HYDRO-GEOLOGICAL ASPECTS OF LAKES AND LAKE-AQUIFER INTERACTION

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INTRODUCTION

A natural lake is a fairly large body of water occupying an inland basin (low-lying geographic area). Lakes cover only about 1 percent of the continents, and contain less than 0.02 percent of the world's water, but they are important **ecosystems** and may be sources of water supply in certain regions.

The term lake is also used to describe a feature such as Lake Eyre, which is dry most of the time but becomes filled under seasonal conditions of heavy rainfall. Many lakes are artificial and are constructed for hydro-electric power supply, recreation (swimming, wind surfing,...), water supply, etc.

Finland is known as *The Land of the Thousand Lakes* (actually there are 187,888 lakes in Finland, of which 60,000 are large) and Minnesota is known as *The Land of Ten Thousand Lakes*. The Great Lakes of North America originated in the ice age. Over 60% of the world's lakes are in Canada; this is because of the deranged drainage system that dominates the country.

Lakes are extremely varied in terms of origin, occurrence, size, shape, depth, water chemistry, and other features. Lakes can be only a few hectares in surface area (i.e., less than a square kilometer), or they can be thousands of square kilometers. Their average depth can range from a few meters to more than a thousand meters. Lakes can be nearly uniformly round, or they can be irregularly shaped. Their water can be highly acidic (as in some **caldera** lakes), nearly neutral, or highly alkaline (as in soda lakes). Lakes can be low in nutrients (oligotrophic), moderately enriched (mesotrophic), or highly enriched (eutrophic).

Lakes may be fresh-water or salt-water (saline). Most of the world's largest lakes are fresh-water, with some exceptions (e.g., Caspian Sea, Aral Sea, and Great Salt Lake). Fresh-water lakes contains less than 1 gram per liter of salt, whereas saline or **hypersaline** lakes, such as the Great Salt Lake (Utah), may contain more than 250 grams per liter. Saline lakes typically occur in **arid** climates, and occupy closed basins (low areas which lack stream outflow).

WORLD'S TEN LARGEST LAKES (IN TERMS OF SURFACE AREA)		
Name and location	**Area km ^{2}**	**Volume km ^{3}**
Caspian Sea (saltwater) Turkmenistan, Kazakhstan, Russia, Azerbaijan, Iran	386,400	78,200
Lake Superior (largest freshwater lake) United States, Canada	82,100	12,230
Lake Victoria Kenya, Tanzania, Uganda	69,485	2,700
Lake Huron United States, Canada	59,600	3,537
Lake Michigan United States	57,800	4,920
Lake Tanganyika Burundi, Tanzania, Zaire, Zambia	32,900	18,900
Lake Baikal Russia	31,500	22,995
Great Bear Lake Northwest Territories, Canada	31,153	2,381
Lake Malawi (formerly Lake Nyasa) Malawi, Mozambique, Tanzania	29,604	6,141
Aral Sea (saltwater) Kazakhstan, Uzbekistan	28,687 (in 1998), was 68,000 (in 1960)	181 (in 1989), was 1,040 (in 1960)

ORIGIN OF NATURAL LAKES

There are a number of natural geological processes that can form lakes. Although many of these processes occurred in the geologic past, lakes continue to form and to be destroyed. A tectonic uplift of a mountain range can create bowl-shaped depressions that accumulate water and form lakes. The advance and retreat of glaciers can scrape depressions in the surface where lakes accumulate. Lakes can also form by means of landslides or by glacial blockages.

Lakes are formed by geological, climatological, biological, and extraterrestrial (meteorites) mechanisms. While most lakes are formed by catastrophic events, others are created more gradually. Based on the mode of formation of lakes, the lakes can be classified as:

1. Lakes formed by **Tectonic** activity
2. Lakes associated with **Volcanic** activity
3. Lakes formed by **Landslides**
4. Lakes formed by **Wind**
5. Lakes formed by **Rivers**
6. Lakes formed by **Glaciers** and **Ice**
7. Lakes formed by **Dissolution of Rocks**
8. Lakes associated with **Shorelines**
9. Lakes formed by **Meteor Impact**
10. Lakes formed by **Biological activities**

Lakes formed by Tectonic activity

Tectonic Lakes are formed by movements of the earth's crust in such a way as to create a basin that can fill with water. Uplifting of the earth has created a number of lakes that were often modified by glacial scouring activity. Lake Superior is of mixed glacial and tectonic origins.

