Water: Science and society

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Water is an extraordinary natural phenomenon. Its attributes, its role in the functioning of the Earth, and its importance in society excite interest in all branches of knowledge. Because no life can sustain without it, water constitutes a source of economic and political power. The future of modern technological society in a world of burgeoning population may depend as much on judicious water management as on availability of cheap energy. The connections between scientific knowledge and the human context of water are examined to understand how the complex task of living with water may be judiciously approached.

Keywords: Science, society, water.

IN contemporary society, water is a major theme of scientific, economic, political, social, and human debate. There is widespread concern that the future of peace and prosperity in a finite Earth will depend on our civilized ability to share the limited water resources of the world. There is also recognition that such civilized sharing of water is fraught with unprecedented scientific, social, and human challenges interwoven in complex ways. Towards constructively approaching these challenges, this paper outlines our contemporary scientific understanding of water, the philosophical underpinnings that guide water management, and the connections among these. The focus is on comprehending water as a natural phenomenon. It is fitting to start by noting the awe that water has inspired in the minds of ancient and modern humans alike.

In a comparative study of religions, Max Müller[1] examined the Hindu perception of creation from the Rig-veda, in which two ideas of an uncreated and self-developing world, and of a creator or maker run side by side. The world is spoken of as having been originally water without light (*salilam apraketam*; Rig-veda, X.129.3). The water contained in an egg from which everything else sprang forth (Rig-veda, X.82.5). No one knows whence this creation emanated. Even the gods came after it. He who is called the seer in high heavens, he may know, or even he may not. This speculation of ancient Hindus is surprisingly compatible with current understanding of origin of life on the Earth. Based on fossil evidence from western Australia, eastern South Africa, and elsewhere, it is believed that single-celled bacteria and stromatolite colonies flourished in primitive oceans some 3.5 billion years ago. Just as the ancients, modern science has not quite figured out how water came to possess the first egg from which everything else sprang. However, water is an essential component of inorganic mixtures from which chemists, in their quest to understand the origin of life, attempt to produce complex organic molecules.

Among the profound questions that intrigue modern earth scientists is that of the origin of water on the Earth. Deming[2] points out that plate tectonics was established on the Earth's crust only some 2.5 billion years ago, at the beginning of the Proterozoic, and that the nature of the crust during the previous two billion years of Earth's history is unknown. Available evidence suggests that the continental crust originated through hydrolysis of the primitive crust, and that this required large volumes of water. Such large volumes of water, it is speculated, came slowly from extra-terrestrial accretion.

Attributes of water

From deep space, the Earth presents a unique, colourful appearance, unlike other members of the solar system. This uniqueness is largely due to water, both because of its role as a geological agent and its role in sustaining life as we know it. The attributes of water responsible for the extraordinary role it plays on the planet are worth examining.

Water is among a few substances that exist under solid, liquid and gaseous states within the range of temperatures conducive to the existence of life. In the liquid state, it is a slightly compressible fluid, capable of storing mechanical energy and releasing it to do work. Unlike most other substances, water expands upon solidification. Among natural materials, water probably possesses highest heat capacity, and very high latent heats of melting and evaporation. By virtue of its kinetic energy of motion, its strain energy of compression, and its high capacity for sensible and latent heat, water is an extraordinary geological agent, shaping the Earth's surface by denudation and deposition, and governing the evolution of the Earth's crust.

Water is a bipolar molecule, with two positively charged hydrogen atoms on one side of an oxygen atom, which has excess electrons on the other. As a result, a water molecule is oppositely charged, to become bipolar ends. This polarity difference bestows water with some distinct properties. One is that it is electrically attracted to hydrophilic surfaces. Another is that water molecules link together by hydrogen bonds to form cage-like clusters that can trap electrically neutral molecules (non-electrolytes), and electrically charged

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ions. The latter attribute renders water to be an universal solvent. In combination, these two attributes render water to be a pre-eminent geochemical agent in the lithosphere which is dominantly composed of silica and silicates whose surfaces are hydrophilic. Another consequence of polarity is the phenomenon of capillarity. In soils with hydrophilic soil grain surfaces, and in the xylem of plants, capillarity plays a major role in supplying water and nutrients to plant roots, and in transporting water against gravity to leaves to facilitate photosynthesis.

