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Chapter

Sustainability of Human, Plant, and Aquatic Life: A Theoretical Discussion from Recharge to Discharge

Joe Magner and Modreck Gomo

Abstract

Groundwater comprises about 1.7% of the earth's total water and over 30% of the total freshwater supply. Is there enough groundwater to meet human, plant, and aquatic life needs? In many parts of the world, yes; however, with changing demographics and concordant land use and climate change, the distribution and availability of groundwater may not be sustainable. This chapter considers some of the current and past stressors of groundwater by using case examples from around the world. We explore hydrogeologic settings where anthropogenic activity has impaired or has the potential to impair human, plant, and aquatic life. Stressors include well pumping, mining, climate change, chemical use, water law/regulation, and manipulation of surface water. These examples serve to inform those concerned about sustainable management and offer insight into the links between groundwater, climate, and land use.

Keywords: aquifer, discharge, groundwater, recharge, landscape, sustainable

1. Introduction

Human life requires clear, clean, and adequate water to physically survive [1]. Besides direct consumption, water is needed to grow and prepare food. The source of the water for human use comes from the sky and then takes varying paths into the human body, plants, and aquatic life. Fifty percent of the world population obtains their water from groundwater; however, the number is larger when considering that 40% of streamflow is derived from groundwater discharge into a channel during baseflow [1].

Aquatic life is 100% dependent upon water, and when water disappears or changes temperature or becomes contaminated, fish and other organisms die or move or adapt. When a watershed changes vegetation or the amount of impervious surface, the hydrologic pathways shift from infiltration-evapotranspiration to subsurface/interflow to overland runoff. Aquatic life tends to degrade and even disappear as a watershed loses the sustained steady discharge of groundwater into fluvial habitat [2].

Whether human, plant, or aquatic life, groundwater is life-giving; without groundwater our quality of life and the quality of rare plants and aquatic life are less than optimal! Apart from connate water (water held in storage from a different climatic era [3]), groundwater is renewable—the question we address is how we sustain groundwater to meet the current and future demands of human, plant, and aquatic life. The answer is embedded in watershed management; land use decisions in both space and time greatly influence the hydrologic pathways and processes, which also influence human, plant, and aquatic life.

This chapter uses examples of hydrogeologic landscape settings in North America, Europe, Asia, and Africa to illustrate the theoretical movement of water from the sky upon, over, into, and through a watershed. We will address a range of settings and scales to elucidate systems' understanding. It is our hope that this approach will help the reader see critical thresholds that sustain human, plant, and aquatic life in a changing environment. Future groundwater managers will need to grasp the ramifications of their decisions, because like a large ship in the ocean, we can turn or stop the vessel before it may be too late. Well thought-out management decisions about future groundwater supply and demands are needed more now than ever before.

2. Recharge to discharge

What do we mean by *recharge*? It is the water that infiltrates beyond the vadose zone (unsaturated zone) to add to the phreatic zone (zone of saturation); this zone may or may not be an aquifer but part of runoff via interflow and the variable source area that contributes to surface water [2]. Water that *infiltrates* the soil surface does not automatically become groundwater. When plants are present, roots will sequester infiltrated water and pull the water through the plant for physiological needs such as cooling via transpiration. When plants die or go dormant, infiltrated water can move via gravity to the top of the water table or zone of saturation. Temperature can be a factor if water in the vadose zone freezes and becomes immobile until a soil thaw occurs. In the northern hemisphere, the soil thaw occurs in the spring (late March to April). Typically, this is the time of the year water *percolates* through soil pores or fractures to become groundwater. Water that moves in the saturated zone is constrained by the pores (void space) and the pressure or hydraulic head moving groundwater known as *transmission*. The pathway and destination of the groundwater depend on the permeability of the geologic material. Transmissive material is considered an aquifer where water moves relatively quick based on forces of gravity or extraction. Because the earth is not uniform in topography or the size of geologic materials, groundwater will typically move to a *discharge* location over some period. Discharge refers to a point or plane where groundwater is released back to the open free surface. In a natural watershed, these areas of discharge are known as springs, headwater streams, wetlands, ponds, lakes, or even an oasis in the desert [2]. Except for a spring or oasis, it may not be apparent that groundwater is being pushed to the surface. Often, instrumentation is needed to measure groundwater discharge to a surface water body. Yet, where humans have placed a pipe in the ground or water well, discharge occurs through abstraction or pumping for domestic consumption and crop irrigation. The question raised in this chapter is if human interjection in terms of vegetation, land surface management and infrastructure; wells and channel control are changing future sustainability? Human actions have consequences!

3. Hydrogeologic landscapes

The following case examples illustrate both temporal and spatial scales of differing groundwater systems by physical location, topography, geology, vegetation, climate, and land use. We then explain the recharge to discharge story and comment on human alteration and/or benefit, plant floristic value and/or impact, and aquatic life needs and/or impact.

3.1 Large-scale African systems

Table Mountain Group (TMG) aquifer is a regional fractured-rock aquifer located in South Africa where the climate changes with elevation. The aquifer is a major source of water supply for agricultural and urban water requirements in the Western and Eastern Cape Provinces of South Africa [4]. Where the shale layers are not present, groundwater recharge can move deep into the transmissive sedimentary bedrock.

Figure 1 shows a schematic illustration of groundwater recharge and discharge areas and linkages of interaction between surface water and groundwater resources in the TMG aquifer [5]. Groundwater recharge mainly occurs in the higher elevation mountainous terrain areas, while natural discharge occurs in lower elevation valleys and foothills. Nevertheless, shallow groundwater occurs in the alluvial deposits, but downward movement is constrained by shale. The shallow groundwater has a shorter residence time and is not influenced by the more thermally connected mountain recharged water. This water is critical for plant and aquatic life, but during drought conditions, the shallow groundwater can be strained.

