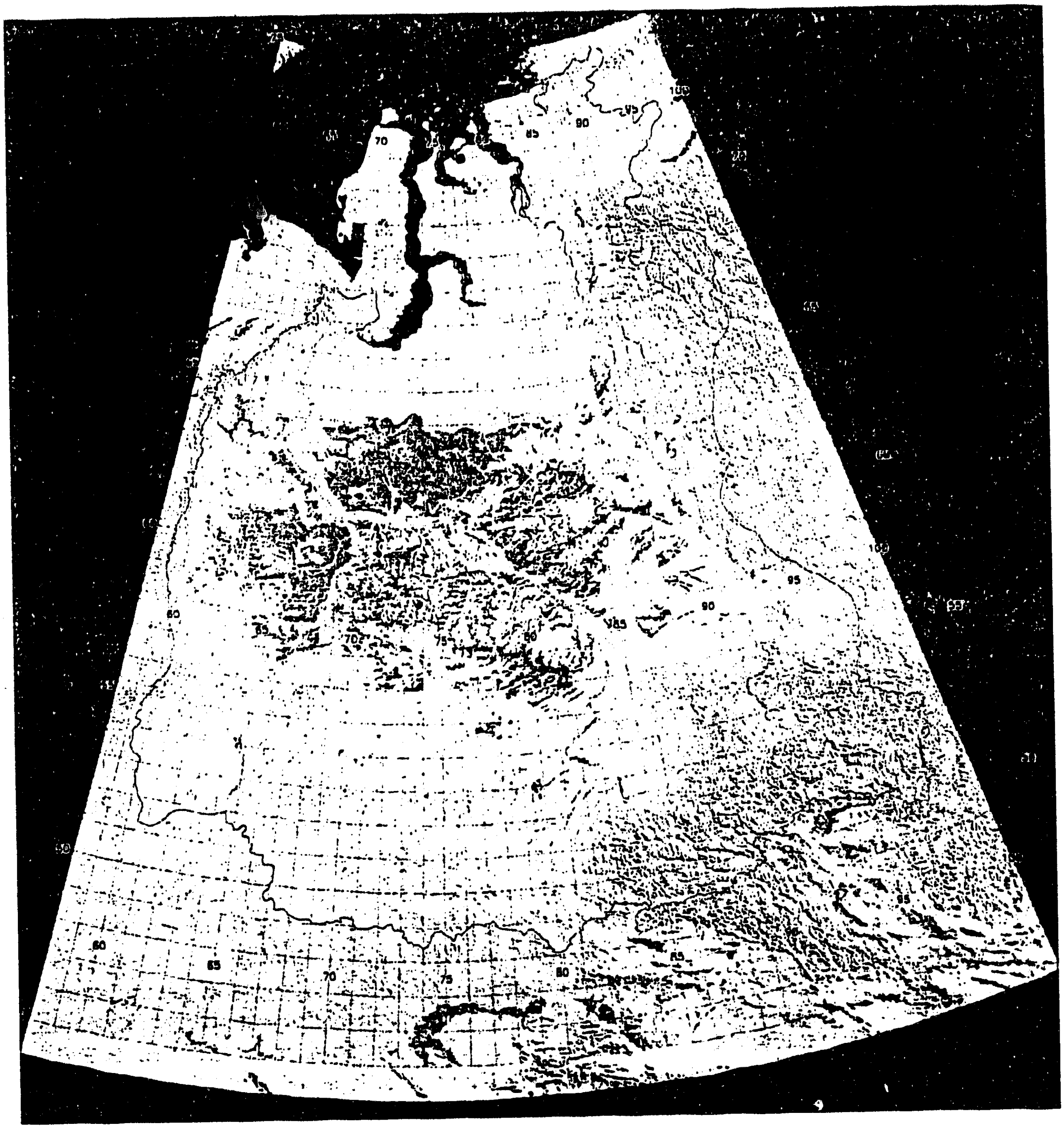


FIGURE 6. Surface Water of the West Siberian Basin. Shown on a shaded-relief image of topography are rivers and lakes (blue), swamps (green), and the regional model boundary (red). Surface water from the Digital Chart of the World, ArcInfo Format (1993).

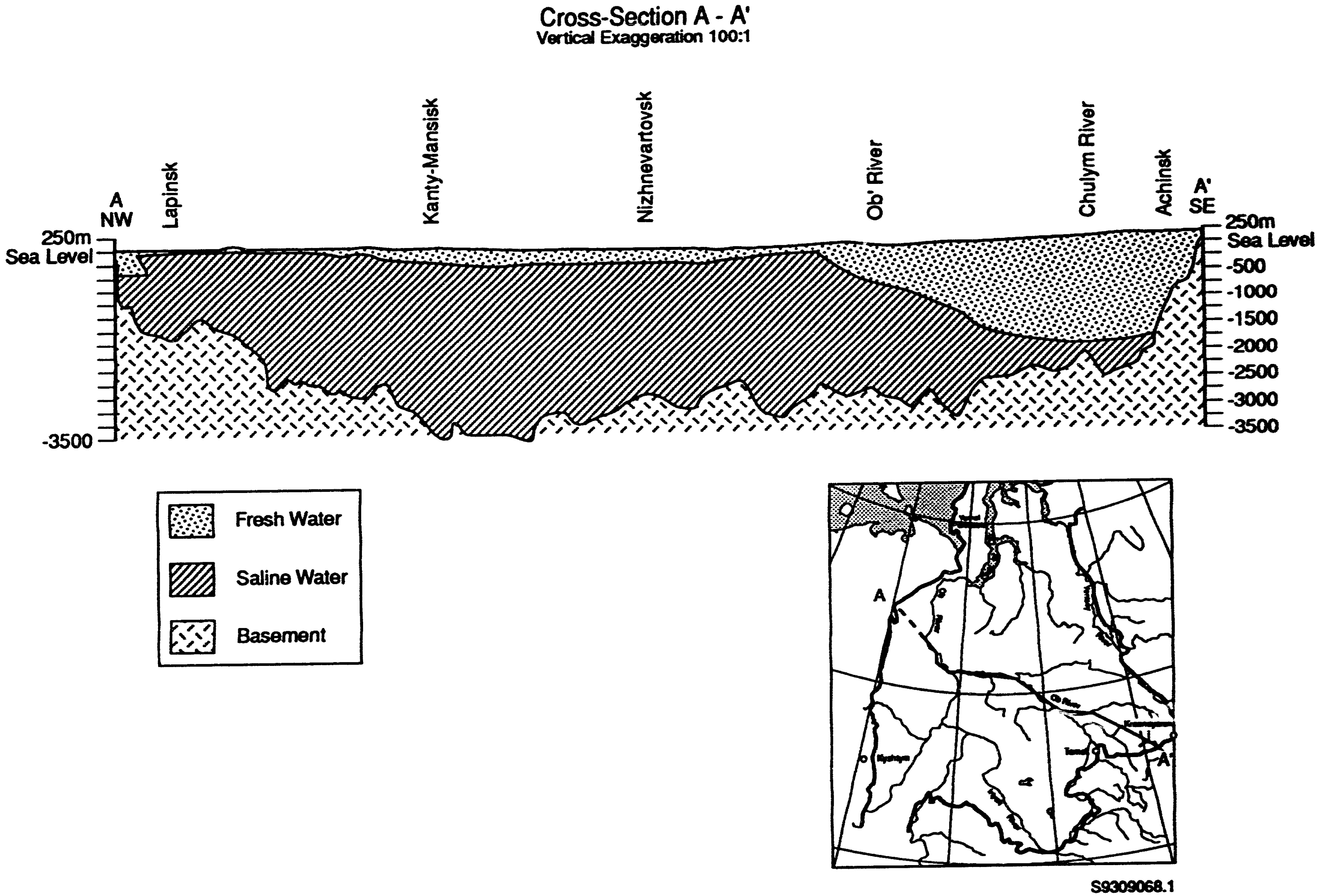
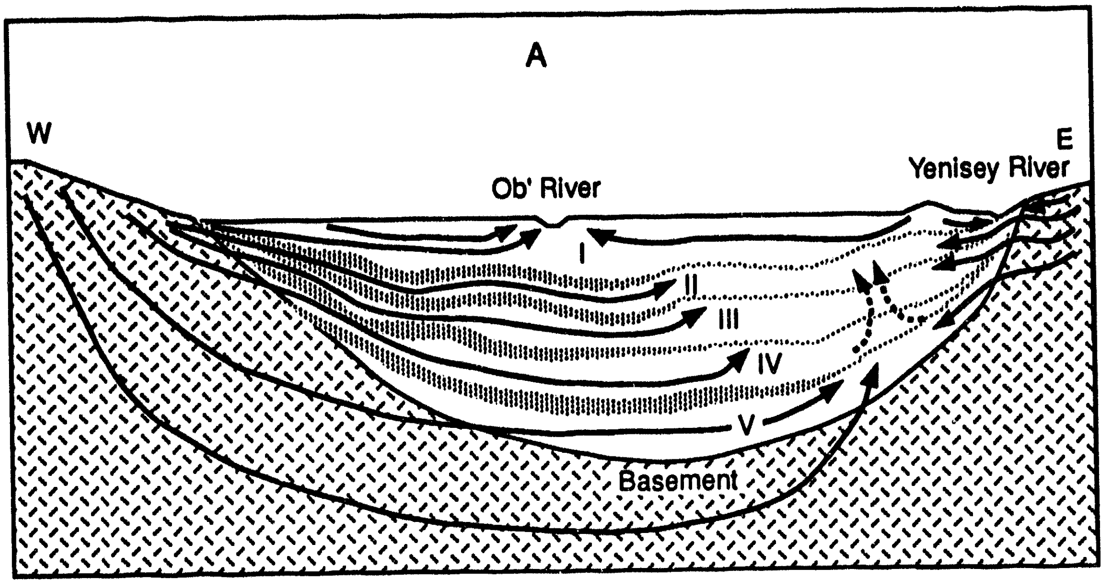


FIGURE 7. Hydrogeologic Cross Section Across the West Siberian Basin Showing Freshwater Wedges and Saline Ground Waters (after Nudner 1970)