Water also possesses unusual phase transformation properties. Among molecules possessing hydrogen bond (ammonia, hydrogen fluoride), water has highest boiling point and freezing point, lying within the temperature extremes of the habitable earth. Consequently, water is versatile in transporting and distributing energy throughout the Earth, over wide ranges of spatial and temporal scales.

The Earth's geological and biological systems are significantly influenced by aqueous chemistry. At the molecular level, the ability of water to dissociate salts into positive and negative ions, and its pronounced capacity to store and release heat energy, facilitate chemical reactions. Ionic interactions on this molecular scale occur by diffusion of various ionic species and self-diffusion of water, driven by gradients of chemical potentials and by electrical forces generated by the differential motion of positive and negative ions.

In rock and soil systems, aqueous reactions are accompanied by interactions with the solid materials, leading to precipitation, dissolution, adsorption, and ion exchange. Many of these reactions are known to be catalysed by microbes that have adapted themselves to extract energy for their sustenance from specific exothermal chemical reactions. In biological systems, osmotic transport of water, selective transport of charged ions through active and passive membranes, and reverse osmosis of ions play major roles.

On a larger scale, water acts as a transporting agent for redistributing products of chemical reactions that occur on the small scale. The transport of dissolved materials by flowing water is referred to as advection. The transport of heat by moving water may result in buoyancy-induced circulatory motion, referred to as convection. Cytoplasm, the essential component of all living cells, within which synthesis of molecules and transfer of energy occur, is an aqueous complex made up of 70 to 90% water. In higher animals, blood constitutes an extraordinary aqueous system that transports suspended solids, dissolved chemicals and gases. Blood is a non-Newtonian fluid with variable viscosity.

In the functioning of earth and biological systems, water is in a continuous state of motion on many spatial scales, from that of a molecule to that of a mountain. Motion implies work, and the energy needed to move water comes primarily from the sun, and, to lesser extent, from the depths of the Earth. As water moves, and work is done in the process, energy gets continuously dissipated as heat. The nature of this process is such that the dissipated heat is stored in a way that is unavailable to do any further mechanical work. Such stored energy is referred to as entropy, and in natural processes, entropy continuously increases.

The attributes of water presented above, albeit sketchy, enables examination of the role of water in the functioning of the Earth.

The hydrological cycle

Among the planets of the solar system, the Earth is distinguished by the existence of moderate temperature conditions conducive to sustenance of life as known to us. These moderate conditions are partly due to the Earth being neither too far away from nor too close to the sun, and partly due to the presence of water on the Earth. Water, because of its special attributes, responds to incoming solar radiation by absorbing, transporting and redistributing heat energy throughout the Earth. To get a glimpse into this role of water, one has to understand the hydrological cycle, a phenomenon that is at once deceptively simple and profoundly complex.

The total volume of water in the hydrosphere is estimated to be about 1.36×10^9 km^3, of which 97.3% is locked up in the oceans as sea water, and another 2.1% in ice caps and glaciers[3]. Freshwater, critical for sustenance of terrestrial life (plants, animals, and humans) constitutes about 0.6% of the total water inventory. A bulk of this freshwater occurs as groundwater and as soil water, which can be extracted only by plants. Freshwater in lakes, streams and the atmosphere constitutes less than 0.05% of all water on the Earth. Atmosphere alone contains only about 13,000 km^3, or 0.001% of the Earth's water inventory.

Essentially, the hydrological cycle consists in the condensation of atmospheric moisture in the form of rain and snow, its subsequent movement through streams and rivers to the ocean, its circulation through soils and rocks, and its eventual return to the atmosphere via evaporation and transpiration. Implicit in this simple concept is the need for mobile water. The availability of such mobile water, as contained in rivers, streams, groundwater, and the atmosphere, and the small portions available for evaporation in the oceans, lakes, and the soil, is less than 0.05% of all the water available on the Earth. Yet, this small quantity of water, through vigorous cycling, has dictated the geological and biological history of the Earth for billions of years. That so little can do so much is fascinating .

