CONTAMINANT HYDROLOGY

COLD REGIONS MODELING

Edited by

S. A. Grant
I. K. Iskandar

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Preface

Approximately 50% of the Earth's land mass is frozen at some time during the annual cycle: 20% of the land contains permafrost, and the other 30% is underlain with discontinuous permafrost or is subjected to several freeze/thaw cycles per year.

Terrestrial environmental contamination in cold regions is an increasing concern in many areas of the world because it affects some of the most traditionally pristine areas and because environmental cleanup in cold regions presents substantial operational difficulties that may increase costs considerably. Moreover, the extreme temperature range, soils and geology, the unique biological diversity, the freezing and thawing of pollutants, and the impact on human activities make environmental site assessments and remediation challenging tasks.

While much has been learned about contaminant fate and transport in cold regions, much more remains to be done, especially in understanding the effects of cold region environments and predicting the effectiveness of candidate remedial actions. Additionally, it is difficult for decision makers to keep abreast of the results of the most recent research, and thus they are less able to make cost-efficient and effective choices. This lag in understanding prolongs remediation of contaminated sites, extends the diversion of resources, and increases the final costs of cleanup.

Approximately 60 scientists and engineers from the United States, Canada, England, and Russia attended a workshop held in Anchorage, Alaska in August 1995. The objectives of the workshop were to

- provide a forum and direct communications between the users and developers of contaminant transport models;
- facilitate exchange of expertise between European and North American environmental scientists and engineers;
- define the status of cold regions contaminant transport models; and
- identify knowledge gaps and recommendations for basic research needs for cold regions contaminant transport.

The 14 chapters of this book constitute the proceedings of the workshop. Section I consists of four chapters that discuss the nature of contaminant hydrology in cold regions:

Chapter 1 provides an overview on problems of contaminant hydrology in Siberia.
Chapter 2 describes a direct measurement method for air distribution in soils.
Chapter 3 details the use of subsurface frozen barrier and recovery trench for contaminant removal.
Chapter 4 highlights strategies for development of cost-effective amelioration procedures for oil spills in cold regions.

Section II consists of five chapters that present example applications of models for cold regions:

Chapter 5 details basic guidelines for conducting groundwater modeling to meet environmental requirements.
Chapter 6 addresses the hydrogeological problems in developing the diamond-bearing deposits in northern regions of Russia.
Chapters 7 and 8 provide examples on the use of freezing to concentrate solutes in liquid radioactive waste and to contain radioactive wastes in permafrost, respectively.
Chapter 9 describes the use of a hierarchical neural network for interpretation of ground-penetrating radar and for permafrost and stratigraphic layer identification.

Section III comprises five chapters on development of models for cold regions:

Chapter 10 discusses the permeability of frozen silt to organic contaminants.
Chapter 11 presents a pore-scale model for soil freezing.
Chapter 12 presents simulation models that were recently developed to describe the fate or movement of chemicals in seasonally frozen soils. In addition, coupled water, heat, and solute transport models in unsaturated soils have been advanced. The effect of freezing and thawing processes on contaminated redistribution has also been addressed.
Chapter 13 provides a general modeling approach for heavy metals retention kinetics in soils.
Chapter 14 summarizes a field and modeling study of groundwater contaminant transport in a discontinuous permafrost region.

The workshop was cosponsored by the U.S. Army Cold Regions Research and Engineering Laboratory, the USAE Waterways Experiment Station, the U.S. Army Research Office, and the U.S. Army Material Command. Representatives from the U.S. EPA, DOE, USGS, USDA, AEC, U.S. Army Corps of Engineers, and several universities attended the workshop.

We wish to thank the authors for their contributions and time. Financial and logistic support were provided by the cosponsors. In particular, we wish to acknowledge the following individuals: Dr. Jerry Comati and Carole O'Connor of the European Research Office for facilitating the attendance of several professionals from outside the U.S.; Douglas Johnson and Crystal Fosbrook of the Public Works, U.S. Army, Alaska Command, and Mark Wallace of Alaska District, Corps of Engineers, for hosting the workshop in Anchorage; John Rouillad and his wife, Dianna, for providing logistics and field support for us and the participants. We gratefully acknowledge Donna Harp, Susan Hardy, David Cate, and Edmund Wright at CRREL for typesetting and technical editing.