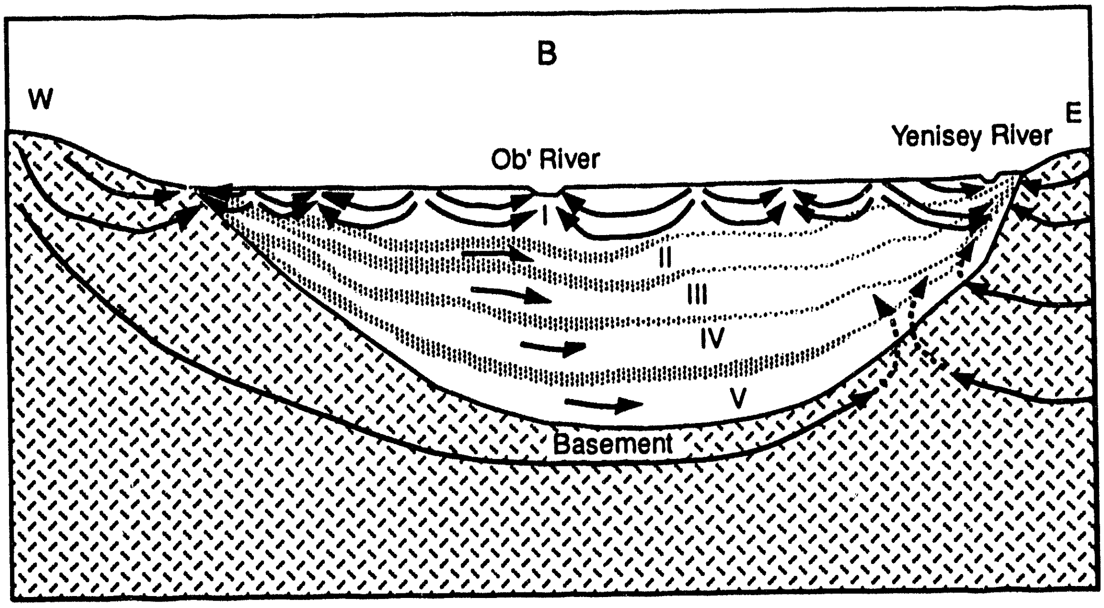


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FIGURE 8. Competing Conceptual Models for Interactions Between Local and Regional Ground-Water Flows in the West Siberian Basin. a) Substantial deep recharge results in significant flow in deep aquifers. b) A small fraction of precipitation to deep recharge results in small quantity, low velocity, heavily mineralized flows in deep aquifers, with little interchange with surface waters.

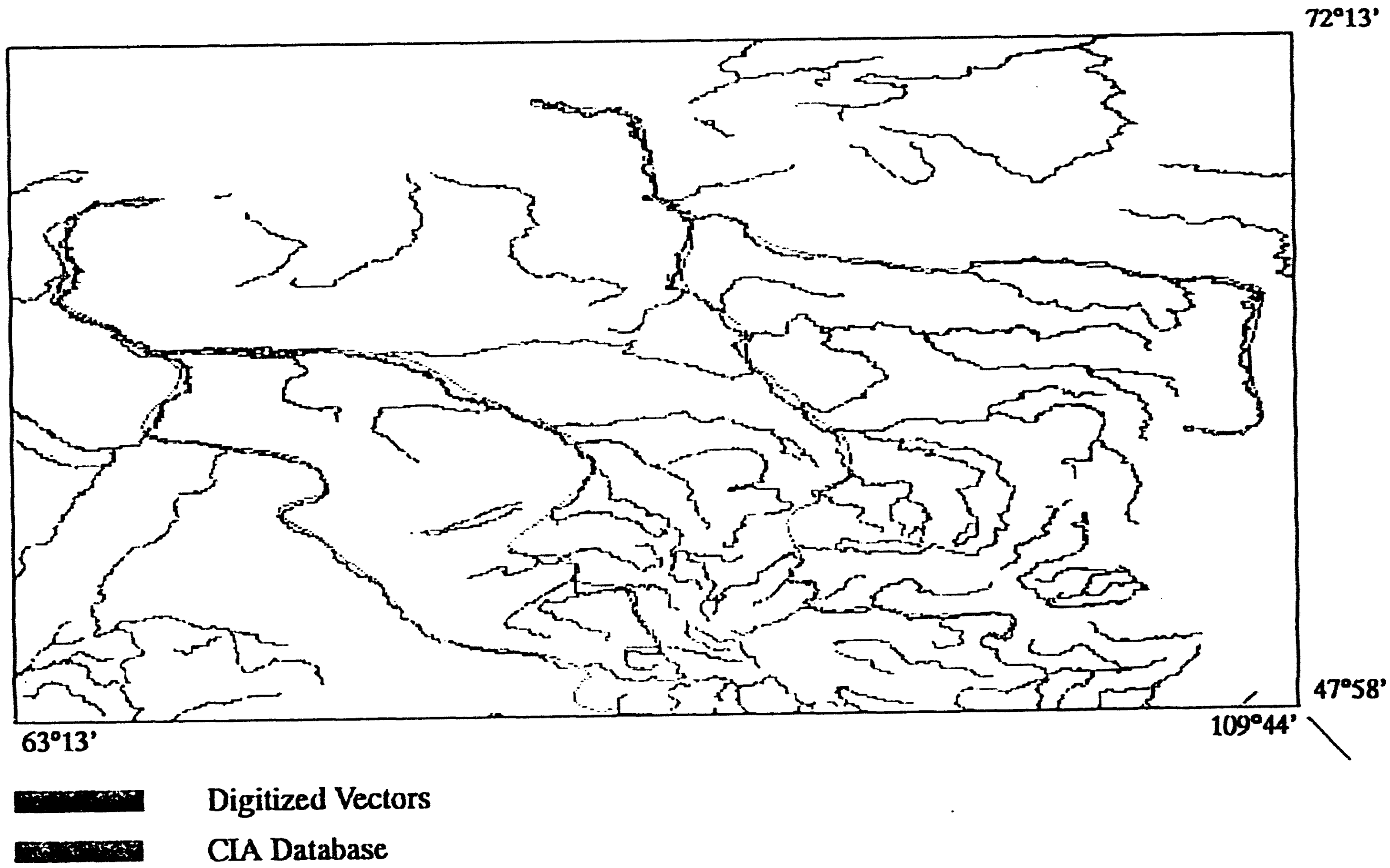

FIGURE 9. Quality Control Check of "Best Fit" Map Projection Comparing Back Projected Rivers with Rivers from CIA World-Wide River Database

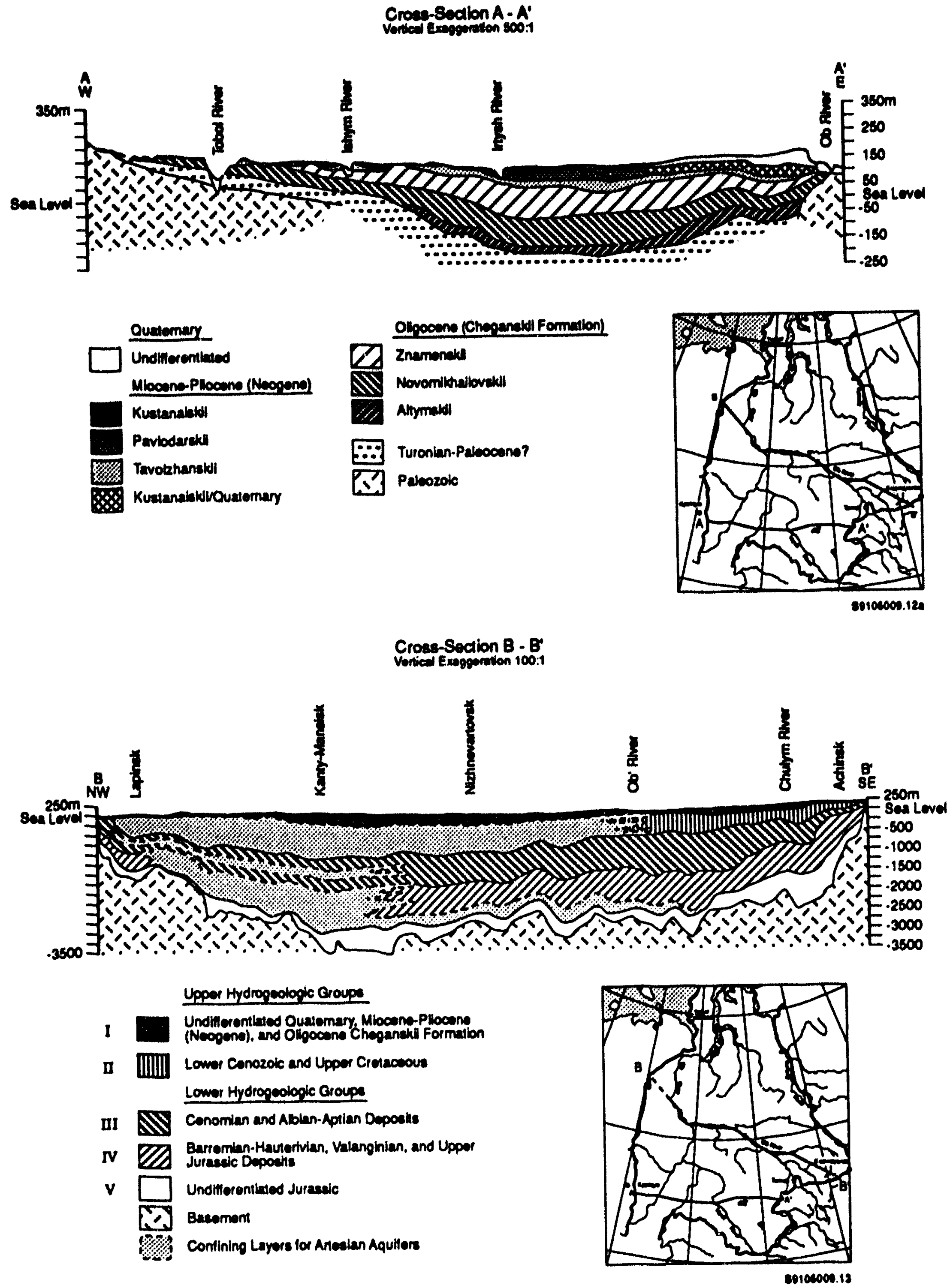

FIGURE 10. Cross Sections of the Hydrostratigraphic Units of the West Siberian Basin (after Nudner 1970). Cross-section A-A′ is at the latitude of the three sites of interest; cross-section B-B′ crosses the basin through the deepest part of the multilayered, confined aquifer part of the basin