The main pathways of natural discharges from the TMG aquifer include 11 thermally heated springs and numerous cold spring discharges up through the quaternary and alluvial sediments providing baseflow to streams and reservoirs, wetlands, and seepage to the ocean [4].

Groundwater discharges naturally and through man-made abstraction via wells. Groundwater is used for portable urban water supply and a variety of agricultural activities. The groundwater is a driving force which sustains human health and regional economy. Natural groundwater discharges from the TMG aquifer contribute to surface water resources in two major ways: firstly as contributions to the flow regime of mountain and foothill streams and rivers and secondly as groundwater contributions to wetlands and other aquatic ecosystems inclusive of marine discharges [4–6]. These natural discharges which take place in different ecotones and scales, as influenced by the subsurface heterogeneity, have an important role for nourishing and sustaining the plant and aquatic life systems in different ways.

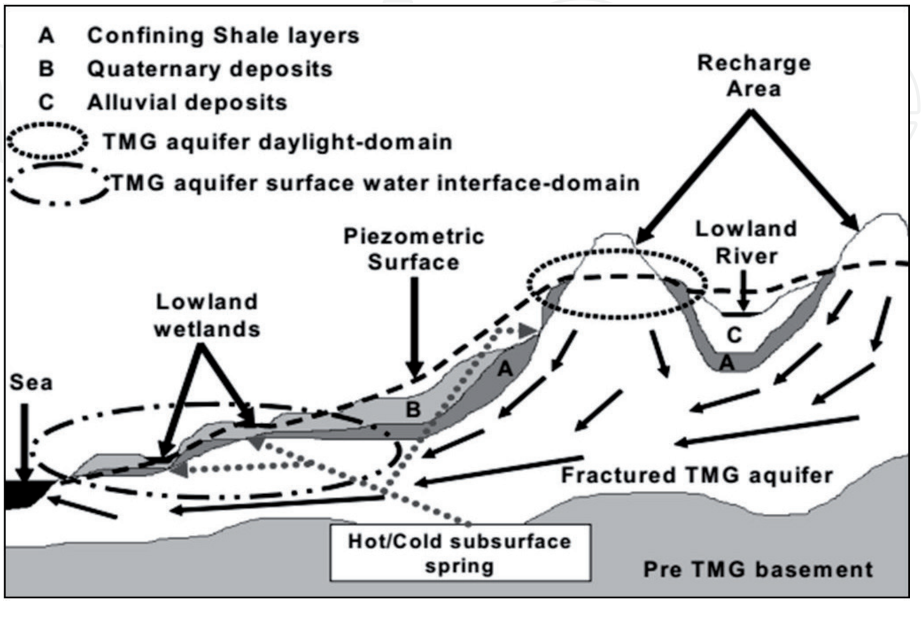

Figure 1.
A schematic illustration of the main groundwater recharge and discharge areas and linkages of interaction between surface water and groundwater resources in the TMG aquifer [5]. Source: [5].

Plants and fish adapt to the temperature and mineral content of the discharging groundwater. As shown in **Figure 1**, protecting the deep groundwater recharge areas is foundational to sustain human, plant, and animal health.

The Stampriet Transboundary Aquifer System (STAS) is shared between Namibia and Botswana, South Africa (**Figure 2**). The largest portions of the aquifer occur in Namibia's arid region which extends to Western Botswana and a small part of South Africa's Northern Cape Province. Auob and Nossob ephemeral rivers constitute the major surface water resources. The groundwater system is composed mainly of the unconfined Kalahari aquifer units overlying the Auob and Nossob confined sandstone aquifers [7].

Research has shown that most of the recharge occurs in the northwestern portion of the watershed in Namibia (**Figure 2**). The recharge typically occurs over a large diffuse area through the unconfined Kalahari formation. Water then preferentially recharges the confined aquifer systems where hydraulic heads and aquifer permeability converge. Several studies strongly suggest that sinkholes and bedrock faults act as the main pathways for preferential recharging of confined aquifers [8–10].

Natural groundwater discharge from the aquifer mainly occurs through evapotranspiration. Groundwater from the aquifer systems evapotranspires due to the aridity of the region. The Auob and Nossob rivers are ephemeral and lack consistent groundwater discharge; only a minimum contribution of groundwater discharge occurs through baseflow into the rivers. Nevertheless, evapotranspiration is also an important process to maintain/sustain the vegetative ecological balance. Given this reality, managers should not expect a robust healthy aquatic life.

Groundwater discharge from the transboundary aquifer also serves basic human needs for drinking and domestic use. Groundwater from the shared aquifer also supports a wide range of industries contributing economic growth and job creation.