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I.K. Iskandar received his Ph.D. degree in soil science and water chemistry from the University of Wisconsin, Madison, in 1972. He is currently a Research Physical Scientist at the Cold Regions Research and Engineering Laboratory (CRREL) and a Distinguished Research Professor at the University of Massachusetts, Lowell. During his tenure at CRREL, Dr. Iskandar developed two major research programs. The first, on land treatment of municipal wastewater, which he successfully coordinated and supervised for 9 years, concerned the research on transformation and transport of nitrogen, phosphorus, and heavy metals. The second program examined environmental quality in cold regions. In the early 1980s, Dr. Iskandar's research efforts were focused on the fate and transformation of toxic chemicals in soils, development of nondestructive methods for site assessments, and development and evaluation of *in situ* remediation alternatives. He was the first to propose the use of a frozen ground barrier for containment of toxic waste. He is a fellow of both the Soil Science Society of America (SSSA) and the American Society of Agronomy (ASA), a vice president of the International Society of Trace Elements Biogeochemistry, and a member of the International Union of Soil Science.

Dr. Iskandar has edited or co-edited 10 books. He has written more than 20 chapters of books; published more than 100 technical and reference papers and reports; presented more than 55 invited lectures, seminars and symposia; and made 45 other presentations.

Dr. Iskandar has organized and co-organized many national and international workshops and symposia. His numerous awards include the Army Science Conference, 1979; the Army Research and Development Award, 1988; CRREL Research and Development Award, 1988; and several exceptional performance awards from the U.S. Army Cold Regions Research and Engineering Laboratory.

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Contents

SECTION I

The Nature of Contaminant Hydrology and Case Studies for Assessment

CHAPTER 1

Problems of Contaminant Hydrology in Siberia

O.F. Vasiliev

CONTENTS

INTRODUCTION

Siberia has the largest area and the richest natural resources in Russia. It covers a great part of North Asia and stretches for more than 7000 km from the east slope of the Ural Mountains to the mountain range of the Pacific Ocean watershed (the mountains confining the Kolyma Basin) in the east, and for about 3500 km from Cape Chelyuskin in the north to the Altai Mountains in the south. A comparatively small southern area of the West Siberian Lowland lies in the territory of the Kazakhstan Republic. This part of Kazakhstan (Northeast Kazakhstan, parts of Semipalatinsk, and Pavlodar regions) belongs to the single natural and geographical complex of Siberia. The Siberian region covers somewhat above 10 million km^2 or around 7% of the land territory of the Earth (Mikhailov, 1976).

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Geographically, Siberia is situated in the middle northern latitudes and partially in the high northern latitudes, within the temperate and cold climate zones, a fact that governs its natural features. The southern mountain borders favor the formation of a sharp continental climate over most of the territory. The most distinctive feature is the long winter period, with very low winter temperatures. The average annual temperature almost everywhere in Siberia is below 0°C. As a consequence, about 70% of the region falls into the permafrost zone.

HYDROLOGY

Precipitation is distributed rather unevenly over the territory (from 100 to 2500 mm $year^{-1}$, decreasing toward the east) and over the seasons (Mikhailov, 1976). The common characteristic of the Siberian geographical structure is its hydrographic unity and the unique hydrologic regime of rivers. The overwhelming majority of rivers belong to the Arctic Ocean basin, and only a small part of the Transbaikalian region is drained by tributaries of the Amur River. The Ob, Yenisei, and Lena, which are among the world's largest rivers with a total annual runoff of about 1500 km^3, constitute the basis of the river network in Siberia. As for the total annual runoff of all Siberian rivers, it is somewhat above 2500 km^3, i.e., approximately 7% of the overall flow of the Earth's rivers. Most Siberian rivers are fed by thawed snow and ice in spring and by rains in summer and autumn. The groundwater feeding is usually small, often below 10%. For almost all the rivers, 80 to 90% of the annual flow takes place during the warm periods and no more than 7 to 15% in winter. The major flow occurs at the high water periods, which are in late spring in the southern and middle regions of Siberia and in early summer in the north. In Siberia, almost 90% of country settlements and large cities are located in the river valleys (Mikhailov, 1976).

TOPOGRAPHY

The significant extent of Siberia from north to south and from east to west causes a great diversity of natural landscapes. The overall surface area is 14% tundra and forest-tundra biomes, 42% taiga, 5% forest-steppe, 4% steppe, and 35% mountain and hills (Koropachinskii et al., 1994). From the latest data, the forest coverage is estimated to be 3300×10^3 km^2 (Sokolov et al., 1994).