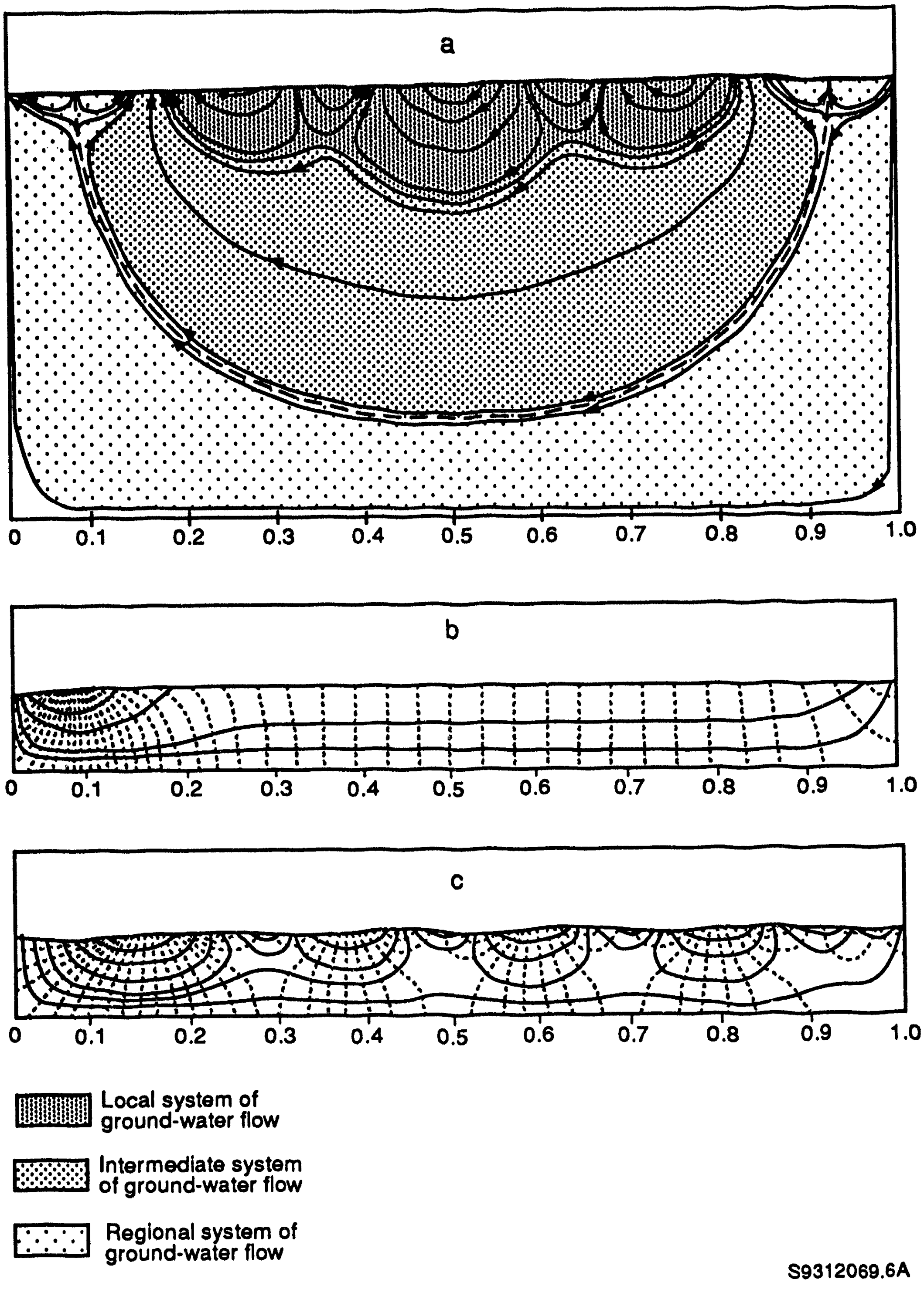

FIGURE 11. Relative Partitioning of Recharge into Local and Regional Flows. a) Coexisting shallow, intermediate, and deep systems showing small fraction of recharge going to regional flow system, b) substantial regional flow in homogeneous aquifer with little surface relief, and c) more common generation of shallow, local flow systems in homogeneous aquifer with surface relief (after Toth 1963; Freeze and Witherspoon 1967).

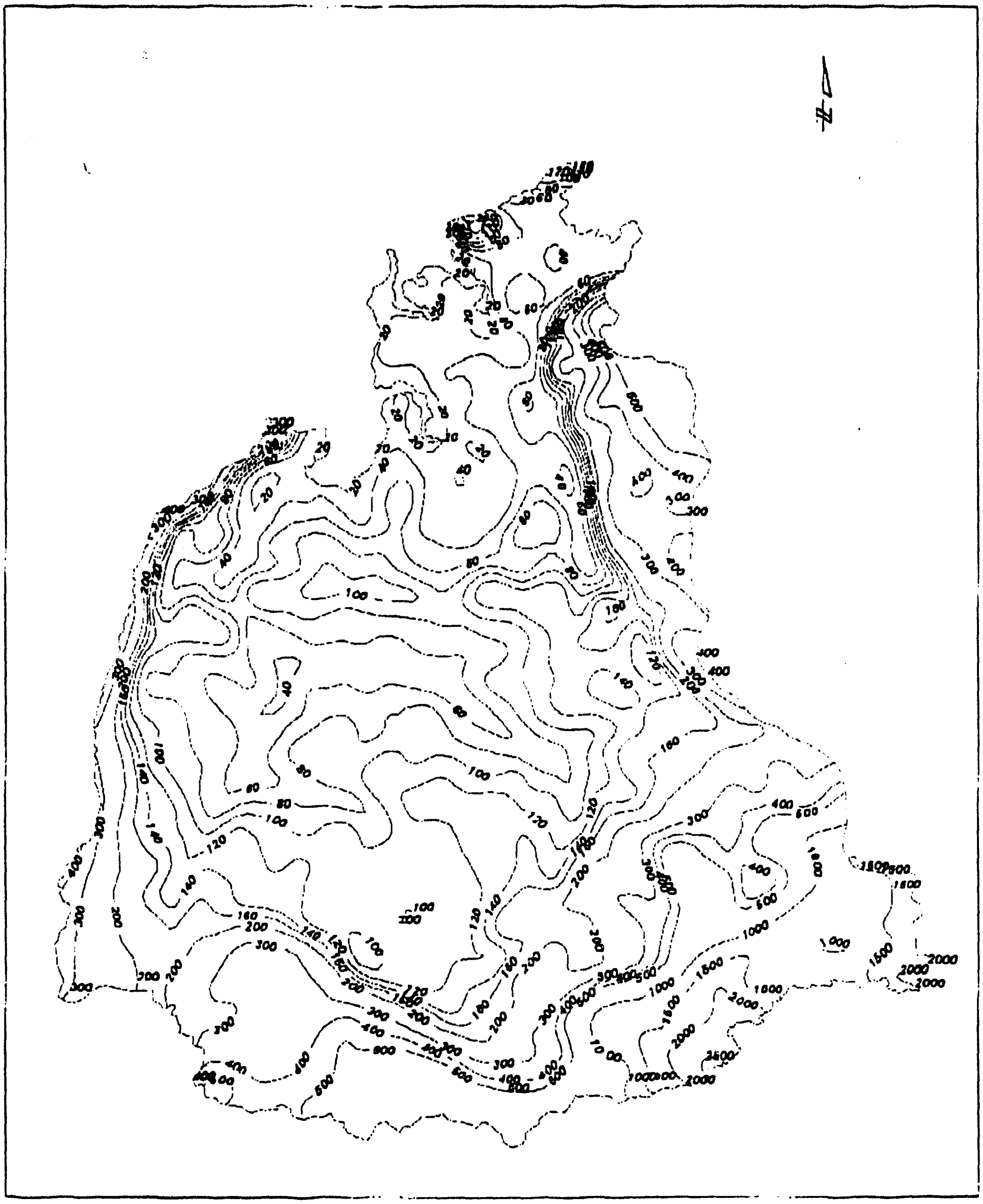

FIGURE 12. Final Derived Water Table for the West Siberian Basin Hydrogeologic Model