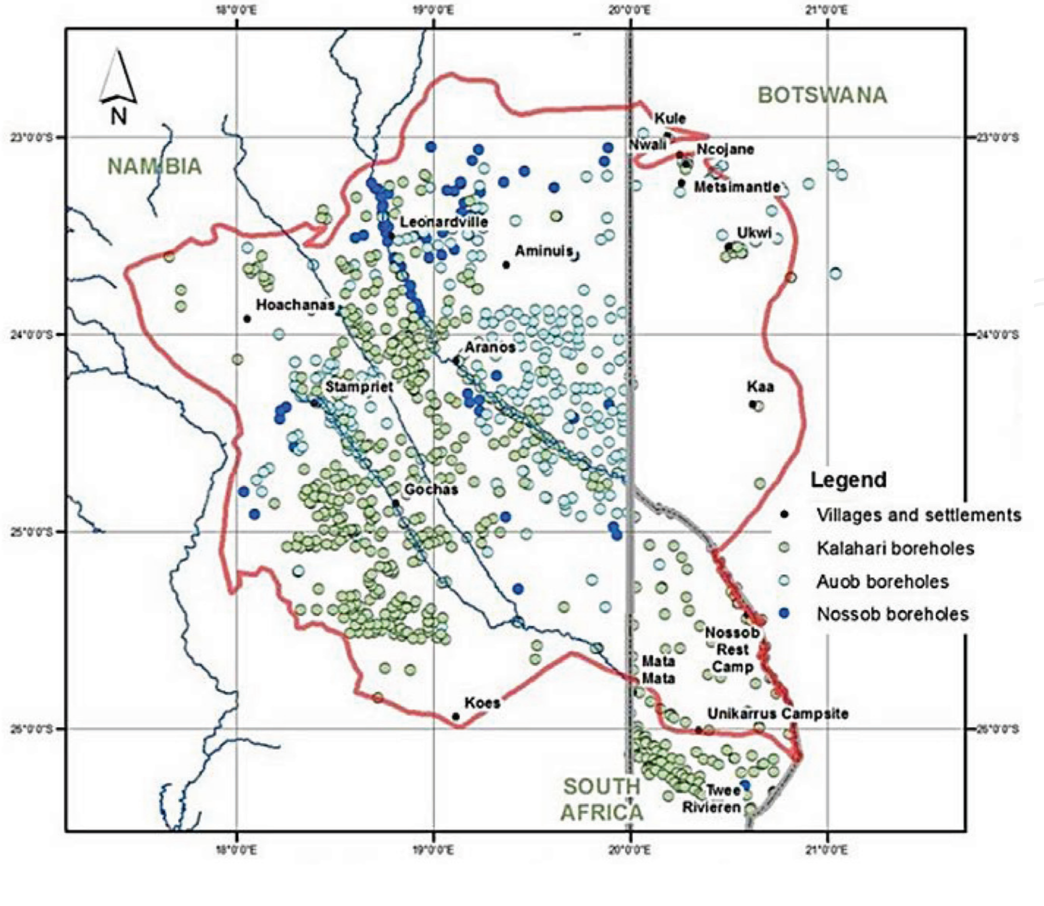

Figure 2.
Stampriet Transboundary Aquifer System and boreholes tapping from the aquifer [7].

Figure 3 shows the relative percentage of land use for each river system [7]. While the scale of groundwater use is different in the three countries, groundwater discharge through abstractions appears to be sustainable.

3.2 North American outwash sandplains: wildlife and irrigated row crops

The Anoka Sand Plain in Minnesota, USA (**Figure 4a**), and the Central Sands region of Wisconsin (**Figure 5**) are formed by rapid glacial melting which allowed meltwater to carry fine sediment south toward the Mississippi River; however, coarse-grain sediment was dropped out quickly to form large flat areas composed mostly of sand with gravel.

Because dense compacted till was laid down by ice advances from Canada, infiltrating water can fill up the surficial sand and gravel aquifer but not move laterally unless a stream, lake, or wetland exists. Stream gradients in these regions are flat because the landscape is flat. In low-lying terrain, the groundwater manifests itself as large wetland complexes, whereas higher ground contains oak-prairie savannahs and crops. Some of these areas are protected by federal and state wildlife legislation [12], but most of the land is in some form of agricultural management. Because the soil has a high sand content, summer evapotranspiration can quickly dry up the upper topsoil, such that only deep-rooted plants survive the warm summer temperatures. High-value crops, such as potato and other vegetable crops, require irrigation to optimize plant vigor and specialty crop quality. In other locations, drainage via ditches is required to prevent crop loss. Some wetlands have been drained to grow grass, known as sod. Because sod is a high-value crop, pumps and lift stations are needed to prevent crop loss due to saturation. Because outwash regions are very flat, groundwater moves slowly unless an artificial gradient is created by ditches and pumps. There is an ongoing battle between nature and human development; the subdevelopment of homes, streets, parking lots, and shopping malls leads to urban runoff and stress upon the plant and animal (wildlife) ecological equilibrium.

In the Central Sands region, intensive agricultural production has led to elevated nitrate-nitrogen concentrations which have threatened domestic drinking water users [14]. Aquatic life does not thrive well in flat channel gradients and sandy substrate; the flat terrain does not allow an adequate cold-water fishery, even though water temperatures in some channels are controlled by groundwater. Nevertheless, amphibian, mammal, and bird wildlife are abundant in wildland areas. Without governmental protection, these areas are at risk of losing their biodiversity [15].

3.3 Incipient karst: non-laminar groundwater flow

Well-developed karst features are present in several parts of the world, most notably Croatia in Europe and Kentucky, USA. Incipient karst differs from developed karst because solution enlargement of fractures has not created caves. The thickness

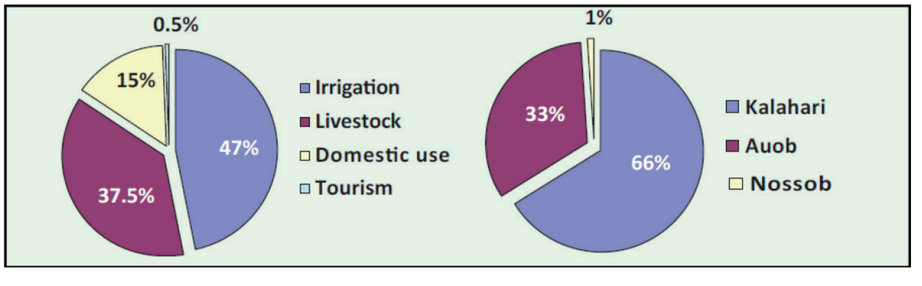

Figure 3.
Groundwater use and abstraction per aquifer type in the Stampriet Transboundary Aquifer System. Source: [7].