The atmosphere

The hydrological cycle is largely driven by solar energy. Of the total solar energy received on the Earth's surface, about 40% is returned to the atmosphere as latent heat of evaporation, and another 18% as sensible heat. Within the atmosphere, water plays a significant role in the redistribution of energy through meridional or longitudinal convection cells, as well as through zonal or latitudinal circulation patterns. The average annual precipitation over the entire surface of the Earth is estimated to be about 100 cm, amounting to a total volume of about $5 \times 10^5 \text{ km}^3$. This is about 39 times the total quantity of all water in the atmosphere, implying that the average residence time of water in the atmosphere is about 9.4 days. Yet, this atmospheric circulation is dynamically linked to the much larger time-scales of circulation of surface water (years to decades) and groundwater (decades to centuries), and has influenced the Earth's evolution over billions of years.

Climate results from a complex interaction of solar energy with the Earth's hydrosphere and the atmosphere. A knowledge that has emerged over the past few decades is that the very large heat capacity of the Pacific Ocean, in combination with the disposition of the trade winds, is responsible for the global climatic phenomenon known as El Niño. Every few years, this phenomenon is known to create abnormal climatic conditions from the west coasts of the Americas to Asia and Australia. Long-term climate variability is a function of fluctuations in incoming solar radiation and of the release or retention of energy by the atmosphere. Variations in the intensity of solar radiation falling on different parts of the Earth because of slight changes in the Earth's orbit (Milankovich cycles) can cause the advance and retreat of ice caps on a time scale of tens of thousands of years. Current concerns about global warming stem from the changes in storage of energy in the atmosphere arising from an increase in the concentration of carbon dioxide. Palaeoclimatic studies have indicated that droughts lasting for over a century occurred in western North and South America during the medieval times[4].

Pristine rain water is a very dilute solution, containing a few parts per million (ppm) of total dissolved solids, in addition to small amounts of suspended aerosols and dust particles. In areas proximal to the oceans, the aerosols may include salt. Rainwater contains about 8 ppm of dissolved oxygen. The small amount of carbon dioxide in the atmosphere dissolves in rainwater to render it mildly acidic. The mild acidity and dissolved oxygen set the stage for chemical weathering of the lithosphere. The twentieth century witnessed significant increases in sulfur dioxide in the atmosphere, arising from the burning of fossil fuels. The oxidation and subsequent dissolution of this sulfur dioxide led to enhanced acidity of atmospheric precipitation in certain industrialized part of the world. This discovery has since led to serious efforts to reduce such sulfur dioxide emissions.

Surface water

Of the precipitation reaching the Earth, a portion flows over the land to constitute runoff. Although most streams seek the base level of the oceans as their final resting place, streams of closed inland basins may end up in seasonal lakes and playas. Interruption of surface run-off through natural and human causes gives rise to lakes. Streams and lakes together make up surface water bodies. As streams move water from higher to lower elevations, potential energy is converted to kinetic energy. As the moving water encounters frictional resistance of the stream bed, work is done. On an appropriate time scale, a balance arises between the impelling gravitation forces and resistive forces, and this balance is reflected in the myriad drainage patterns of watersheds. A working hydrological hypothesis is that drainage networks represent the most efficient organization for conveying a maximum quantity of water and sediments from source areas to areas of discharge. A corollary is that, if human actions disturb the existing pattern, natural forces will act towards asserting a new equilibrium. The watershed constitutes the most rational unit for understanding the functioning of streams. Because a large river is made up of a multitude of small streams, each with its own watershed, a large watershed is a hierarchical assemblage of numerous small ones. The interrelationships among watersheds of different spatial scales are of fundamental interest to geomorphologists, hydrologists and water managers.

Stream-flow generation occurs following rain storms or following spring melting of snow at high latitudes. Both these tend to be seasonal and are restricted to a few months in a year. There exists a noticeable time-lag between the duration of storm precipitation on the one hand, and duration and pattern of stream run off on the other. This time lag is a function of the shape and size of the catchment, geology, soils, vegetation, and antecedent moisture conditions. In perennial streams, the flow during non-stormy seasons is maintained by gradual release of water into the stream from the groundwater system. This component of the flow is referred to as base flow, in contrast to the seasonal storm flow component. The existence of base flow is a clear indication that groundwater and surface water together constitute a single interconnected resource. If one follows a river from its source in upland watersheds to its delta, the stream is found to recharge the groundwater reservoir in the upper reaches, especially where there is an accumulation of coarse gravel and sand. Downstream towards the delta, the river tends to receive inflow from groundwater.

