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Global Water Scarcity and Watershed Management Planning: A Case Study of Clear Lake, IOWA, USA

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Abstract

Water is one of the most precious resources on the planet. More than 1 billion people do not have access to a source of clean drinking water, and around 3 billion experience water scarcity at least one month per year. This has caused a serious threat to many parts of the world. Given the challenges of population growth, overuse of water, growing pollution, environmental degradation, and changes in weather patterns due to global warming, many countries worldwide face increasing water scarcity. Water shortages have a great impact on human health, socio-economic development, and the environment. The water cycle is a vital process as it enables the availability of water for all living organisms and regulates weather patterns on our planet. There are many human activities that adversely affect the water cycle, such as inefficient irrigation practices, use of fertilizers, manures, pesticides, animal husbandry activities, deforestation of woods, pollution due to industrial effluents and domestic sewage, combustion of fossil fuels, stream-channel alteration, mining, and changes in land use patterns. These activities can contaminate water resources, increase soil salinity, and lower the amount of groundwater. Watershed management planning is a process that results in a plan of how to best protect and improve the water quality and other natural resources in a watershed. This paper describes the necessary steps for updating a typical existing watershed management plan for the Clear Lake watershed in north central Iowa, USA as a case study. The lake is impaired for algae, nutrients, and bacteria. While significant progress has been made to reduce the amount of pollutants since 2011, there remains some work to be done to restore the water quality by 2030.

Subject Areas

Hydrology

Keywords

Water Scarcity, Water Cycle, Climate Change, Watershed Management Planning, Clear Lake-Iowa

1. Introduction

Water scarcity is the lack of sufficient available water resources to meet the demands within a region [1]. Human use of freshwater resources has increased steadily over the centuries. It is unlikely that this trend will change given the continued growth of the population and the widening utilization of water for agricultural, industrial, municipal, and recreational purposes. This situation has caused growing concerns over the availability of adequate water supplies to accommodate the future needs of societies [2]. Climate change has worsened the water crisis worldwide, as rising temperatures lead to more unpredictable weather and extreme weather events, including floods and droughts [3]. Water overuse has resulted in the deterioration of water quality. Seepage of mineral fertilizers, such as phosphates and nitrates, pesticides, and herbicides into surface and subsurface waters has made them unfit for human consumption and also disrupted aquatic ecosystems. Lakes and rivers also have been contaminated by the improper disposal of sewage, and the discharge of untreated industrial wastes. Addressing water scarcity requires a multidisciplinary approach. Water resources must be managed with the goal of equitably maximizing economic and social welfare without compromising ecosystem functioning [4]. The water cycle is an infinite process of water circulation worldwide. Under normal conditions, the water cycle works as a natural recycling system, constantly replenishing the earth's supply of water. The water cycle has several important benefits, such as providing freshwater, climate regulation, ecosystem support, sustaining agriculture and food production; creating hydroelectric power; and contributing to water purification by eliminating contaminants as they flow through the system, such as through the infiltration and percolation processes [5]. Some aspects of the water cycle can be utilized by humans for direct economic benefit. For example, humans directly change the dynamics of the water cycle through dams constructed for water storage, and water withdrawals for industrial, agricultural, or domestic purposes.

2. Assessing the Current Global Water Scarcity

Currently, some 1.1 billion people worldwide lack access to water, and around 3 billion find water scarce for at least one month of the year [6]. These shortages will worsen in the coming decades, especially in cities and urban areas according to UNESCO and the latest edition of the UN World Water Development Report [7]. There are two general types of water scarcity: physical and economic. Physical water scarcity is the result of a region's demand outpacing the limited water resources found there. According to the Food and Agricultural Organization (FAO) of the United Nations [8], around 1.2 billion people live in areas of physical scarcity; many of these people live in arid or semi-arid regions. Physical water scarcity can be seasonal; an estimated two-thirds of the world's population lives in areas subject to seasonal water scarcity at least one month of the year. The number of people affected by physical water scarcity is expected to grow as populations increase and as weather patterns become more unpredictable and extreme. Economic water scarcity is due to a lack of water infrastructure in some countries or to the poor management of water resources where infrastructure is in place. The FAO estimates that more than 1.6 billion people face economic water shortages. As a result, nearly 829,000 people die every year from diarrheal diseases, and 297,000 of those deaths occur among children under the age of five according to the World Health Organization [9]. There are many factors that contribute to global water scarcity, including Population growth; Climate Change and global warming; Pollution that causes contamination of water sources; Industrial waste, oil spillages, and waste discharge into water sources that make it unsafe for drinking, Overuse of water by human consumption and irrigation; and Destruction of water catchment areas, such as deforestation to pave the way for human settlement. However, the most critical factors are population growth and climate change [10].