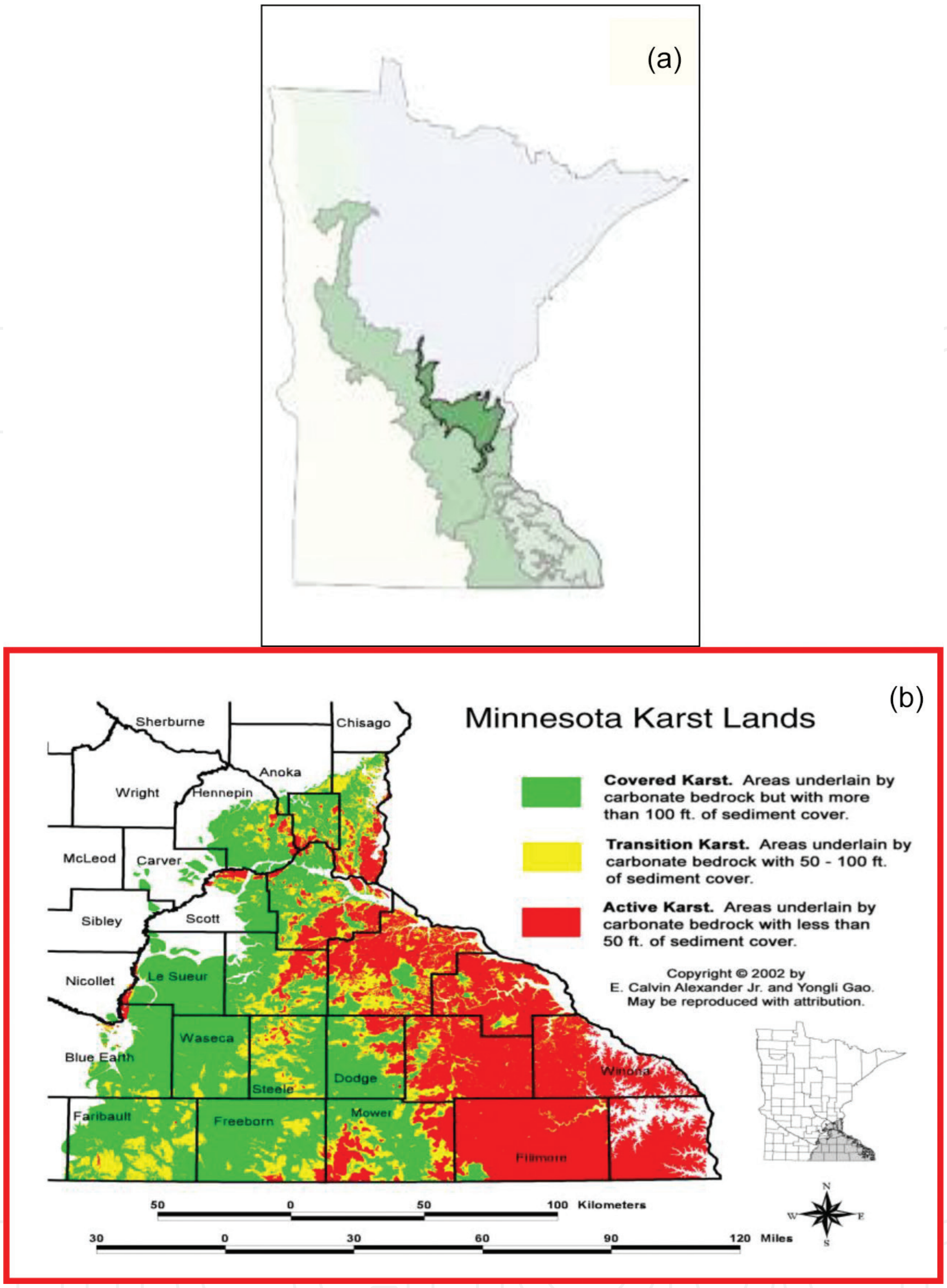

Figure 4.
(a) Illustration of the boundary of the Anoka Sand Plain highlighted in central Minnesota—darken area with a border. (b) Karst areas southeast of the Anoka Sand Plain in Minnesota [11]. Source: Environmental Trust Fund.

of soil cover somewhat defines the boundary between incipient and developed karst (**Figure 4b**). Developed karst is dominated by sinkholes, underground cave streams, and point-source springs. Incipient or immature karst aquifers can have rapid water movement but may not have a landscape dotted with sinkholes and springs where cave streams resurge. Soil pipes are present, but they open and close quickly depending on cohesive soil bridging over bedrock. Subsurface erosion occurs through rock fractures in both carbonate and sandstone rock if the overlying soil is dominated by silt. The silty soil will bridge above a cavity until the soil-bearing strength is exceeded or triggered by changes in soil moisture or land use. The lack of abundant sinkholes makes land use development challenging because short of ground-penetrating radar or other geophysical measurement, there is no way to be certain a structure will not be swallowed by catastrophic collapse at some future date [16].