The Earth's erosional cycle is intimately intertwined with the hydrological cycle. The upper reaches of a river constitute source areas where sediments are generated by mechanical and chemical denudation. Sediments are transported in the form of bed load and suspended load. Because a stream's ability to do work depends on its kinetic energy, sediment transport occurs mainly during storm runoff. Thus, sediments remain mostly in storage on valley flanks and stream channels, moving periodically. The residence time of sediments of a major stream may be of the order of centuries to millennia. Sediments include both organic and inorganic matter on which many plant and animal communities of the lower reaches may depend for their nourishment. Streams thus play an important role in nutrient cycling.

In perennial streams, water quality will vary seasonally, the salt content being noticeably higher during base flow periods. In general, the cation content of stream waters is indicative of the composition of the host rocks in the catchment, while the anion content is indicative of the chemical processes that are active. The chemical role of suspended sediments in streams is now attracting increased attention because electrically active surfaces of clays, colloids and organic matter have the ability to adsorb and transport metals, pesticides, and other toxic chemicals.

A significant development during the second half of the twentieth century has been the recognition that it is impossible to study streams and lakes without simultaneously understanding the living communities of plants and animals associated with them. These communities, referred to as ecosystems, represent an adaptation of the various organisms to the physical, mechanical and chemical environment provided by streams, lakes, and wetlands. Aquatic ecosystems are classified, depending on water velocity, sediment texture, water chemistry and other factors in riparian, littoral, lacustrine, estuarine and so on. Organisms of ecosystems, from planktons and invertebrates, to plants, fish, and higher animals undergo stress when the physical and chemical conditions of surface water bodies change, either naturally or due to humans.

Groundwater

Following precipitation, a part of the water infiltrates below land surface to replenish the soil and the groundwater reservoir. Here, the term soil denotes the region between the land surface and the water table, while the term groundwater refers to all water below the water table to great depths. In the soil, both water and air coexist in the pore spaces. A profound consequence is that the capillary water in the soil can only be extracted by plant roots, within certain range of conditions. Groundwater, on the other hand, can be extracted by humans through wells. Groundwater and soil water together constitute the lower part of the hydrological cycle. It is fascinating to follow the path of water from the time it enters the groundwater reservoir and the time it emerges back at the land surface. This path is at the core of the concept of regional groundwater motion. This motion is largely driven by gravity, modified at depths by the Earth's internal heat.

At higher elevations of a watershed, infiltrating rain water moves vertically down through the soils to the water table, and continues to move under gravity. These are areas of groundwater recharge. The flow path responds predictably as it encounters layers of different resistance (permeability). Where the resistance is low (aquifers) the path tends towards horizontal, and vertical where resistance is high. A consequence is that the path is deflected gradually from vertically down in recharge areas to vertically up in the lower parts of the valley (discharge areas), where wetlands and swamps can be seen. At greater depths, the deflection of flow path back to the land surface is aided by buoyancy forces and thermal pressurization associated with the Earth's geothermal heat. Depending on local geological conditions, the length of a flow path may vary from a few hundreds of meters to hundreds of kilometers. The journey of water from the time it enters a recharge area to the time it sees daylight may take from a few weeks to millions of years.

Because water is an universal solvent, with ability to carry heat and do mechanical work, the groundwater flow path dictates the geochemical evolution of soils, rocks and mineral deposits. Water plays a vital role in the functioning of ecosystems. In general, water that enters the recharge area is mildly acidic and oxidizing. As it migrates from the recharge area, its anionic content changes from bicarbonate to sulfate to chloride dominant. Discharge areas tend to be characterized by anaerobic, reducing conditions, with relatively high concentration of dissolved solids. Along the flow path, the interaction between water and the solid matrix is governed by thermodynamic considerations of mass balance, mass action, electrical neutrality, electron conservation, and phase rule. A consequence of these constraints is that groundwater continuously scavenges and precipitates salts along its flow path. The distribution of soils, minerals and rocks in the Earth's crust is a manifestation of this geochemical action of groundwater. Analogously, the adaptation of microorganisms and plants to chemical changes along the groundwater path is reflective of ecosystem variations.

Groundwater that is deflected back to the land surface is ready to be transported back to the atmosphere to complete the hydrological cycle.