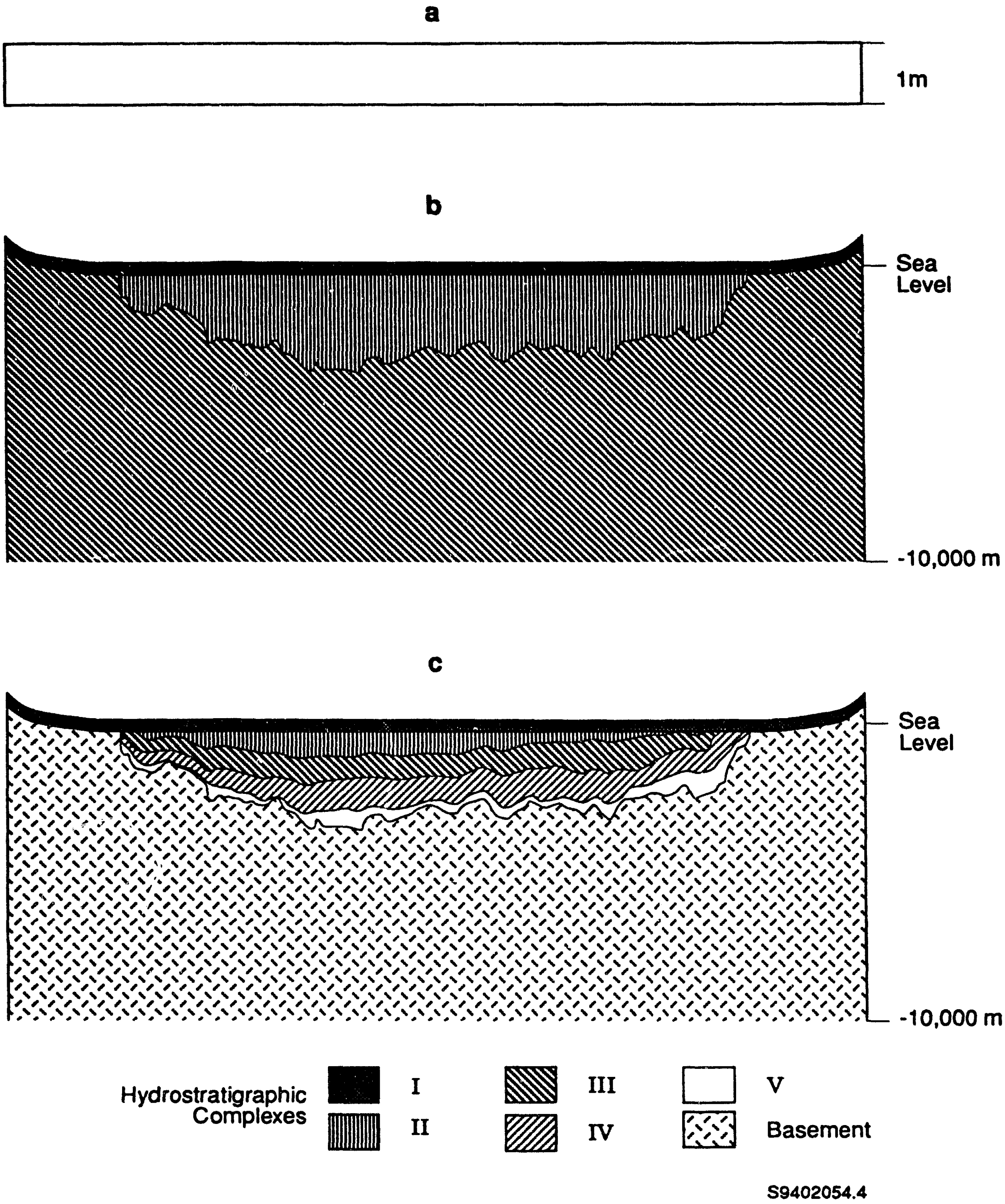

FIGURE 13. Conceptual-Model Cross Sections for Calibration of the West Siberian Basin Regional Hydrogeologic Model. Shown are a) uniform thickness and uniform transmissivity single-layer model, b) three-layer model, and c) full multilayer model representing Nudner's (1970) conceptual model.

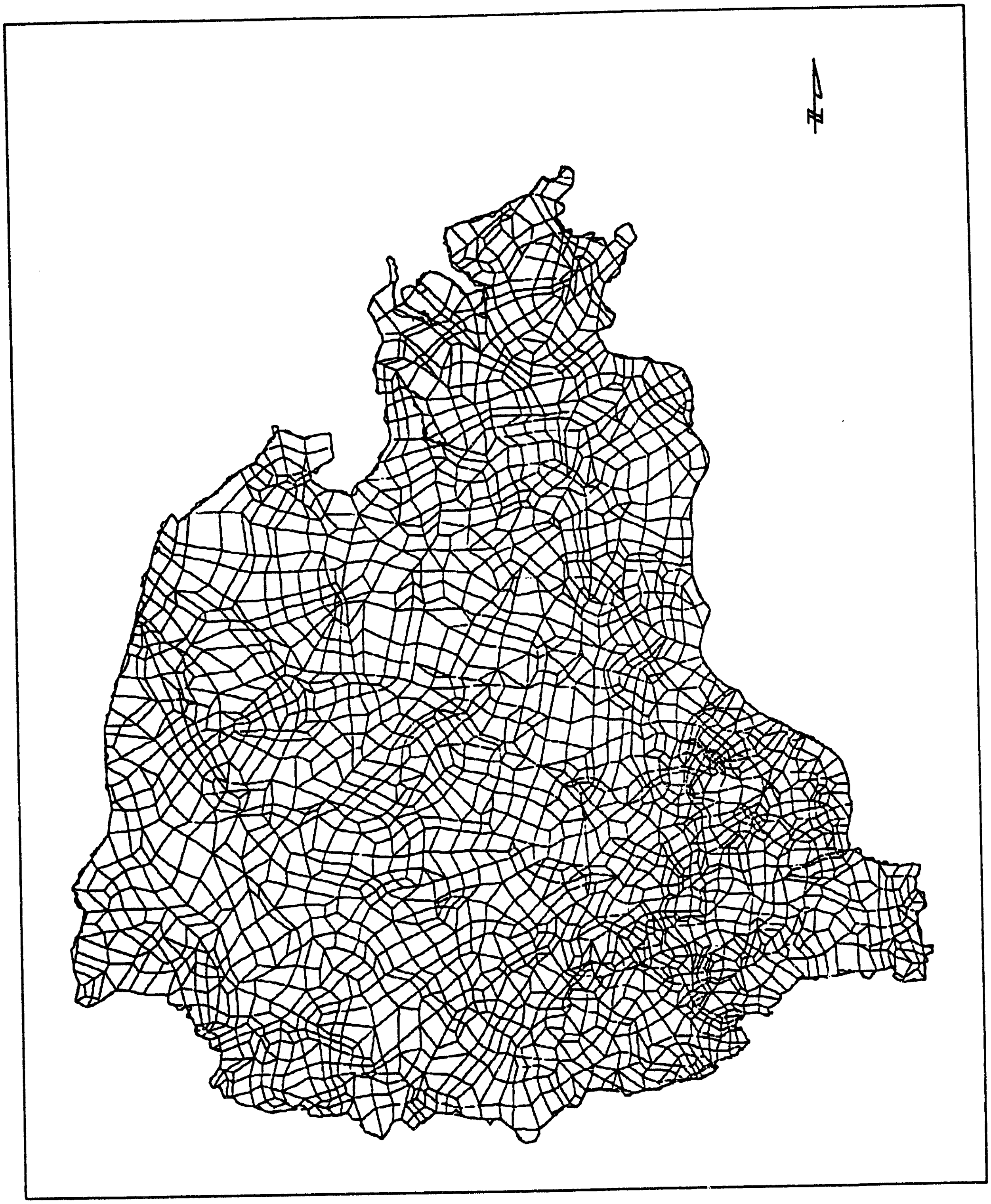

FIGURE 14. CFEST Finite Element Grid for the West Siberian Basin Regional Model

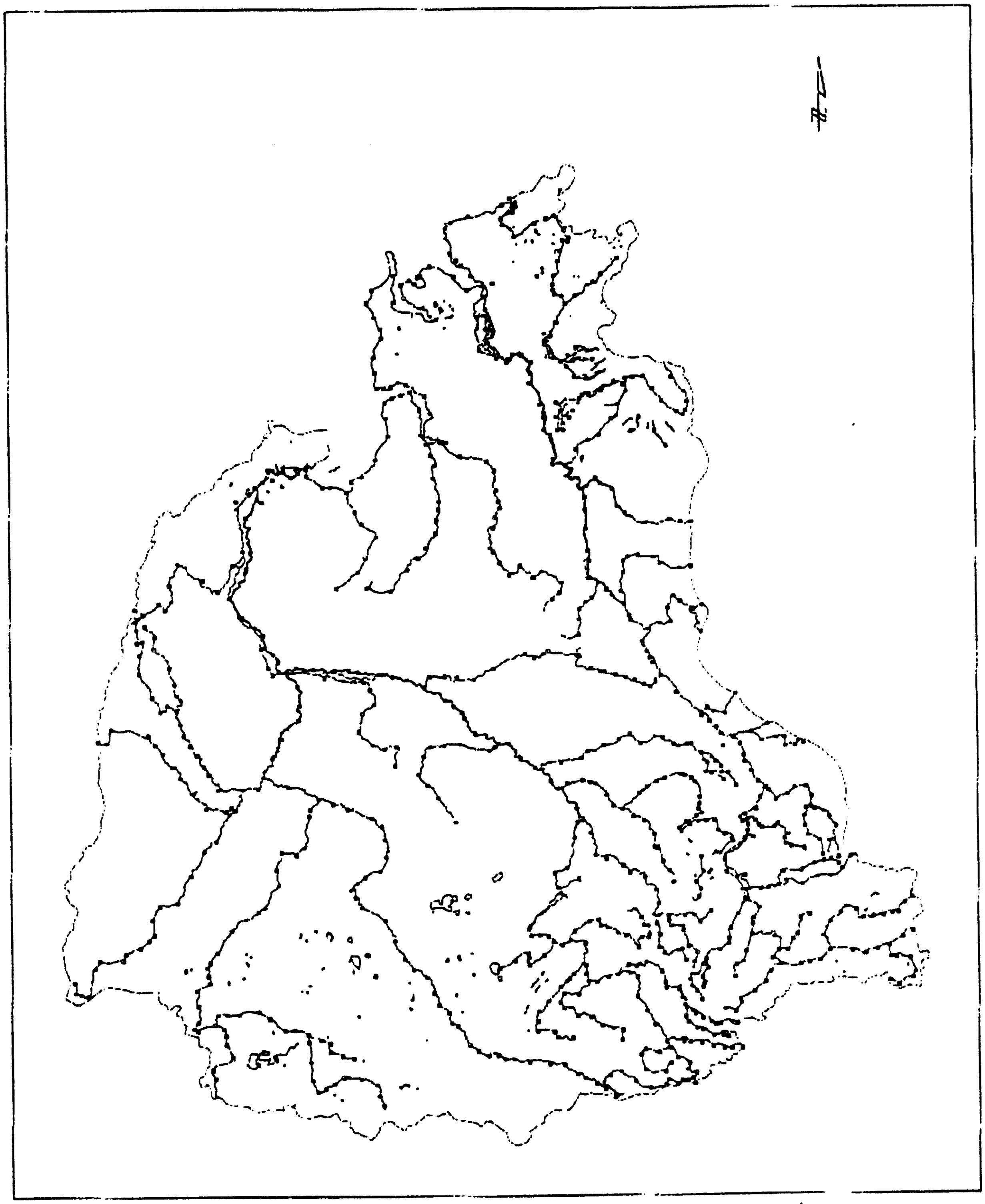

FIGURE 15. River Nodes in the Finite Element Grid for the West Siberian Basin Regional Hydrogeologic Model Used to Define Prescribed-Head Boundary Conditions