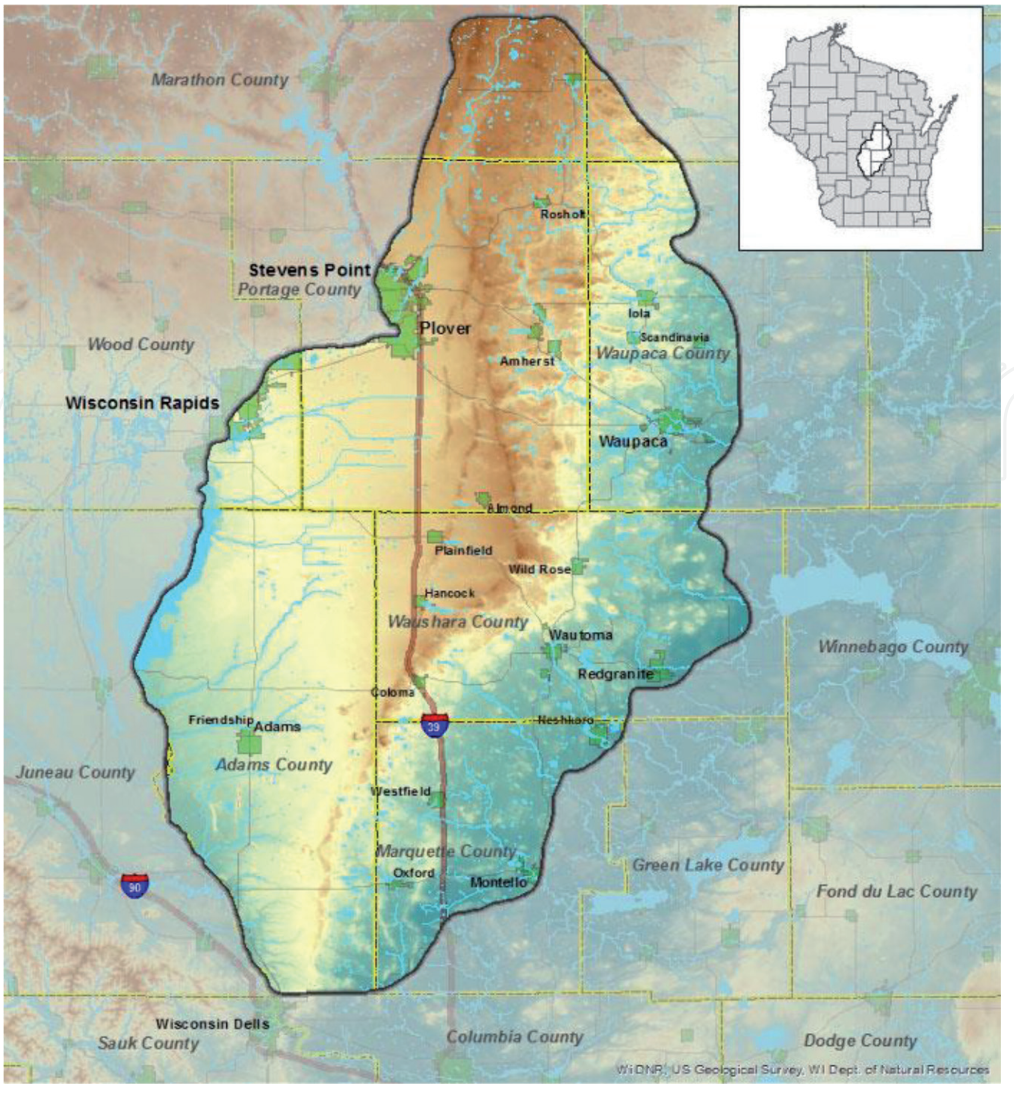

Figure 5.
Location of the Central Sands region in Wisconsin [13]. Source: WiDNR webpage.

With a changing climate, the risk of weak carbonic acid water in contact with limestone/dolomite fractures may drive fracture-opening enlargement, increasing the uncertainty of making sustainable groundwater management decisions. If all fractures below the landscape have a similar size and connectivity, Darcy's law and laminar flow can be assumed and modeled; however, nature's enlargement processes are not uniform but chaotic. This chaos leads to highly unpredictable flow paths and pollutant transport in relatively short time scales: on the order of minutes-to-days compared to months-to-years for Darcian flow. Hydrocarbons, pesticides, nutrients, and bacteria have been observed to move from the surface/near surface into shallow domestic wells and spring-fed streams over short time scales [17]. Future groundwater management will require a field monitoring effort that is more rigorous than sand and gravel systems. Tracking water and solute movement will require a monitoring system like those used in urban watersheds where water movement responds quickly to new precipitation. The largely unknown factor is storage; sustainability will depend upon creating watershed storage to buffer adverse ecosystem service change.

3.4 Midwest US Corn Belt: shallow groundwater

Midwestern states of the USA produce the largest amount of corn grain on the planet. To achieve the massive amount of grain production, the land must be intensively managed to optimize crop growth. Large equipment for planting and harvesting, state-of-the-art agronomic practices from seed, chemical inputs to the grain storage, and marketing drive the Midwestern US economy. The landscape was once a vast sea of deep-rooted prairie grass and wetlands which helped form black fertile carbon-rich soil. In many locations soil wetness created uncertainty in crop management. To address this problem, wide-scale ditch drainage began over 100 years ago to optimize plant growth in wetland environments. Today fewer ditches are dug, but the use of plastic corrugated and perforated pipe that is placed into the soil with laser accuracy is a booming business. This land use practice helps remove excess water in the upper meter of cohesive soil; typically, sandy soils do not use subsurface pipe to improve soil aeration. The cohesive soil acts like incipient karst allowing water in the soils to move rapidly into the pipe because of fractured soil structure. In some ways the subsurface pipe functions like an urban environment producing pipe flow that transfers water to streams and ditches during and after a rainfall event. This change in hydrologic connectivity has caused downstream channels to enlarge over time leading to unstable banks and beds. Further, the chemicals applied to farm fields can move downward into the pipe and cause eutrophication of downgradient surface water. Nitrate-nitrogen has increased with increased placement of pipe; this has, in turn, led to Gulf of Mexico hypoxia [18]. To find a sustainable solution to this problem, water managers will need to find ways to hold water back and treat polluted runoff. Building soil health, regulating pipe discharge, and using bioreactors and saturated buffers are tools to be examined to minimize sediment and nutrient problems to downstream waterbodies.

3.5 Eastern Himalayas: Mizoram springs—will they be sustainable in the future?

Located in the northeastern states of India, east of Bangladesh (**Figure 6**), this landscape is extremely steep with long narrow valleys. The soils are very thin over shale or sandstone. The vegetation is thick and lush given the monsoon rainfall for 5 months of the year. Even though the landscape is covered in perennial vegetation, the water will only infiltrate centimeters before it enters the sandstone or converges as a headwater stream running off to a river some 2500+ meters below.

People depend on water infiltrating the sandstone and then resurging downgradient as a spring for human use during the non-monsoon season. If the landscape is disturbed by slash and burn agriculture, then less aquifer recharge occurs. The solution requires more sustainable agricultural land use and strategically planned capture of monsoon runoff water. The magnitude and intensity of rainfall during the monsoon season may be shifting in a way that is limiting aquifer recharge to occur. If more water is running off the landscape compared to past decades, then land use must adjust to hold back runoff. This not only means less bare soil but improved soil infiltration and aggregate stability. Topsoil must be highly valued and managed to optimize soil health [19]. In selected ravines, a portion of overland runoff should be laterally diverted wherever a slope break occurs; this practice can provide focused recharge into sandstone aquifers to augment water storage and availability during the non-monsoon seasons.