Lake Baikal, located in eastern Russia, formed in the Baikal Rift of the Siberian Platform. Lakes Tanganyika, Malawi (formerly Nyasa), Kivu, Turkana, Mobutu, Magadi, Naivasha, and Natron lay along the East African Rift Valley. Other crustal movements influencing lake formation include uplift of the seafloor (Caspian Sea and Aral Sea), and uplift around a central basin (Lake Victoria).

The Basin and Range Province of the western United States contains tectonic lakes in the valleys between **fault-block** mountains (Lake Tahoe, California-Nevada border). Many Basin and Range lakes are remnants of larger lakes that existed 10,000 to 30,000 years ago, during the **Pleistocene epoch** (Ice Age). The Great Salt Lake, which covers 2,500 to 6,000 square kilometers (960 to 2,300 square miles) and is about 10 meters (33 feet) deep, is a remnant of Pleistocene Lake Bonneville, which covered 50,000 square kilometers (19,300 square miles) and was 300 meters (980 feet) deep.

Lakes associated with Volcanic activity

Lakes formed by volcanic activity tend to be relatively small. Lakes may form within the crater of an active but quiet volcano, in a caldera produced by explosion and collapse of an underground **magma** chamber (Crater Lake, Oregon), on collapsed lava flows (Yellowstone Lake, Wyoming), and in valleys dammed by volcanic deposits (Sea of Galilee, Israel).

Lakes formed by Landslides

Lakes created by landslides form in stream valleys behind the dam created by a landslide. These lakes are short lived and do not remain for long times.

Lakes formed by Wind

Lakes of Aeolian Origin are formed when wind erosion creates shallow depressions which contain water seasonally (e.g. temporary Dune lakes in sandy areas).

Lakes formed by Rivers

These lakes are formed by river activity, where the erosional and depositional action of river water can isolate depressions to form lakes (e.g. plunge-pool lakes below former waterfalls and oxbow lakes in former river channels, such as those along the Ganga and Brahmputra River).

Small, crescent-shaped lakes called oxbow lakes can form in river valleys as the result of meandering. The slow-moving river forms a sinuous shape as the outer side of bends is torn away more rapidly than the inner side. Eventually a horseshoe bend is formed and the river cuts through the narrow neck. This gap now forms the main passage for the river and the ends of the bend become silted up.

Lakes formed by Glaciers and Ice

By far the most productive maker of present-day lakes were the glaciers. Between one million and ten thousand years ago, during the Pleistocene, our planet experienced a series of four ice ages (expansions and recessions of glacial ice over the land surface). At times of maximal ice cover, 31.5% of the earth's surface was covered by glaciers. The last glaciation (called the "Wisconsinan" - 10,000 to 125,000 years ago) was responsible for shaping the landscape of northern temperate regions. It created the vast majority of lakes now present in Canada, including the Great Lakes. Today, glaciers cover about 10% of the earth's surface and persist only in areas with abundant snowfall.

Thermokarst lakes

These lakes form by water seepage through cracks in the ground into the permafrost, which on freezing, forms a polygonic network of ridges that contain subsequent meltwater. Repeated freeze thaw cycles can lead to expansion of these water filled cracks into a lake. A large number of arctic thaw lakes have an elliptical shape, with the long axis in the northeast/southwest direction across the prevailing winds. This orientation arises because currents produced by wind action erode and thaw permafrost at ends of the long axis of the ellipse lying across the wind. Thermokarst lakes are formed in Arctic when large amounts of ice deep in the permafrost melt, especially if plant cover is disturbed or destroyed.

Ground Moraine Lakes

Ground moraine is the general term used for any accumulation of glacial origin including boulders, sand, and gravel, left on a surface over where a glacier was formerly present. **Kettle Lakes** occupy depressions produced by the melting of large chunks of ice that were left within the ground moraine when its parent glacier melted. Kettle lakes do not necessarily form immediately after the glacier's recession. If the ice chunk is insulated by an overburden of drift, it can persist long after its parent glacier has disappeared.

Lakes formed by morainal impoundment develop in mountainous regions where terminal and lateral moraines dam a river valley.

Lakes are also formed by hydraulic force on a ground moraine form during temporary decreases in the rate of glacial melting when recessional moraines were left behind. Meltwater, streaming under pressure beneath the ice, washed out deep elongate basins in the drift and lakes occupy these depressions today.

Glacial Scour Lakes

These lakes are formed when glaciers erode bedrock, carving basins that are now filled with rainwater. The Great Lakes are examples of glacial scour lakes.