3. Human Activities that can Alter the Water Cycle

Urbanization: Increased impervious cover associated with urbanization alters the natural cycling of water. Urban construction, such as buildings and roads prevent water from infiltrating the soil. This leads to more runoff, flooding, erosion, and pollution of waterways. These changes degrade the quality and quantity of water and harm the aquatic ecosystems. Increased frequency and severity of flooding, channel erosion, and destruction of aquatic habitats commonly follow watershed urbanization [11].

Irrigation: The effects of irrigation include changes in the quantity and quality of water and soil. An irrigation scheme draws water from groundwater, rivers, lakes, or overland flow, and distributes it over a certain area. Irrigation greatly affects the water cycle since these systems tap water from natural sources, which causes surface runoff and leaching. The presence of irrigation systems also carries away the fertilizers and other pollutants used in farming to these natural sources. In addition, irrigation can cause waterlogging and soil salination on the land being irrigated. Some irrigation schemes use water wells for irrigation. As a result, the overall water level decreases [12].

Deforestation: The removal of trees has a major impact on the water cycle. Trees release water vapors when they transpire, and it further creates a humid environment. This water vapor evaporates into the atmosphere where it accumulates before precipitating back to the Earth as rain, or snow. If trees are cut down, there is less water to be evaporated into the atmosphere and subsequently less rain, which can lead to drought and even desertification. On the other hand, infiltration and runoff can also be affected by deforestation. Normally, tree roots soak up rainwater, ensuring an adequate amount of infiltration and reduced levels of runoff. However, deforestation promotes the opposite course of action, which is decreased infiltration and higher amounts of runoff, which can cause more flooding and mudslides that lead to water pollution [13].

Wetland Drainage: Draining water from wetlands for development can result in decreased recharge to groundwater and increased flooding in the developed area. Wetlands collect and store water from the surrounding landscape during rain or snowmelt, and filter sediments and nutrients before slowly returning water to the water cycle. When wetlands are drained, the local drainage area is connected to downstream flows. As erosion continues over time, the high-energy water cuts stream beds lower and lower, disconnecting the stream from its floodplain, causing the stream to act like an agricultural drainage ditch, and hence, lowering groundwater levels [14].

Agricultural Expansion: Agriculture can have several impacts on the water cycle, such as: reduced vegetation cover, increased runoff, depletion of both surface water and groundwater, pollution of surface and groundwater with pesticides and fertilizers, and elevated concentrations of nutrients, fecal coliforms, and sediment loads. The increased nutrient loading from animal waste can lead to eutrophication of water bodies which may damage aquatic ecosystems [15].

Mining: Discharged mine effluent and seepage from tailings and waste rock impoundments can pollute water sources. Spill and tailing, erosion, sedimentation, acid mine drainage, lowering of water table, subsidence, disturbance on hydrological cycle and rainfall can all impact surface and groundwater. A mine with acid drainage can have long term devastating impacts on rivers, and aquatic life [16].

Sewage and Industrial Discharges: Before rainwater runoff merges into the river, it mostly picks up a variety of pollutants. In rural areas, the pollutants mostly include pesticides, herbicides, fertilizers, and wastes from faulty septic systems. In urban areas, the pollutants include gas, oil, pet waste, fertilizers, pesticides, salt, and treated human waste from sewage treatment plants. Such waste when dumped into the water bodies contaminates the water bodies and in turn, affects the water cycle [17].