Evaporation and transpiration

Water in contact with the atmosphere in surface-water bodies, the oceans and the soil is susceptible to undergo phase change and reenter the atmosphere as water vapour. This transformation may occur in two ways: evaporation and transpiration. Evaporation is the direct conversion of liquid water into water vapour from open water surfaces, and from the soil surface close to the land surface. Transpiration is the process by which water, after participating in photosynthesis, is given off to the atmosphere as water vapour from the stoma of plant leaves.

As one would expect, the potential for evaporation is very high in warm, desert regions. However, actual evaporation is limited by the availability of water. In the case of soils in desert areas, as water evaporates from near the land surface, additional water has to be brought up from the water table below. If the soil near the land surface becomes too dry, the associated strong decrease in soil permeability can cut off water supply from below and inhibit evaporation. Thus, evaporation could be self-limiting in desert areas. Water needed to sustain the growth cycle of plants is referred to as consumptive water. Consumptive requirements of individual plants may widely vary from desert plants (xerophytes) to deep-rooted plants (phreatophytes). It is difficult to separately estimate evaporation and transpiration over a given area. Therefore, it is common to estimate their combined contribution, known as evapotranspiration.

Water budget

Regardless of whether one wishes to manage water in a small watershed, a state, a country or even the world, the first step is to get (a) an average sense for the total amount of water brought in by precipitation, the amount of water that becomes part of runoff, groundwater recharge, and evapotranspiration, and (b) the variability of these quantities about the average value over long periods of time. This water budget, subject to uncertainty, is the basis for water resources planning. Although the relative magnitudes of these components will depend on a variety of factors, it appears that evapotranspiration constitutes the largest of the three components, ranging from about half to more than two-thirds of total precipitation. The remainder is divided between surface runoff and groundwater recharge.

Nutrient cycling

Water on the Earth is so intimately tied up with life that a discussion of the hydrological cycle is incomplete without a look at nutrient cycles. The numerous chemical elements that are required for the sustenance of life are referred to as nutrients. It is revealing to briefly look at how three of these, carbon, nitrogen, and phosphorus are used over and over again to sustain life.

Photosynthesis is the primary process by which inorganic carbon comes to be fixed in the body of plants, and through plants in almost all other living things. This process depends entirely on atmospheric carbon dioxide, which constitutes a small fraction of one per cent of all carbon on the Earth. Plants do not have the ability to extract carbon from soils and rocks where it is available in abundance. Nitrogen, on the other hand is most abundant in the atmosphere. Yet, plants cannot extract nitrogen from the atmosphere, but from the soil where it has to be first fixed by microbial and other causes. Phosphorus, a vital nutrient, is soluble in water only under very restricted range of acidity and oxidation conditions. Plants have to rely on this narrow set of conditions to extract phosphorus for their sustenance. Water plays an important role in chemical reactions of all these cycles. The implication is that the nutrient cycles are intimately and delicately intertwined with the hydrological cycle. Perturbations of the hydrological cycle can lead to significant impacts on nutrient cycles, imposing stress on ecosystems.

Water and society

Simultaneously with spiritual veneration for water, ancient civilizations showed great creativity in understanding water and harnessing it for human needs. Three millennia before Christ, King Menes of Egypt[5] diverted the Nile with a 15-m dam to found Memphis, his capital city. About the same time, Egyptians began using the earliest instruments (Nilometers) to measure flood stage of the Nile so as to plan the diversion of water for agriculture. About 1760 BC, Hammurabi conquered the Euphrates and Tigris with a network of irrigation canals, and set in place the earliest known human laws for regulation, distribution, and maintenance of the irrigation structures. Around 1700 BC Joseph's well in Egypt reached down to a depth of 100 m to intercept the water table, while sinnors (water tunnels) were used in Palestine and Syria to divert water from natural springs to towns. Recent archeological excavations in the Rann of Kutch have revealed an ancient town, Dholavira, that flourished between 3000 and 1500 BC[6]. This carefully planned town possessed an elaborate system of diversion structures, reservoirs and wells to provide year-round water supply in an arid environment. Ever since, control of water for human benefit, and for wielding power has been part of human history the world over.