A great part of Siberia (in particular West Siberia) is covered by wetlands with bogs. The area of wetlands in West Siberia is estimated as 800×10^3 to 900×10^3 km^2, including about 400×10^3 km^2 of peat bogs (Pomus, 1971; Neishtadt, 1971; Kats et al., 1963). The total area of wetlands in Siberia is about 2000×10^3 km^2.

DEMOGRAPHY

A low population density and a very nonuniform distribution of the population over the territory are the distinctive demographic features of the Siberian region.

There are only 24 million people throughout this extended area. Only the agricultural forest-steppe band of West Siberia and Kuzbass contains comparatively populous regions (40 to 60 people per km^2). A high concentration of industrial enterprises in a number of large industrial centers and the prevalent superlarge enterprises characterize industrial progress in Siberia (Mikhailov, 1976).

ENVIRONMENTAL CONCERNS

Because of the intensive development of various branches of economy in Siberia, in particular in its northern regions, many complicated environmental issues have arisen. These are related to water resources management and protection, as well as to usage and disturbance of natural systems, including those which are closely and inherently connected with hydrologic systems.

Ecological well-being of the cold regions is heavily affected by the chemical contamination of hydrologic systems, including watersheds, surface water, and groundwater.

The contamination of hydrologic systems in Siberia has different characteristics and scales in various cases. The response of natural systems (ecosystems), whose functioning is tightly connected with water cycling (or water exchange processes), depends very much upon the stability in different landscape zones (tundra and forest-tundra, taiga, peat bogs, etc.). Occurrence of permafrost plays a significant role. As is well known, cold-region ecosystems with their high vulnerability and low regenerating capability are especially sensitive to direct and indirect human impacts.

Industrial development in Siberia gave rise to various kinds of environmental damage and, sometimes, even devastation. The damage includes distortions in the behavior of hydrologic and hydrogeologic systems, their qualitative state, and in the stability of landscapes, particularly in permafrost areas. Vast areas of Siberian territory have been subjected to environmental changes related to the contamination caused by environmentally detrimental technologies and engineering equipment.

There are many examples of large-scale local contamination of lands and waters in Siberia, because of various industrial activities such as oil and natural gas extraction, processing of mineral, wood, and other natural resources, and use of transport systems. Oil refineries and metallurgical plants (ferrous and nonferrous) contribute to both direct and indirect contamination of watersheds and hydrologic systems due to discharge of wastewaters, emission of gaseous effluents (airborne pollutants), and disposal of wastes in tailing dumps.

THE OB-IRTYSH RIVER SYSTEM

Large-scale pollution of waters and soils occurs in the Ob-Irtysh River basin, one of the largest river basins of Siberia and the world. Some small and midsize tributaries of these large rivers, such as Inya, Tom, Chulym, Vakh, and Ishim, are highly contaminated, especially in the areas of industrial activities. While earlier pollution of river waters took place mainly in the upper stretches of the Ob-Irtysh River system (in the most populated and industrialized southern regions of the West Siberia), during the last 30 years the areas of industrial and urban pollution on the West Siberian territory expanded a great deal and reached the northern regions. That is the negative result of the development of the West Siberian oil and gas production complex. Therefore, the problem of oil contamination of watersheds (covered with enormous peat-bogs), rivers, and their floodplains in the Middle Ob River basin has become most urgent today.

We shall give some figures to better envisage the scales of the environmental impact of this industrial complex. There are almost 200,000 km of pipelines used in the regions of Tyumen and Tomsk. The pipelines have been constructed since the mid-1960s and they have been used under heavy technological and environmental conditions. To intensify oil production, water is often injected into an oil formation to increase reservoir pressure. A negative impact of this is the introduction of brine waters from aquifers into the system, which leads to the intensive corrosion and rapid wear of pipes. As a result, up to 2500 to 3000 pipe-break accidents take place per year, resulting in oil losses estimated at 1 to 2% of the total production (Mikhailova, 1995). As a consequence of these failures, crude oil and brine waters are released in very large quantities on watersheds and into water bodies. The region's flat relief, an abundance of wetlands, bogs and lakes, low gradients of streams, a cold climate, and permafrost aggravate environmental consequences.

The accidents involving the oil pipeline network, wells, and pumping stations are the main source of contamination of watersheds and water bodies by oil hydrocarbons and brine salts. The use of slime storage pits at well sites, as well as the release of oily wastes from the technological systems, also plays an essential part in the contamination of hydrologic systems by oil hydrocarbons. The small rivers and some tributaries (e.g., the Vakh) of the Ob River, which are situated on (or contain) oil fields, are subjected to a considerable degree of the contamination.