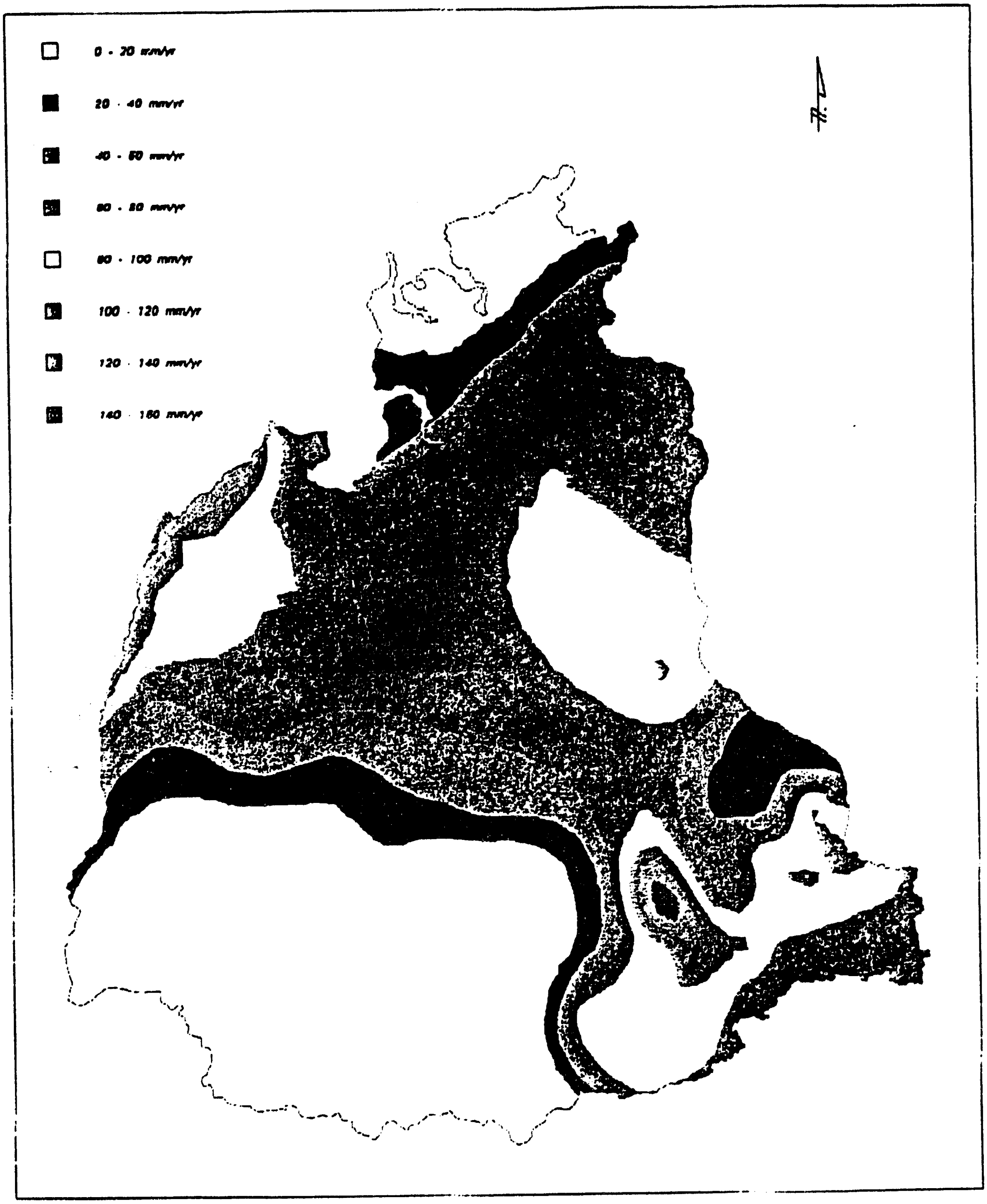

FIGURE 16. Recharge Zones for the West Siberian Basin Regional Hydrogeologic Model

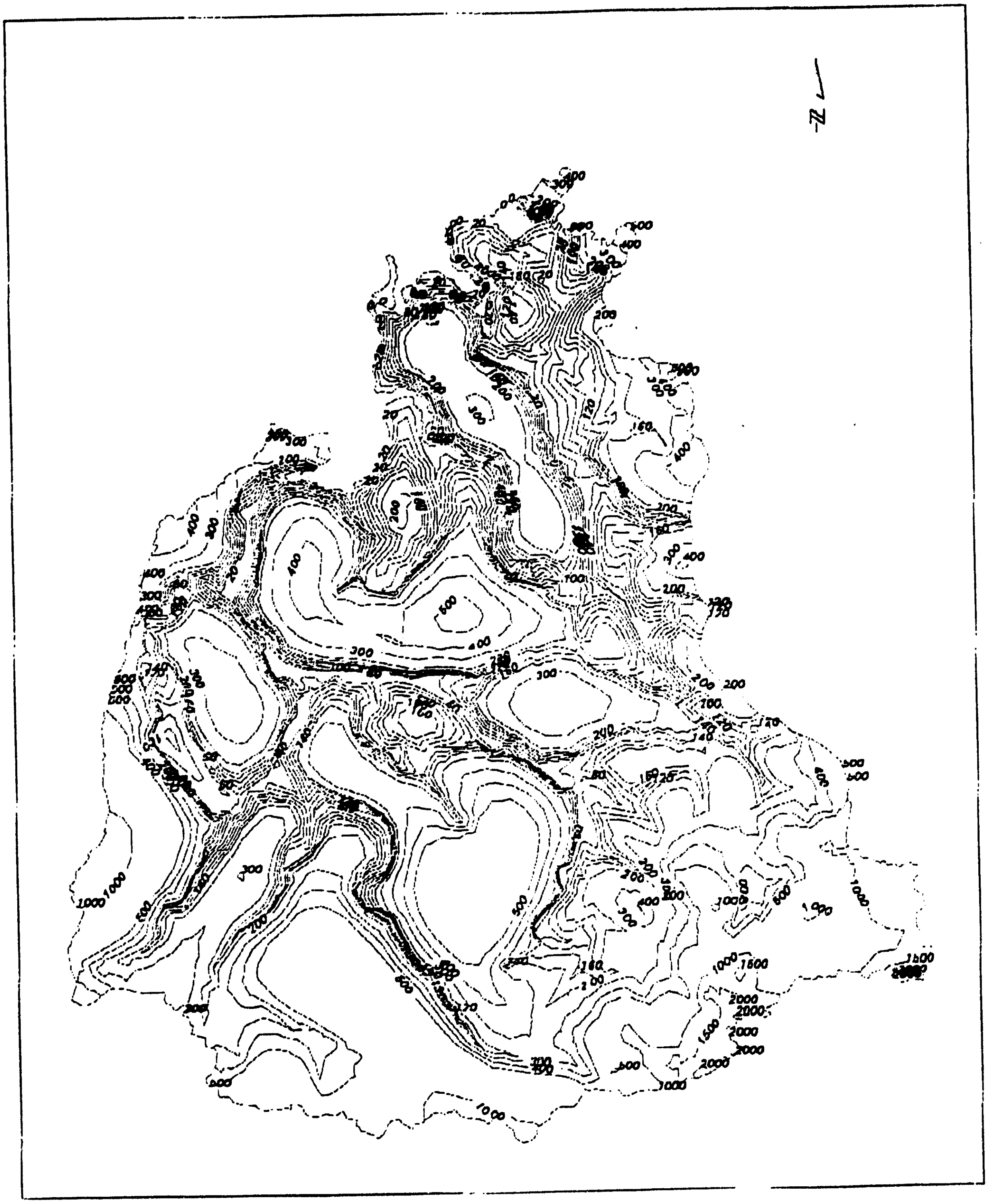

FIGURE 17: CFEST Results for Simulation 1. Hydraulic head contours in mMSL, variable contour spacing.