Fiord Lakes

These lakes develop when fiords rise above sea level as a result of isostatic rebound (uplift of land after being depressed by ice). Fiords were formed in western Canada within narrow, deep basins in glacially deepened valleys and are also found extensively throughout coastal regions of the eastern Arctic.

Cirque Lakes

These are ice scour lakes that form in the upper portion of mountainous areas where lakes occupy amphitheater-shaped depressions formed by the erosional action of glaciers.

Paternoster Lakes

It is the name given to a series of cirque lakes at successively lower elevations. Viewed from the air, they look like a string of silvery beads and gain their name from this fact.

Glacial Relict Lakes

These are remnants of giant lakes that were once filled with glacial meltwater but now exist as separate bodies of water.

Periglacial lake

This lake is one in which part of its margin is formed by an ice sheet, ice cap or glacier, the ice having obstructed the natural drainage of the land.

Subglacial lake

This lake is one which is permanently covered by ice. They can occur under glaciers and ice caps or ice sheets. There are many such lakes, but Lake Vostok in Antarctica is by far the largest.

Lakes formed by Dissolution of Rocks

Formed by dissolution of soluble rock (often limestone) by percolating water
e.g., $CaCO_3 + CO_2 + H_2O \longleftrightarrow Ca^{2+} + 2HCO_3^-$

Sink holes may form quickly and be short-lived (dolines) cave ponds and mound springs - often have strange and unique biota. Some lakes come into existence as a result of sinkhole activity. Areas with numerous solution lakes are known as **'Karst topography'**

Lakes associated with Shorelines

Coastal Lakes often form along irregularities in the shoreline of the sea or large lakes. Longshore currents deposit sediments in bars or spits that eventually isolate a fresh or brackish water lake. Isostatic rebound (uplift of land after being depressed by ice) in the eastern Arctic has resulted in the formation of large numbers of shallow lakes behind beach ridges which were offshore bars exposed through uplift.

Lakes formed by Meteor Impact

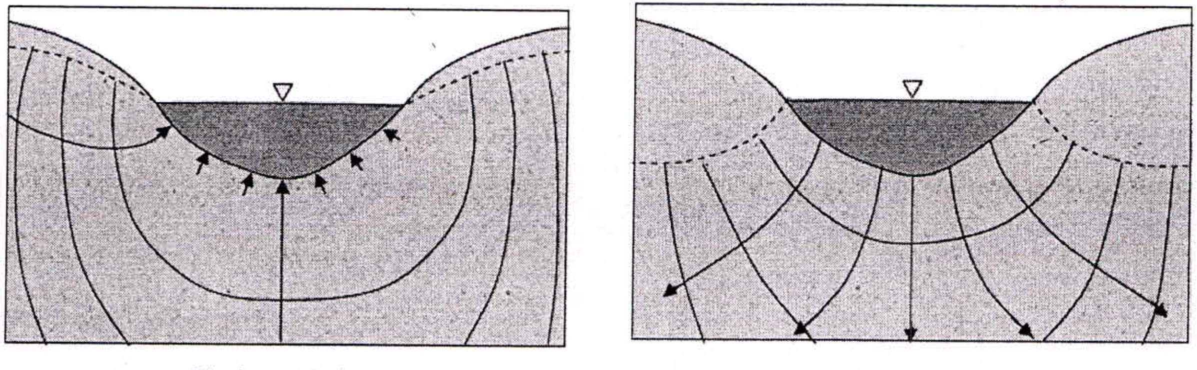
Lakes Created by the impact and explosion of meteorites are characterized by a high rim and circular outline. Both New Quebec Crater Lake on the Ungava Peninsula in Quebec and Crater Lake in Oregon, U.S.A. are of meteoritic origin.

Lakes formed by Biological Activity

Lakes Created by plants and animals can be formed in different ways. Dams of *Sphagnum* sp. (moss) and other bog plants have also been reported to impound some lakes in Nova Scotia. The damming activity of beavers results in the impoundment of streams with subsequent flooding of the landscape. Reservoirs are impoundments created by humans through the damming of river valleys. Because of high rates of sedimentation, reservoirs tend to be short-lived.