Pollutants transferred by air contribute to the contamination of extensive territories. The contribution of airborne pollutants (including hydrocarbons) in the contamination of watersheds is not estimated well. One of the sources of such a contamination is flaring of associated gas at gas separator outlets, in particular the emissions of the airborne dripping oil remaining after incomplete burning. Aromatic hydrocarbons play a significant part in oil contamination of water bodies and snow cover (Mikhailova, 1995).

All these result in the large-scale and substantial contamination of soils and waters by oil hydrocarbons in the Middle Ob River basin. The salinization of river waters by the brine salts amplifies the environmental impact.

The chemical contamination of the rivers in the Tyumen North and the rivers' low ability for self-purification have already brought about negative consequences for the aquatic ecosystems. The most visual of them is the damage of fisheries in the Middle and Low Ob River. The following data for the fishing harvest in the Tyumen region (according to the data by Mikhailova, 1995) give evidence to it:

Average harvest in years 1940 to 1964 (32×10^3 t/year)
Estimate of harvest at present (16 to 17×10^3 t/year)

Thus, the decline is about 40 to 50%.

THE TOM RIVER BASIN

Another example of large-scale environmental contamination is the situation in the area of Kuzbass Industrial Complex, which is located in the Tom River basin (a right tributary of the Ob River). In this case, a complicated environmental situation has resulted from the fast development of a number of industrial activities, including coal mining and processing of ferrous and nonferrous ores and other natural resources. Together with the growth of urban settlements, the industrial activity and lack of measures for environmental protection have caused substantial pollution of air, lands, and waters.

The Tom River is 827 km long and drains a watershed area of 62,000 km^2. The total mean annual runoff of the river is 34.1 km^3/year (1080 m^3/s). The basin contains several environmentally devastated urban and industrial areas of the Kuzbass Industrial Complex, which is the most important center of coal mining in Russia and one of the centers of metallurgical and chemical industries located in such cities as Kemerovo, Novokuznetsk, and others. The Kemerovo region is one of the most densely populated and heavily industrialized areas in Siberia, with well-developed supporting agricultural activities. In that region, some urban areas, industrial sites, and stretches of the Tom River and its tributaries are badly contaminated.

The Tom River system is the main source of water supply for the Kuzbass region and the ultimate collector for the industrial, municipal, and agricultural wastewaters. Over 1000 industrial plants and human settlements discharge incompletely treated wastewaters into the Tom River and its tributaries. The washout of the pollutants from the municipal territories and industrialized areas, wastes from the cattle-breeding complexes, and the pollutant runoff with surface waters from the agricultural lands are also very substantial. In addition, our recent data of field observations suggest that airborne pollutants play an essential role in contaminating the watershed area and its surface waters. As a result, the river waters contain practically all types of pollutants (a variety of organic compounds, heavy metals, and others).

Although the Tom River basin is situated in a southern part of West Siberia, the climate of this area is typically continental with a long and cold winter period. That gives the river a hydrologic regime with a very nonuniform seasonal distribution of runoff. The river reflects its mixed origins where input of snow melting prevails (during the period of spring flood, about 70% of total runoff is released). At the same time, winter is characterized by very low discharges (because of limited groundwater feeding); the part of the total runoff that is related to this period is only about 5%.

Such hydrological conditions are most unfavorable both for water supply (lack of water and low levels) and for the quality of river water. The latter is due to the fact that the concentrations of a number of point-source pollutants reach high levels because of low dilution.

A project has been proposed aimed at mitigating the water quality state and the hydrological regime along the lower part of the river: near Kemerovo and downstream. The concept of the project was to create a rather large river reservoir by constructing a dam near Krapivino, a settlement located upstream from Kemerovo, and to regulate river flow (runoff) providing sufficient discharges to dilute the pollutant load at the low-water periods. Construction work started in 1975, but in 1989 was stopped according to a governmental decision: the project had to be considered once more for a new environmental impact assessment (Vasiliev, 1998).