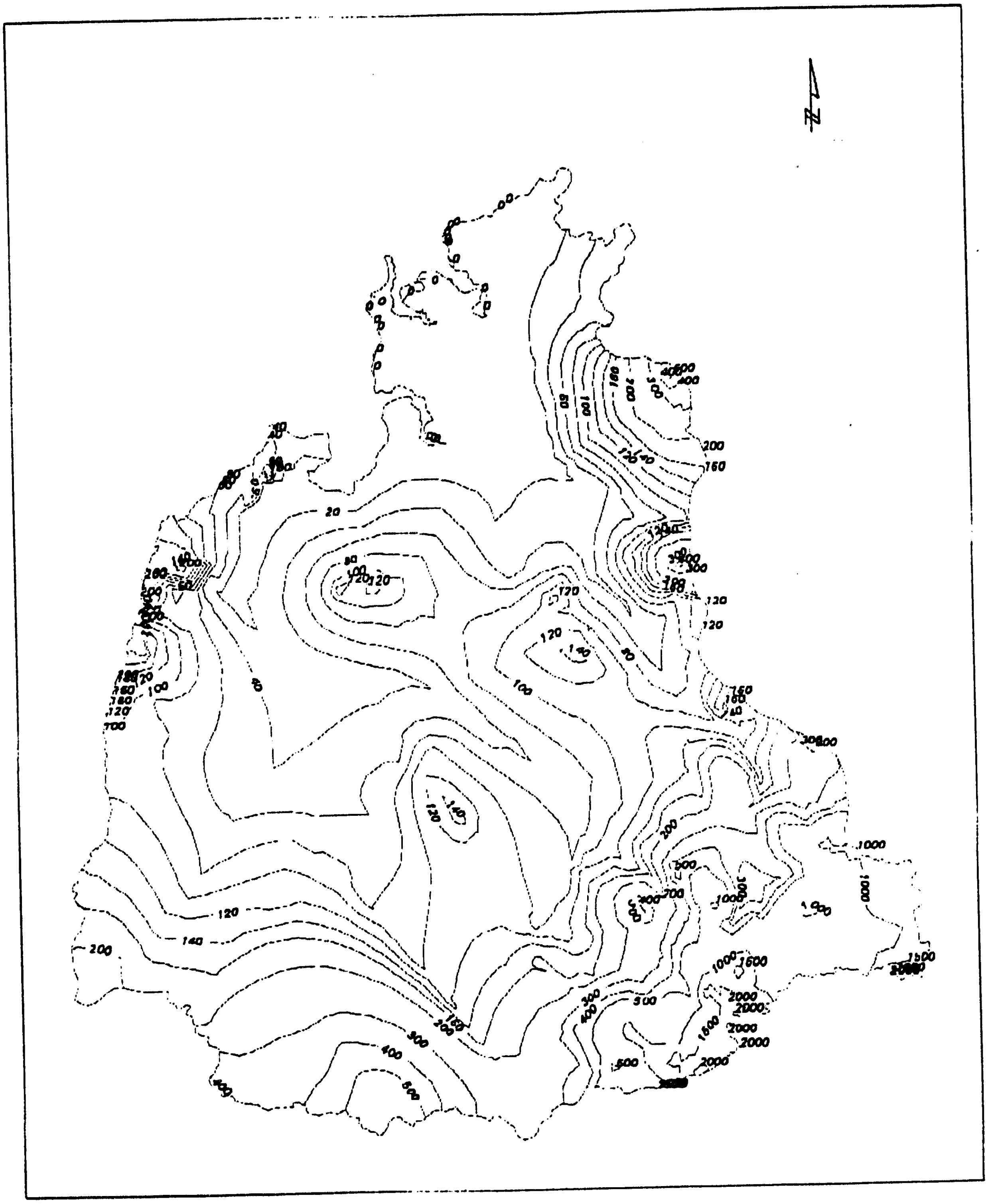

FIGURE 18: CFEST Results for Simulation 2. Hydraulic head contours in mMSL, variable contour spacing.

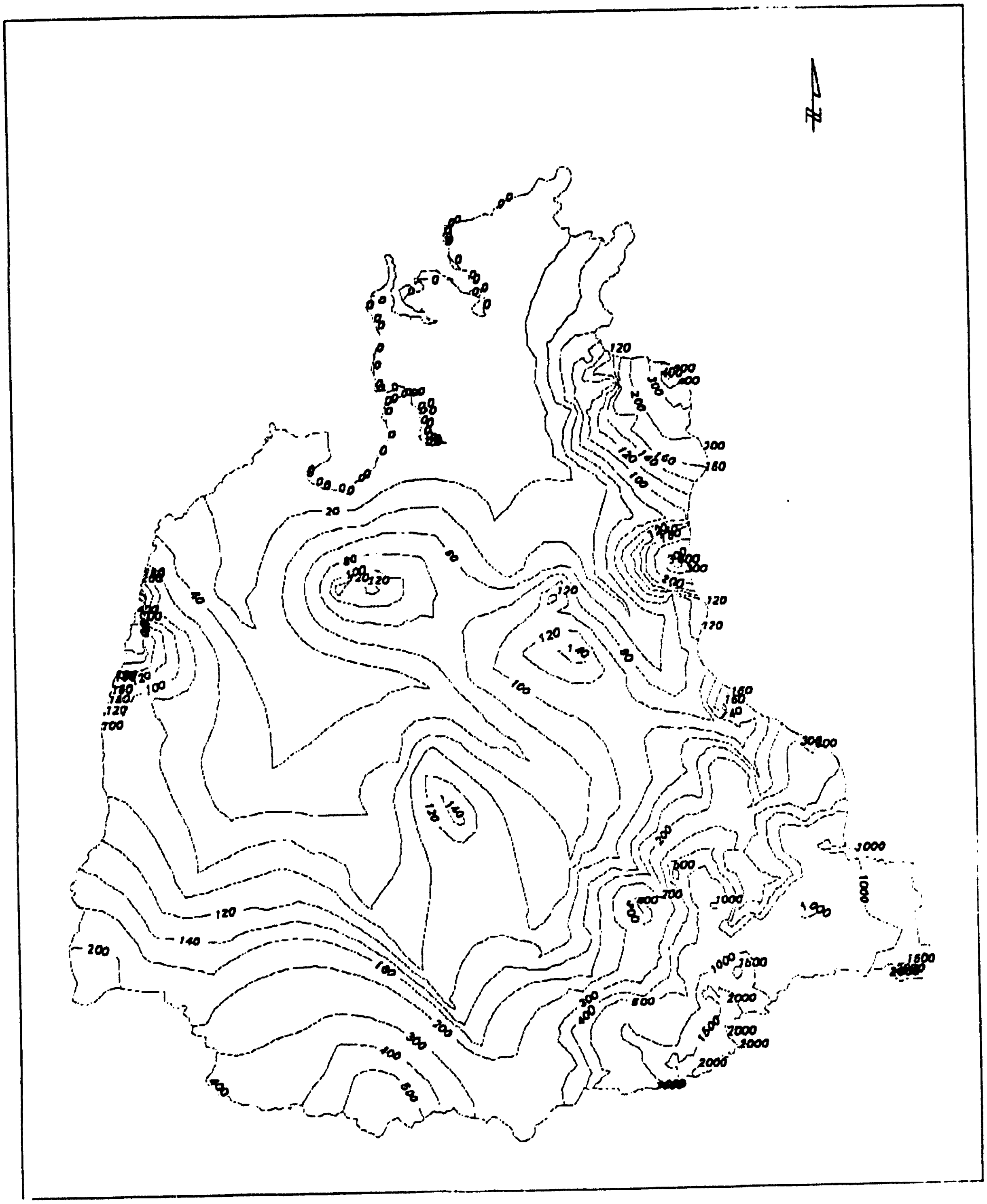

FIGURE 19: CFEST Results for Simulation 3. Hydraulic head contours in mMSL, variable contour spacing.

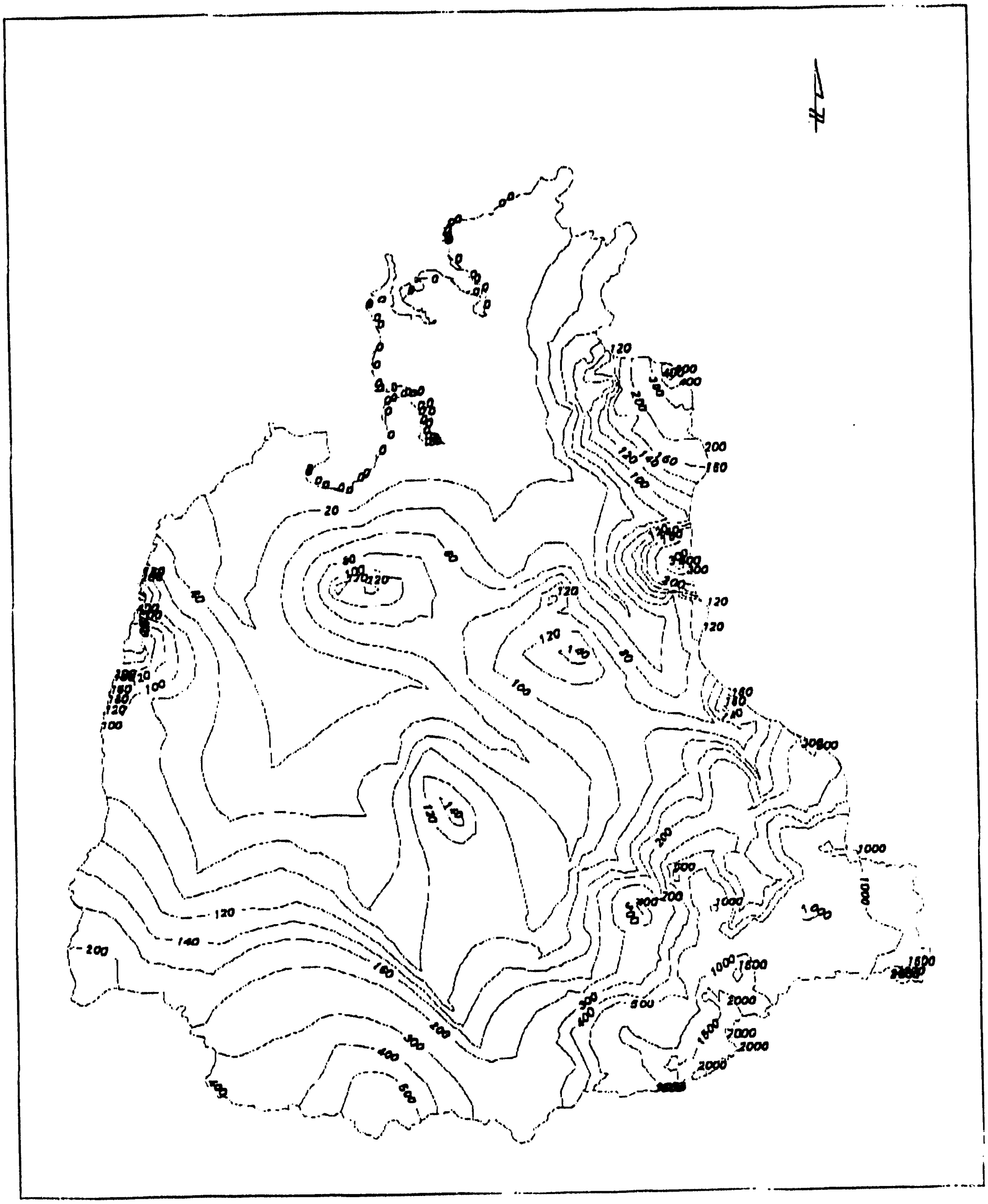

FIGURE 20: CFEST Results for Simulation 4. Hydraulic head contours in mMSL, variable contour spacing.