3.6 Eastern front of Rocky Mountains: alpine to semiarid water law

Located along the eastern front of the Rocky Mountains in Montana (**Figure 7**), this landscape is weathered due to wind and water erosion. At high elevations (4000 meters+), temperatures remain cool to cold, so vegetative growth is stunted [20].

The region is managed to capture and hold snow for summer water supply to the dry eastern plains. Soils are loamy over metamorphic bedrock, so there is no deep

Figure 6.
Location of Mizoram in Asia. Source: Google Images.

recharge, just overland and interflow to channels that are formed by snowmelt. Near the toe-slope of the range, water can spill into meadows where more organic-rich loamy soils are mixed with stratified layers of sand and gravel and cobble, allowing snowmelt water to infiltrate and recharge shallow aquifers. Because of a less steep gradient in places, landowners have dug ditches to divert streams into pasture lands. Both natural and diverted waters resurge in wetlands or springs depending on the geologic constraints. However, the water that does not evapotranspire will move out across the land only to infiltrate into the sediment/soil depending on the nature of the geologic material. This occurs because the source of the water is still snowmelt from high-alpine elevations. Though the water has been geochemically transformed by passing through rock and sediment, it is not groundwater in the sense of an aquifer that provides decadal storage. Further, because this water does not always remain in the stream channel as it flows east downstream, users do not receive the benefits of the alpine water because the water will seep through the channel bed into an aquifer. The new climatic reality demands that water managers examine law and policy to find a sustainable way forward [21].

3.7 The North American Great Lakes and groundwater

The Great Lakes in North America provide unique freshwater resources for humans, plants, and animals. Many small tributaries drain directly to a large lake, but in some geologic settings, groundwater discharges into Lake Michigan through

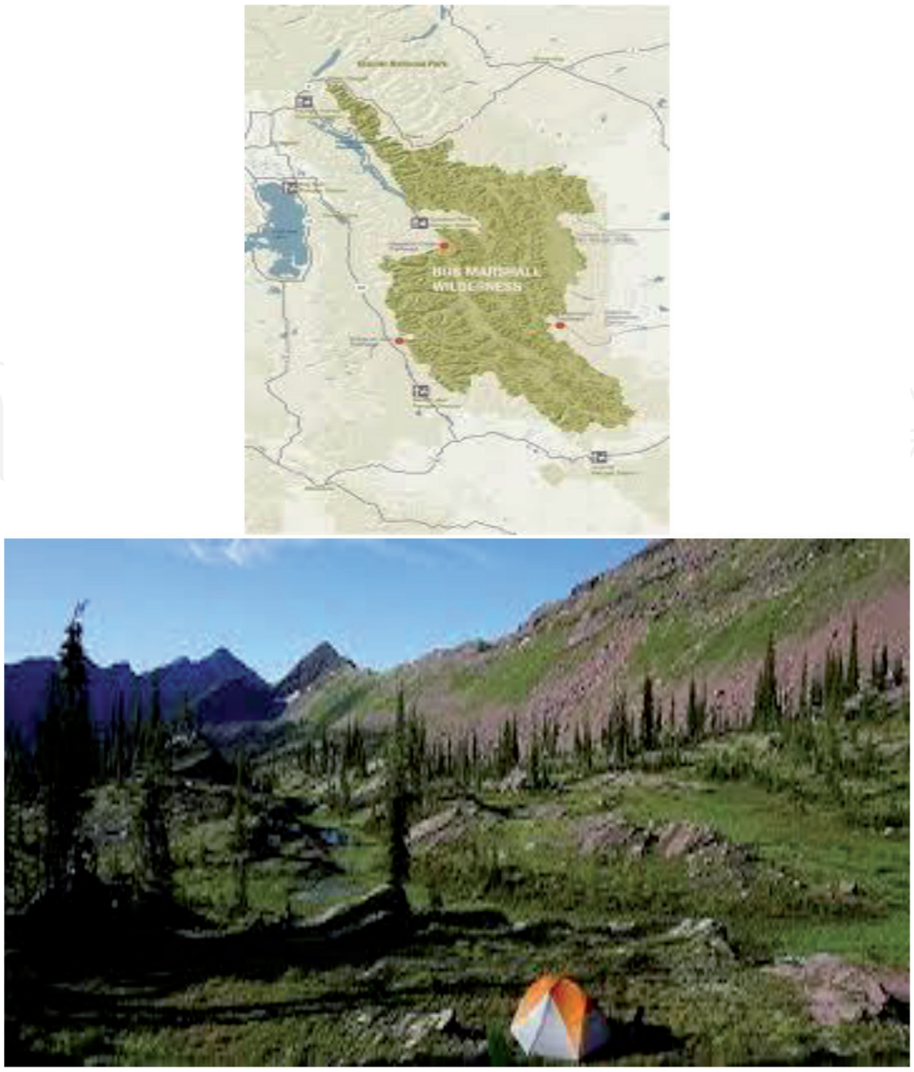

Figure 7.
The location and scenery of the Bob Marshall Wilderness. Source: gravel.org.

sedimentary rock and breach ridge sands. In Door County, Wisconsin (**Figure 8**), coastal springs and wetlands provide ecotones for rare species like the Hine's emerald dragonfly and unique orchids, such as lady's slipper. The Ridges Sanctuary was created in 1937 to sustain plant and wildlife in an area that was rapidly developing to accommodate tourist demands. Near-shore areas were being developed for lodging and food and drinking establishments. Given the high tourist value of Door County, Wisconsin, today, it was possible for people to love the place to death. Specifically, if groundwater recharge areas were paved and rain water redirected to streams, ecosystem services would have been lost. Fortunately, visionaries like Albert Fuller sounded the alarm to the general public and raised awareness to preserve an 18-Ha parcel of land from future development. Over time, studies in Door County, Wisconsin, have provided more information about the natural resources and the need for local government to place restrictions on land development. Groundwater flows from higher ground underlain by dolomite toward Lake Michigan at a rate approaching a cm/second [22]. The large lake waves can push water and sediment back unto the land; over time this process has created sand dunes. At the Ridges Sanctuary, there are a series of dunes with swales, between the dunes are wetlands that provide critical habitat for plants and animals.