Current understanding of the hydrological cycle shows that this phenomenon involving a fraction of one per cent of all water on the Earth sustains all life. Living communities of microorganisms, plants and animals show adaptation to their local environment, comprising the air, the land, the soil and the water. The hydrological, nutrient and erosional cycles on which all living communities depend are delicately interlinked. Undue human intervention with these cycles can force them towards new equilibria that may seriously stress or otherwise endanger existing communities. Global warming, salinization of soils, desertification, endangerment of species, contamination of freshwater supplies, and so on are examples. These impacts are affecting developed and developing nations alike. Large portions of the world's population lack safe drinking water, or elementary sanitation. Simultaneously, the aspirations of a free market society seek to optimize profit through intensive exploitation of water, among other natural resources. Such optimization is better achieved if water can be privately owned. In a finite Earth, constrained by the subtle interactions among the hydrological, nutrient and erosional cycles, there is a conflict between perceived right to unlimited individual profit on the one hand, and on the other, the right of every human being to water that is vital for sustenance. Who owns the water? How should society respond?

Over two centuries following the industrial revolution, science and technology became preoccupied with spectacular successes in understanding and manipulating nature's physical attributes. With concurrent growth of democracy and freedom, the potential for converting technological successes into unlimited profit came to be regarded as a fundamental right. However, science and technology slowly recognized the inevitable constraints imposed by a finite Earth and its living communities on human aspirations to control nature. Perhaps the most important development of the onset of twenty-first century is the recognition that in a finite world with burgeoning population and visions of compassionate living, the paradigm of prosperity through nature subjugation needs to be supplanted by one of civilized adaptation. Although this paradigm shift is emerging, it is by no means universally accepted.

It is not that Western civilization, that has led modern scientific revolution, has always been unaware of the profound conflicts between political control of natural resources and the right of a common citizen to have access to such resources for sustenance. It was simply that post-industrial revolution technological successes overlooked historical traditions. The historical roots of the doctrine of public trust[7] provide a glimpse into how one may approach the conflict between individual freedom to pursue prosperity and the right of everyone to have access to life-sustaining resources.

Based on reason and morality, Greek philosophers distinguished between immutable laws of nature and transient laws enacted by humans[8]. This distinction was borrowed into the Justinian Code of Roman Law enacted during the sixth century AD. In keeping with contemporary experience, it was noted that by the law of nature, the air, running water, the sea, and the shore of the sea were common to mankind, and that no one can be forbidden from access to these. This component of the Justinian Code forms the basis for what is now recognized as the public trust doctrine. During the 13th century, this doctrine influenced the Magna Carta, which guaranteed the access of individuals to rivers and streams. Soon after American independence, the doctrine was incorporated into the Northwest Ordinance of 1787 of the United States of America. Inspired by this Ordinance, public trust became part of the constitutions of the many states that subsequently joined the Union. In the US at present, each state holds water in trust for its people, and has the responsibility to assure that water is put to beneficial use, without waste. Water use is permitted by the state under the principle of usufruct, meaning that the resource itself is not to be impaired in the process of the specified use. Although many states of the American west are now using the moral authority of public trust to enforce controlled and integrated water management, legal challenges to public trust doctrine are common. These challenges tend to interpret public trust narrowly, as being restricted to coastal waters and coastal land. Recent high court decisions from New York, California and Hawaii[7] indicate an increasing judicial trend to expand the scope of public trust to include environmental and ecological concerns in which water plays a central role.

Based on the veneration and awe that water commands from all cultures and religions, one should expect that the spirit of public trust is likely inherent, in one form or other, in the historical traditions of all societies. In the future, one would suppose, these traditions will have to form the basis for water policy, as the available water resources, vulnerable to climatic uncertainty, are stressed by expanding technology and burgeoning population.

Water management in every society is a complex task, subject to competing forces and interests. To guide decision making, therefore, it is very desirable to identify a set of basic premises that all have to abide by. It is apparent that the set of premises must reflect the laws that govern nature of water, the role that water plays in the sustenance of living things, and the human values that define a civilized society. In this spirit, three premises are presented below[9]:

Premise 1: Laws of Nature

The hydrological cycle, the erosional cycle, and the nutrient cycle are subject to immutable physical laws that are beyond human control. So also are the fluctuations in solar energy that drive the Earth's near-surface processes, and the thermal forces of the Earth's interior that drive plate tectonics.