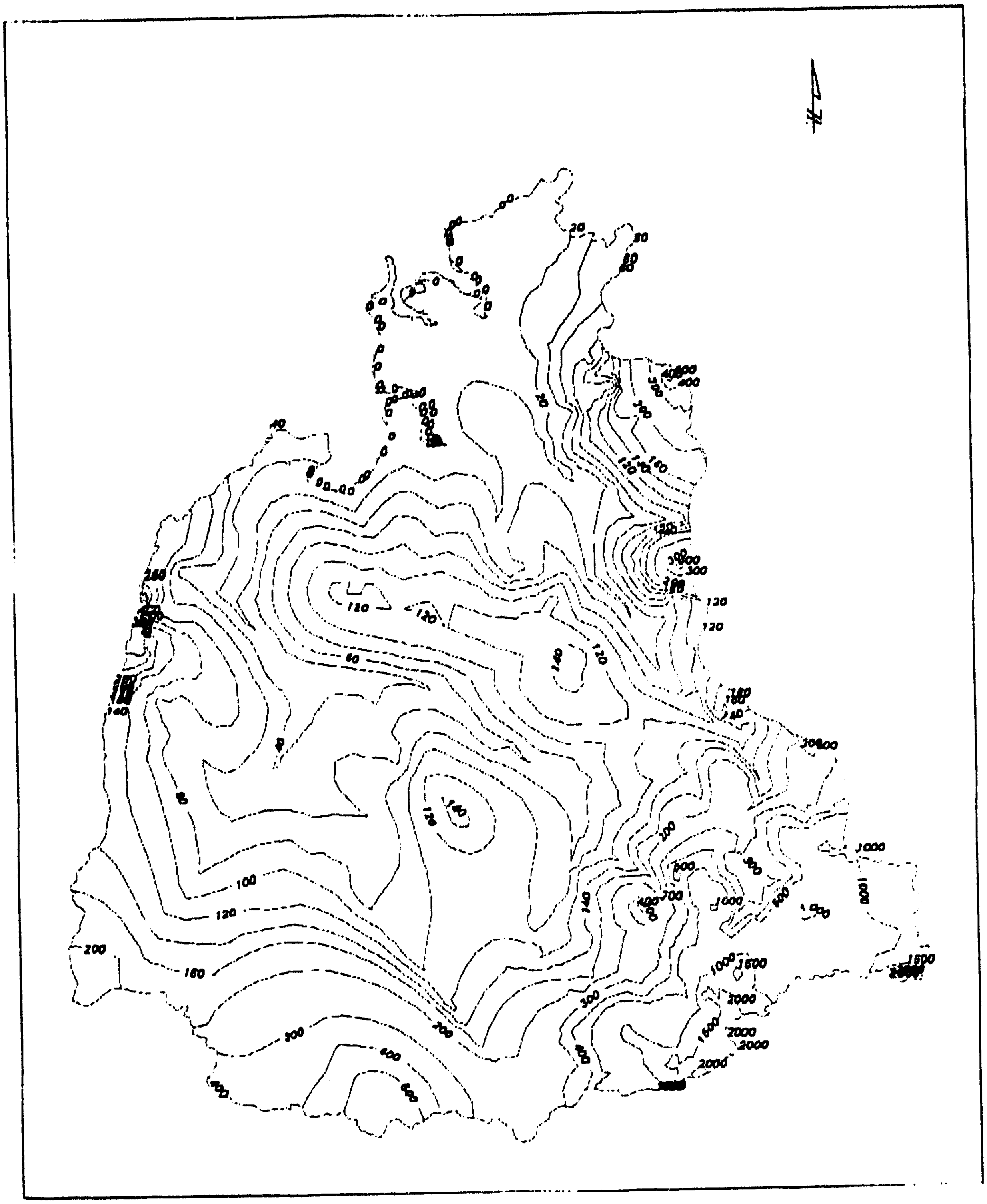

FIGURE 21: CFEST Results for Simulation 5. Hydraulic head contours in mMSL, variable contour spacing.

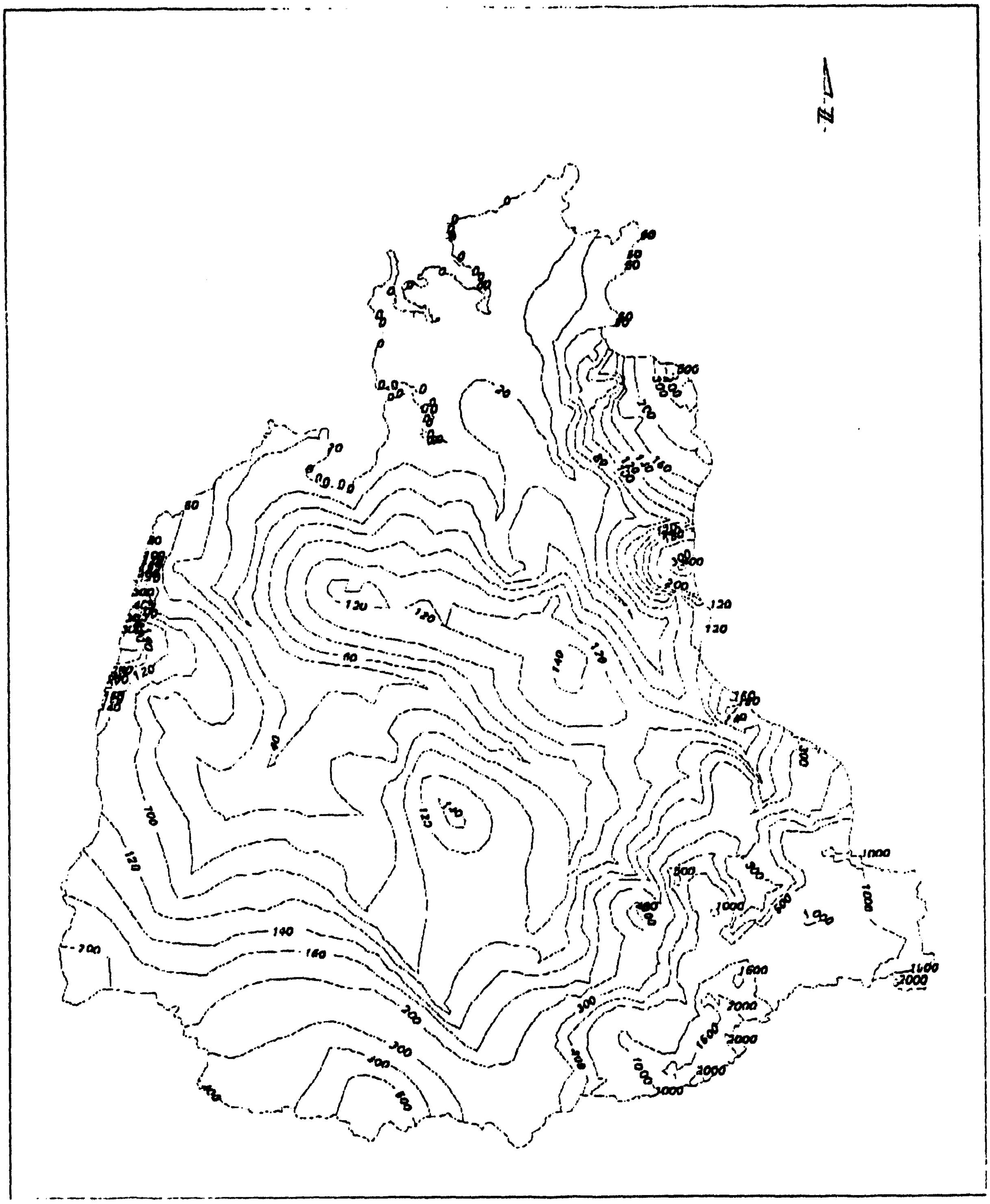

FIGURE 22. Calculated Potentiometric Surface (mMSL) for Layer 1 of the Three-Layer Multilayer Model (see Figure 13)