Along the north shore of Lake Superior, the geology is metamorphic and gives rise to steep gradients within a kilometer of the shoreline, which differs from the relatively flat shoreline of Door County. The water that infiltrates the shallow soil

Figure 8.
The location of Door County in Wisconsin, an aerial view of the Ridges adjacent to Lake Michigan and vegetation. Source: map.co.door.wi.us., mnnps.org.

and moves downgradient toward Lake Superior resurges where the soil becomes too thin over the bedrock. Glacial Lake Duluth left behind linear zones of sediment: some beach sands and other lacustrine silts and clays. In Amity Creek before branches converge, the valley slope flattens, and alluvial material creates an active flood plain over bedrock. In June of 2012, after a year of data collection from the stream and alluvial aquifer, a large magnitude storm event dropped over 15 cm of rainfall in a half-a-day. This event not only flushed channels; it displaced preexisting snowmelt water contained in the riparian aquifer [23]. We have further noted a complete groundwater flushing from the same storm event in the Cross River watershed [24]. The data gathered from these two watersheds indicate a lack of resilience to climate change. To maintain sustainability for the high-valued tourist region, infrastructure development along the north shore of Lake Superior must be constrained to prevent the loss of ecosystem services. All levels of government will need to agree on the vulnerability of the region.

In the Nemadji River basin, lake sediment dominates the movement of groundwater (**Figure 9**). The west end of Lake Superior was formed by beach ridges laid upon coarse till, whereas the central part of the valley is composed of loose lacustrine silts and clays that settled when glacial Lake Duluth drained to the east. This sediment deposition pattern creates a unique groundwater flow system. Water recharges rapidly through sand and gravel in the headwaters but then builds up pressure as it tries to find a discharge path into the Nemadji River. Because there is over 25 meters head drop from the headwaters to the main valley, the valley walls are under hydrostatic pressure and ooze water through the lacustrine silts and clays. Bank and bluff geotechnical failure are a natural phenomenon that creates a continuous turbid water clarity in both discharging groundwater and surface water [25].

The loss of large perennial trees and conversion of land to managed grass crops altered the hydrologic evapotranspiration regime which, in turn, increased runoff and concordant river sediment regime. The Nemadji River system is the most productive trout fishery in Western Lake Superior, but channel bed downcutting has the potential to create fish barriers and block trout migration. Long-term aquatic

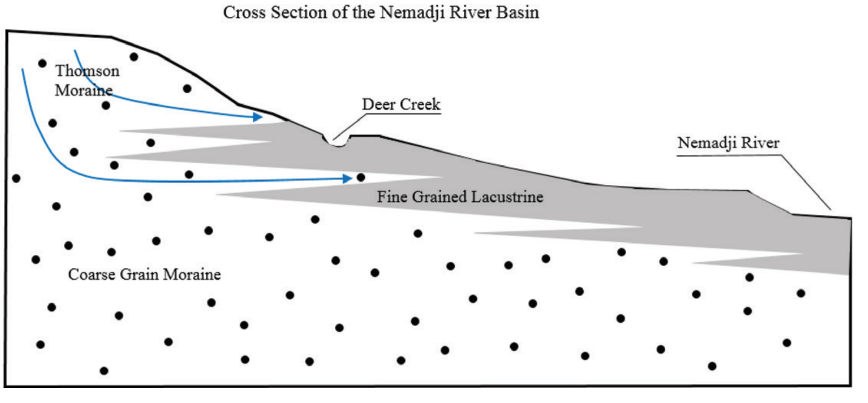

Figure 9.
The location of Lake Duluth on the west end of Lake Superior and illustration of groundwater flow paths southeast of Lake Duluth, Minnesota, in the Nemadji basin [25]. Source: Google Images and Magner PowerPoint.

life sustainability will depend on land use management and then enhances evapotranspiration, reduces runoff, channels enlargement, and allows for fish passage culverts.

3.8 Trapped groundwater: mining the Buffalo aquifer

Connate water is water that is not actively part of the water cycle but groundwater contained or trapped in the earth's crust from some previous time period. In the northern latitudes of North America, Europe, and Asia, this may be frozen groundwater or water left behind in a buried aquifer when glaciers retreated toward the Arctic region.

Climate change in the Arctic region may be liberating frozen groundwater today that has been contained due to a lack of any hydraulic head to move the water toward discharge.

Magner and others [26] used isotopes to estimate the age of water contained in a buried sand and gravel aquifer embedded in the lake clays left behind by Glacial Lake Agassiz. The City of Moorhead, Minnesota (**Figure 10**), needed to expand their water supply and began pumping tests to determine the sustainability of the Buffalo aquifer. The results suggested the high-capacity water abstraction would lead to groundwater mining; thus, the city focused their water supply efforts toward the Red River of the North. Nevertheless, single-family homes with small domestic water demand could pull water from buried sand and gravel. Over a long

Figure 10.
The location of Moorhead, Minnesota, and domestic water. Source: claycountymn.gov and valleynewsalive.com.

period of time, very slow-moving groundwater would likely replenish the buried aquifer water volume; however, this may take millennia. The city of Moorhead, Minnesota, made the right and sustainable decision; however, in California, parts of the Central Valley are sinking as both farms and cities pump harder and drill deeper wells to extract groundwater. The California groundwater is estimated to be 15,000–20,000 years old [27]. This is perhaps the best example of a truly unsustainable groundwater use in the world.