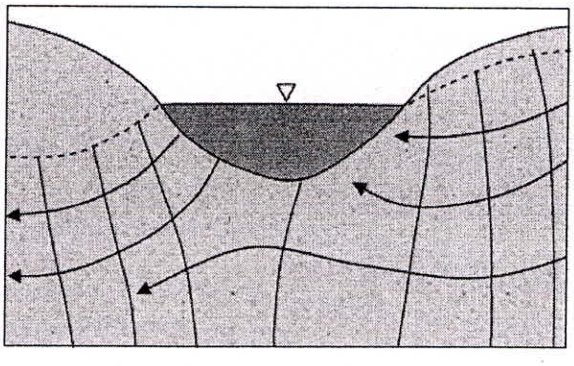
LAKE GROUNDWATER INTERACTION

Lakes interact with ground water in three basic ways: some receive ground-water inflow throughout their entire bed; some have seepage loss to ground water throughout their entire bed; but perhaps most lakes receive groundwater inflow through part of their bed and have seepage loss to ground water through other parts (Fig.1). Although these basic interactions are the same for lakes as they are for streams, the interactions differ in several ways.



Discharge Lake

Recharge Lake



Flow-through Lake

Fig 1: Lake water groundwater interaction

The water level of natural lakes, that is, those not controlled by dams, generally does not change as rapidly as the water level of streams; therefore, bank storage is of lesser importance in lakes than it is in streams. Evaporation generally has a greater effect on lake levels than on stream levels because the surface area of lakes is generally larger and less shaded than many reaches of streams, and because lake water is not replenished as readily as a reach of a stream. Lakes can be present in many different parts of the landscape and can have complex ground-water flow systems associated with them. This is especially true for lakes in glacial and dune terrain, as is discussed in a later section of this Circular. Furthermore, lake sediments commonly have greater volumes of organic deposits than streams. These poorly permeable organic deposits can affect the distribution of seepage and biogeochemical exchanges of water and solutes more in lakes than in streams.

The interaction between groundwater and surface waters are characterised by a high degree of variability and can therefore be difficult to quantify. The variability is a result of climate which defines the hydrological input to groundwater and surface water and the hydrogeological variability within the media and at the interface, where the interaction takes place. The hydrological inputs/outputs in terms of precipitation, evaporation or infiltration can be labour-intensive to measure, but, nevertheless, can usually be quantified with an acceptable uncertainty. The uncertainty in quantifying the exchange of water and solutes between surface water and groundwater can be much greater due to our imperfect knowledge of the geological media at the interface. In case of a lake, the groundwater can either be directed through the the stream, or seep to the surface at the boundary between aquifer and lake and discharge to the stream as overland flow. The determining factors in this case would be the contrast in hydraulic properties of the aquifer and the lake together with the geometry of the system.

In the management (or research) of lakes and rivers, water budgets are always central because they constitute the starting framework when focus is on ecology, the use of the water body for water supply or industry, or recreational use. For example, the residence time of water in a lake can be calculated based on the known/estimated fluxes in or out of a lake. But the interaction between groundwater and surface water is not only important in terms of water budgets, but also because groundwater can transport chemical solutes to surface water bodies. Solutes are therefore also exchanged between groundwater and surface waters. For example, eutrophication of lakes is considered as a result of high nutrient concentrations which may come from groundwater.

The potential vulnerability of groundwater-dominated lakes or wetland/streams has to be further investigated in order to manage and understand not only the exchange of water (water flux, Q) through the interface, but also the exchange of solutes (concentration, C); i.e., we would like to predict the mass exchange flux $J=Q*C$. From a practical viewpoint this ideally involves a few basic aspects: 1) Solute concentrations (e.g. nutrients or pesticides) at the interface of the surface water body and the connecting aquifer have to be mapped and 2) The spatial and maybe also the temporal distribution of the groundwater discharge to the surface water have to be understood and quantified. A complete mapping of discharge and solute concentrations at the interfaces are often not possible due to limited resources, so an integrated approach where data acquisition and modelling are combined is needed. To meet these requirements; 3) the use of hydrogeophysical and environmental tracer techniques can be quite promising for mapping the conditions for seepage on the scale of the lake itself.

Mathematical modeling is used to determine the lake groundwater interaction. The mostly used computer code for lake-groundwater interaction is MODFLOW.

GROUNDWATER MODELING WITH MODFLOW

McDonald and Harbaugh originally develop MODFLOW (MODular 3-dimensional finite difference groundwater FLOW model) in 1984. As the name suggests, the model simulates flow in three dimensions.

Brief description is provided on the physical concepts on which the model is based while avoiding complex mathematics involved. The modular structure consists of a Main Program and a series of highly independent subroutines called "modules". The modules are grouped into "packages". Each package deals with a specific feature of the hydrological system which is to be simulated, such as flow from rivers or flow into drains, or with a specific method of solving linear equations which describe the flow system.