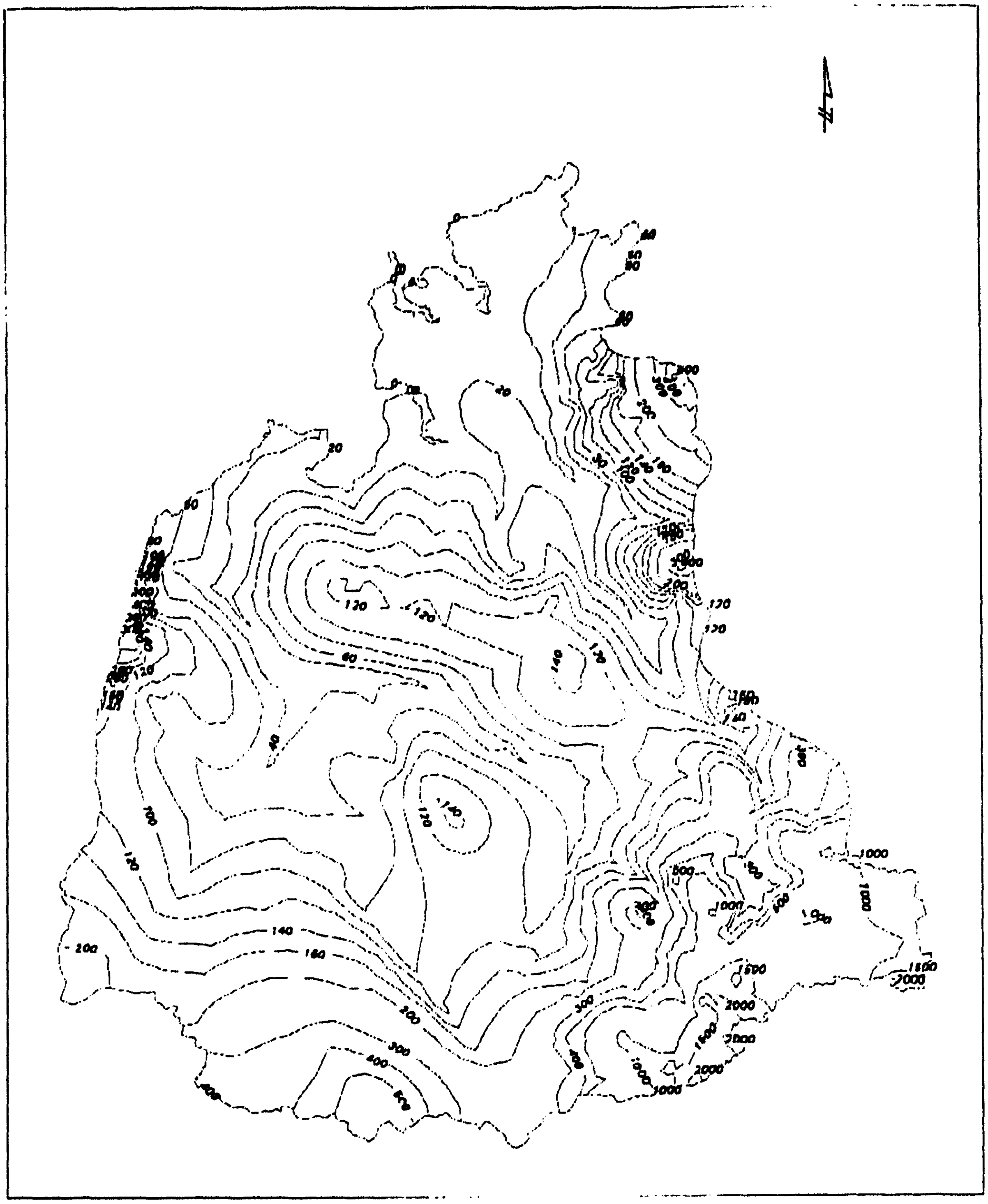

FIGURE 23. Calculated Potentiometric Surface (mMSL) for Layer 2 of the Three-Layer Multilayer Model (see Figure 13)

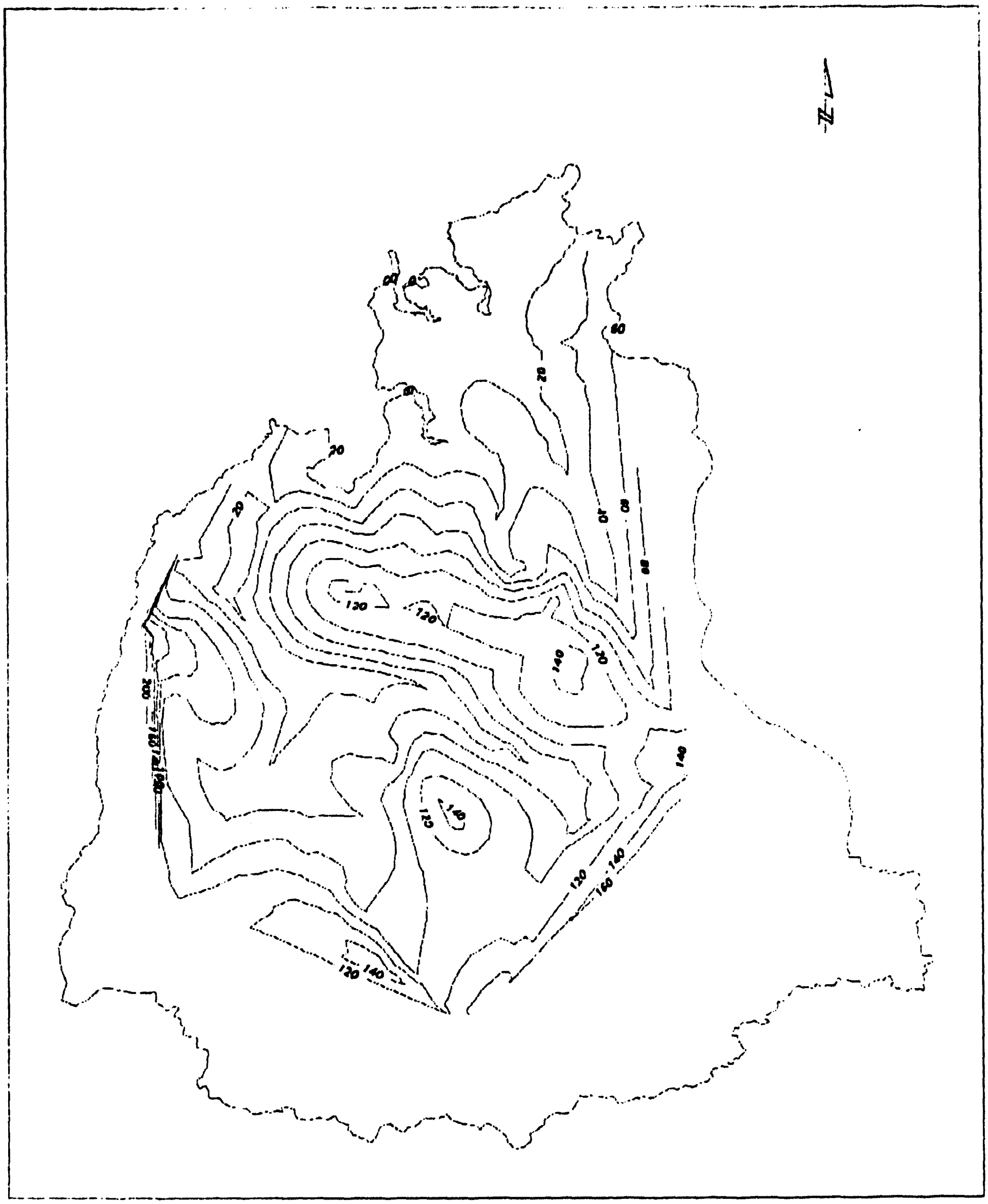

FIGURE 24. Calculated Potentiometric Surface (mMSL) for Top of Layer 3 of the Three-Layer Multilayer Model (see Figure 13)

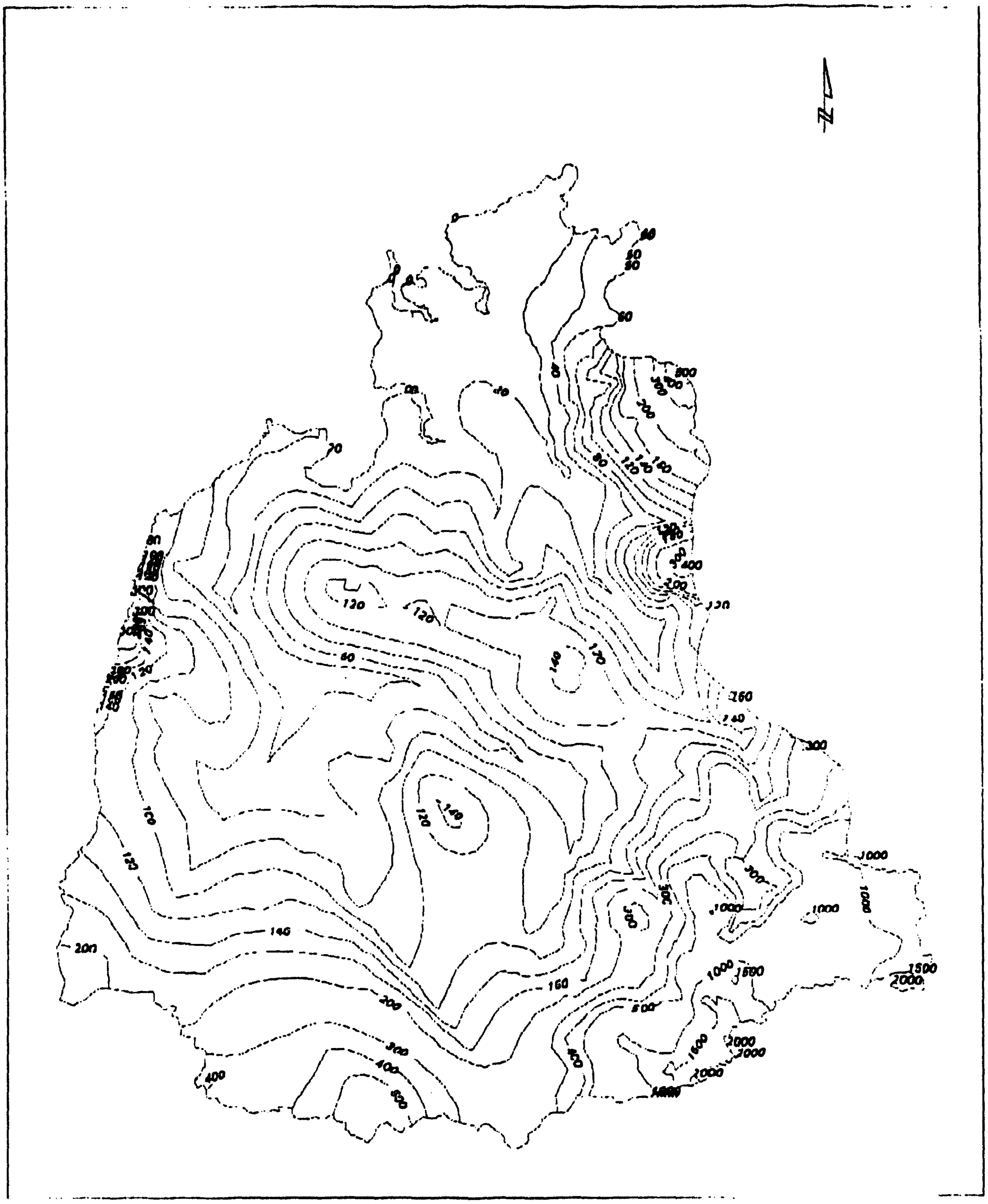

FIGURE 25. Calculated Potentiometric Surface (mMSL) for Bottom of Layer 3 of the Three-Layer Multilayer Model (see Figure 13)

TABLE 1. Average Yearly Flows of Selected Rivers of the West Siberian Basin (Nudner 1970)

River	Discharge (m^3/s)
Yenisey	19,600
Ob'	12,600
Irtysh	3,000
Taz	1,270
Tom'	1,130
Pur	885
Tobol	851
Chulym	770
Nadym	458
Ket'	226

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