3.9 Protecting rare plants

Groundwater contained in a limestone or dolomite aquifer that discharges into a major river basin provides a calcium-, magnesium-, and bicarbonate-rich water that drives rare calciphile plant occurrence, converging streamlines of groundwater flow into valley fen. Shallow flow paths have short travel times based on anthropogenic chloride and sodium typically not found in the deeper flow paths of a carbonate aquifer. Thick calcite accumulations occur in the root zone at the water table.

There is a mixture of upwelling groundwater and water near the surface that can mix and then flow downslope from higher elevations into the fen or toward spring-fed lakes or directly to the river (**Figure 11**). Shallow groundwater decreases downgradient in the calcareous fen as older groundwater pushes up to discharge [28]. Komor [28] believes that encroachment of reed grasses and other invasive species into the calcareous fen may reflect human-caused disturbances in the valley. The land use in this riparian area requires special protection to limit invasive species and preserve the unique plant life. The Minnesota Department of Natural Resources has enacted rules to sustain and preserve calcareous fens in Minnesota.

3.10 Kura River basin: sustainable sturgeon

The Kura River basin (**Figure 12**) has been poorly managed over time [29]. Climate change has shifted the timing of melting snow and the baseflow in the Kura River. But the over extraction of groundwater for industrial and agricultural use has led to an adversely impacted fish habitat, and sturgeon reproduction has diminished over the past half century.

Environmental flows are needed to find a sustainable solution to meet the demands of an important part of the Caspian Sea economy, namely, black caviar. A key factor is the minimum baseflow required to maintain sediment transport and fish habitat. Pools and riffles are fluvial features formed by the transport of coarse-grained sediment: sand and gravel. If channel-forming flows are disrupted with too little runoff, pools will fill with aggraded sand. This problem was further exasperated by industrial harvesting river beds to obtain well-sorted aggregate for road construction. The damage primarily occurred under the soviet era management of the region. Today attempts are made to bring the watershed back to the environmental flows needed to support a sturgeon fishery. This is a recognition by the Azerbaijan officials that valley groundwater is not unlimited and that competing demands of industrial and agricultural interests must include riverine habitat to support fish.

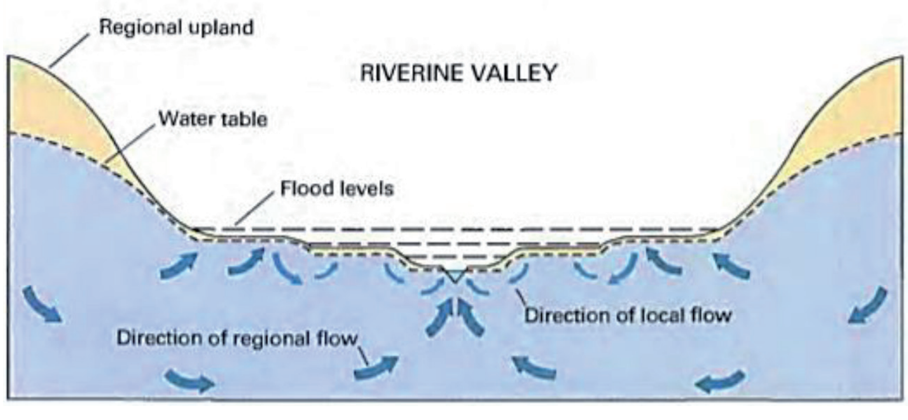

Figure 11.
Illustration of large valley groundwater flow paths like what occurs in the Lower Minnesota River Valley [1]. Source: USGS webpage.

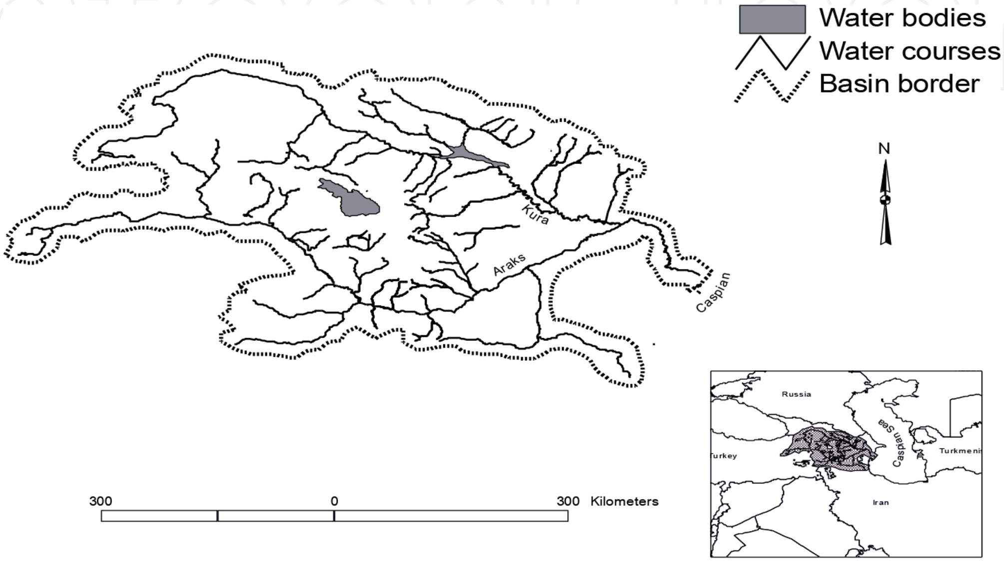

Figure 12.
Location of the Kura River basin west of the Caspian Sea [29]. Source: Abbasov PowerPoint.

4. Conclusion

This chapter has provided some basic information about the relationship between groundwater sustainability and the geology, climate, and land use of various hydrogeologic settings on four continents. This chapter draws from the life experience of the authors and presents case example stories in a manner that hopefully allows nontechnical readers to understand the interface of anthropogenic activity and the sustainability of humans, plants, and animals.

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