Premise 2: Sustenance of Life

The hydrological cycle, the erosional cycle, and the nutrient cycle sustain all life. These life-sustaining cycles are delicately interlinked and respond to the forces that drive the Earth. Humans now possess the ability to significantly disturb the delicate linkages and destabilize the sustenance of various types of living communities.

Premise 3: Civilized Living

Human values of compassion, equity, and justice are intrinsic to civilized living. These require that water, so vital for all life, is not monopolized by any individual or group of individuals. Water should be put to beneficial use, without wastage, in such a way that the integrity of the life-sustaining cycles is disturbed as little as possible at the present time as well as into the foreseeable future.

Water in India

The thoughts presented above provide a rationale to reflect on India's water situation from a philosophical perspective.

India occupies over three million km^2, with enormous diversity of climate, landscape, geology, flora and fauna. It has experienced continuous human habitation for millennia, and the imprints can be readily discerned in India's land-use and water-use patterns. Post-independence India has seen spectacular growth in agriculture, and the onset of the twenty-first century is witnessing unprecedented industrial expansion. Water played a critical role in post-independence India, and it promises to play an even more critical role in India's future.

There is a widespread consensus that six decades after independence, India's water situation is characterized by scarcity and lack of coordinated planning. Large tracts of India are vulnerable to vagaries of floods and drought. In many parts of the country, groundwater levels continue to decline due to overdraft. Assured clean water supplies are lacking in urban centers and in rural villages. India's water future is of much public concern. With great expectation the country looks ahead to economic prosperity. Can such prosperity sustain without adequate, safe, stable supplies of water, and sanitation to all segments of society?

Currently, two major themes are receiving attention to overcome India's water woes: rain-harvesting and inter-linking of major rivers. The first is based on the premise that by intercepting rainfall where it occurs, storing it and using it locally, significant additional water can be brought into use[10]. The second is based on the premise that by moving large quantities of water over hundreds or even thousands of kilometers, modern engineering can homogenize water availability throughout the country.

Both these initiatives merit examination from the larger context of the hydrological cycle. It seems likely that in parts of India, especially in peninsular India, rain-harvesting might already have been fully exploited. For example, Tamil Nadu, occupying one-third the area of California, has 39,000 irrigation tanks, of which 18,600 have water spread in excess of 40 ha[11]. In comparison, there are less than 1,400 man-made reservoirs in California. Andhra Pradesh reportedly has some 50,000 tanks. The impact of these structures on downstream sediment transport, stream flow, and habitats is largely unknown. Similarly, the potential impact of moving large amounts of water across river basins needs attention from the perspective of hydrological, erosional and nutrient cycles. Water resources management is not just about moving water any more. The US, which initiated large water projects during the 1930s, is beginning to examine the wisdom of large scale water transfers.

If both these initiatives can be questioned, what should India do? Judging from our current knowledge of how the Earth functions, nothing magical can be done. These active initiatives need to be assessed in the wider context of the total water system, so as to avoid the mistake of maximizing profit through partial knowledge. The focus needs to be on learning to live within nature's constraints.

Whereas modern business seeks to optimize profit through rapid and efficient exploitation of a resource, earth and biological systems function differently, repeatedly recycling a very small fraction of the inventory. Therefore, attention needs to be devoted to systematic, sustained water resources planning and management. Watersheds, on several interrelated scales need to become units of management, founded on rational concepts of water budgeting and adaptive strategies, geared to early detection of unexpected impacts. Integrated monitoring of water and ecosystems must become an intrinsic and permanent part of water management. The success of such water management will depend on an active, water-literate public. Unprecedented opportunities exist to bring science and society together in a manner that befits India's unique history, character and ambitions.

India's political leaders, administrators and academies of learning may do well to inspire and encourage India's talented youth to take on the tremendous challenges of adapting to earth and biological systems that transcend the bounds of physical sciences. The survival of civilized living may depend on our ability to live with water on nature's terms.

It is appropriate to end with an insight of the ancient poet about the nature of water (Rig-veda, VII.49.2),

> yaapo divyaa utavaa sravanti khanitrimaa utavaa yaa swayam jaa |
> samudraartha yaa soochayapaavakaasta aapo devi iha maamavantu ||

'The waters which are from heaven, and which flow afer being dug, and even those that spring by themselves, the bright pure waters which lead to the sea, may those divine waters protect me here.'

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