From 1990 through 1992, the Institute for Water and Environmental Problems and other institutes of the Siberian Branch of the Russian Academy of Sciences have carried out a research program, the main objectives of which were assessing the water management and ecological state of the Tom River basin and the engineering measures proposed for the improvement of water resources and quality management. This wide-ranging multidisciplinary study has included the collection and analysis of available hydrological, hydrochemical, ecological, and other data on the river system and its watershed area, and field investigations for enlarging this information and assessing environmental impacts of the Krapivino project. The field investigations have been pursued mainly by an extensive survey of hydrochemical, biogeochemical, and hydrobiological data specifying the present state of the Tom River basin: quality of surface and groundwaters; pattern of sediment, soil, and snow pollution; and species diversity under conditions of anthropogenic stress and bioaccumulation of chemicals by the river inhabitants.

The hydrochemical study of water quality reveals that the Tom River and some of its tributaries are heavily exposed to anthropogenic contamination, especially immediately downstream from the large industrial centers. Main pollutants are the organic compounds (petroleum compounds, phenols, polycyclic aromatic hydrocarbons, formaldehyde, aniline, organic chlorine compounds, some amines, naphthalene and its derivatives, and dibutylphthalate and its derivatives), nitrate and ammonia nitrogen, as well as some heavy metals (cadmium, zinc, chromium, copper, etc.). Concentrations of the above substances often exceed drastically the national standards for water quality in natural water bodies.

The pattern of water contamination of the river changes over the annual hydrological cycle. In winter low water, the pollution by petroleum compounds is dominant everywhere along the river. Some stretches of the river are highly polluted by volatile phenols and ammonia nitrogen. Although the spring floodwater dilutes the petroleum compounds, water pollution by pesticides increases everywhere along the river. Also, the level of contamination by formaldehyde, phenols, and nitrate increases locally during the high water period in spring.

As a rule, heavy metals content in the water and bottom sediments does not exceed the normal background. However, there are contaminated stretches near industrial centers (e.g., Novokuznetsk and Kemerovo).

SOURCES OF CONTAMINATION

Currently, the quality of surface waters in the Tom River basin is determined to a great extent by pollution from different sources, including industrial plants, urban sewerage systems, agricultural lands, and urban and industrial areas. Therefore, its essential improvement is impossible without significant reduction of quantities of contaminants emission to air and of water and soil pollution from industrial and urban sources, as well as more careful use of fertilizers, pesticides, and other agrochemicals.

Research was aimed at establishing the scientific basis to develop a strategy for improving the environmental state of the Tom River and its basin. The results obtained thus far have demonstrated conclusively that the water quality problem cannot be considered separately from other environmental issues of the region. It can be done only within the total environmental context of the river basin. There is a need for developing a strategy of integrated management of water and environmental quality on the river-basin scale (Vasiliev, 1998). As far as the fate of the Krapivino reservoir project is concerned, there is not yet a final decision.

An example of industrial impact in the northern environment is that from the Norilsk Mining and Smelting Enterprise, the activity of which is based upon the large-scale exploitation of sulfide copper–nickel ore deposits. The mining technology includes the use of open-cast mines in the permafrost area. Therefore there are two sources of atmospheric pollution here: emissions of gaseous effluents (in particular, sulfur dioxide SO_2) from smelters and weathering of dust from spoil heaps. The deposition of dust and aerosols on the watershed surface results in the substantial contamination of soils, vegetation, snow cover, and waters over a large territory. A similar situation takes place in some other areas of the mining industry in Siberia.

Deep open-cast mines are used for the extraction of diamonds in Yakutia (in the permafrost area as well) at Mirnyi and to the north of Mirnyi in the area of Aikhal. In addition to the air pollution and the disturbance of groundwater regimes, an environmental problem has arisen at Mirnyi because of groundwater drainage: pumping of brine waters from deep aquifers to the Vilyui River resulted in the salinization of river waters.

Gold mining with the use of mercury technology (though the use of mercury is limited now, it is still in use in Siberia) is another example of contamination of river hydrologic systems. Hydrologic processes, including sediment and suspended matter transport, play a governing role in the mercury migration in a fluvial system. There are many river basins in Siberia, in particular in its eastern regions, where the gold mining is an important sector of industrial activities.

Of special interest are the hydrochemical regimes and the behavior of contaminants in river reservoirs situated in the permafrost areas. There are three in Siberia on the rivers: Vilyui (Lena River basin), Khantaika (Yenisei River basin), and Kolyma (East Siberian Sea basin). The Kolyma Reservoir has recently been created in mountainous conditions (the depth near the dam is 120 m). The river basin is under environmental stress caused mainly by the intensive gold mining in this area. Therefore there is a problem of the reservoir being contaminated by the wastes of mining activity and by municipal sewage. The hydrochemical regime of the reservoir,