Ground-water flow within the aquifer is simulated using a block-centred finite-difference approach. Subsurface layers can be simulated as confined, unconfined, or a combination of confined and unconfined. Flow from external stresses (such as, flow through riverbeds, flow to wells, areal recharge and evapotranspiration,) can also be simulated. The finite-difference equations can be solved using a number of solvers.

Model Formulation

The three-dimensional unsteady groundwater flow through heterogeneous and anisotropic porous earth material is given by the partial differential equation:

$$\frac{\partial}{\partial x}(K_{xx}\frac{\partial h}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{\partial h}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{\partial h}{\partial z})-W=S_s\frac{\partial h}{\partial t}$$

where,

K_{xx}, K_{yy}, K_{zz} : hydraulic conductivities along the major axes
h : potentiometric head
W : volumetric flux per unit volume and represents sources and or sinks
S_s : specific storage of the aquifer
t : time

In general, S_s, K_{xx}, K_{yy} and K_{zz} are functions of space, for example: $K_{xx} = K(x,y,z)$, whereas h and W are functions of space and time, e.g, $h = h(x,y,z,t)$. Thus, the above equation describes groundwater flow under non-equilibrium conditions in a heterogeneous and anisotropic medium. This equation together with specification of flow conditions at the boundaries of an aquifer system and specification of initial head conditions, constitutes a mathematical model of ground water flow.

Generally analytical solutions of the equation referred above are rarely possible; therefore, various numerical methods may be used to arrive at approximate solutions. The well-known finite difference method, the continuous system is replaced by a system of simultaneous linear algebraic difference equations and their solution yields values of head at specific points and time. Obviously, these constitute an approximation to the time varying head distribution that would be given by an analytical solution of the flow equation.

AQUIFER - LAKE INTERACTION IMPACT ON WATER QUALITY

The quality of groundwater depends on a large number of individual hydrological, physical, chemical and biological factors. Generally high proportions of dissolved constituents are found in groundwater than in surface water because of greater interaction of groundwater with various materials in geologic strata.

As a result of chemical and biochemical interactions between groundwater and the geological materials through which it flows, it contains a wide variety of dissolved inorganic chemical constituents. A classification of the inorganic species that occur in groundwater is shown in Table-1. The major constituents occur mainly in ionic form and are commonly referred to as major ions (Na^+, Mg^{2+}, Ca^{2+}, Cl^-, HCO_3^-, SO_4^-). The total concentration of these six major ions normally comprises more than 90% of the total dissolved solids in the water. The concentration of the major, minor and trace inorganic constituents in groundwater are controlled by the availability of the elements in the soil and rocks through which it has passed, by geochemical constraints such as solubility and adsorption, and by the sequence in which the water has come in contact with various minerals present in the flow path.

Table-1: Classification of Dissolved inorganic constituents in Groundwater.
(Source: Davis and De Wiest, 1966)

Major Constituents *(>5 mg/l)*	Bicarbonate, Calcium, Chloride, Magnesium, Silicon, Sodium and Sulphate
Minor Constituents *(0.1-10 mg/l)*	Boron, Carbonate, Fluoride, Iron, Nitrate, Potassium, Strontium
Trace Constituents *(<0.1 mg/l)*	Aluminium, Antimony, Arsenic, Barium, Barium, Beryllium, Bismuth, Bromide, Cadmium, Cerium, Cesium, Chromium, Cobalt, Copper, Gallium, Germanium, Gold, Indium, Iodide, Lanthanum, Lead, Lithium, Manganese, Molybdenum, Nickel, Niobium, Phosphate, platinum, Radium, Rubidium, Ruthenium, Scandium, Silver, Thallium, Thorium, Tin, Titanium, Tungsten, Uranium, Vanadium, Ytterbium, Yttrium, Zinc and Zirconium

Apart from inorganic constituents, organic compounds (fluvic and humic acids), and dissolved gases (N_2, O_2, CO_2, CH_4, H_2S and N_2O and Noble gases like Ar, Kr, He, Ne and Xe) are also present in groundwater. But the concentration of these constituents in groundwater is very less as compared to inorganic constituents.

When groundwater rich in inorganic or organic constituents mixes with lake water, the quality of lake water may change.

CONCLUDING REMARKS

- Natural lakes are water bodies formed generally formed by the catastrophic geological events or through slow modification of earths landscape.

- Groundwater playes an important role in the survival of lakes throth groundwater lake interaction.
- Water quality of the lakes is affected by the groundwater quality, which in turn is affected by the geology of the area.