Water extraction: Because humans withdraw vast amounts of water from rivers, wells, and aquifers for agriculture, industry, and residential usage, these resources can become depleted [18].

Dams and Reservoirs: These artificial water sources can be formed by building a dam across a valley, diverting river flow into the reservoir. Although they help to save water, they cause more environmental problems on land and have a big impact on the time concentration of watersheds because of evaporation, which can cause water contamination [19].

Climate change: Human activities, such as the use of fossil fuels and deforestation contribute to climate change, which alters precipitation and evaporation patterns, resulting in extreme weather conditions such as drought and flooding [20].

Greenhouse Effect: As greenhouse gases like carbon dioxide and methane increase, Earth's temperature rises in response. This increases evaporation from both water and land areas. The water vapor then absorbs heat radiated from Earth and prevents it from escaping out to space. This further warms the atmosphere, resulting in even more water vapor in the atmosphere [21].

Emissions: The emissions from vehicles and factories create acidic conditions. Oil and fuel spills from cars and trucks seep into the soil, which can contaminate lakes, rivers, and wetlands.

4. The Future Impacts of Water-Related Problems

Hunger and poverty: Water shortages have a direct impact on crops and livestock, which can lead to food shortages and eventually starvation and poverty in many areas.

Prolonged water scarcity can have devastating effects on public health and economic development. As more people worldwide lack access to safe drinking water and adequate sanitation services, this can spur the transmission of diseases such as cholera, and diarrhea. Also, food-insecure communities can face both acute and chronic hunger, where children are more at risk of conditions from malnutrition, and chronic illnesses due to poor diet, such as diabetes.

Flooding and rising sea levels can contaminate land and water resources with saltwater, and cause damage to water and sanitation infrastructure, such as wells, and wastewater treatment.

Droughts and wildfires can destabilize communities and trigger civil unrest and migration in many areas. Also, the destruction of vegetation and tree cover can increase soil erosion and reduce groundwater recharge, which will increase water scarcity and food insecurity [22].

Glaciers, polar ice caps, and snow fields are rapidly disappearing due to global warming. The resulting meltwater can affect the regulation of freshwater resources in many lowland areas [23].

Growing demand for water as a result of population growth can increase the need for energy-intensive water pumping, transportation, wastewater treatment, and peatlands.

Biodiversity loss: Water scarcity has different negative impacts on rivers, lakes, and other freshwater resources. It harms the environment in several ways including increased salinity, nutrient pollution, and the loss of floodplains and wetlands. Also, ecosystems and biodiversity, such as freshwater fish are threatened by the scarcity of water resources [24].

International conflicts: Many freshwater sources transcend international borders, and there are some hot spots where transboundary waters are a source of tension and conflict between neighboring countries, such as the Nile Basin tension between Egypt and other riparian states.

5. Watershed Management Planning

A watershed plan is a strategy and work plan for achieving water resource goals in a geographically defined watershed. The planning process involves a series of steps to characterize existing conditions, identify and prioritize problems, define management objectives, and develop and implement protection or remediation strategies. Watershed management plans identify water quality problems, propose solutions, and create a strategy for putting those solutions into action. Watershed management plans are for planning purposes, tracking, and measuring implementation of watershed improvement projects. The primary purpose of a watershed management plan is to guide watershed coordinators, resource managers, policymakers, and community organizations to restore and protect the resources of water, biomass, soil, energy, and humans in a given watershed. These plans reflect the needs and demands of the different environmental, cultural, and socio-economic conditions that present the basic concepts related to resilient watershed management, and, through the description of a case study, which illustrates the process for formulating a resilient watershed management plan, from the analysis of the enabling environment to the definition of the risk management measures to implement [25].

6. A Case Study—Clear Lake Watershed Management Plan, Iowa, USA

Clear Lake is located in north central Iowa, USA. Clear Lake is impaired for algae, nutrients, bacteria, and turbidity. The existing watershed management plan was approved in 2011. Clear Lake is categorized by the Iowa Department of Natural Resources (IDNR) as a significant publicly owned lake for its high economic and recreational values. Clear Lake was placed on Iowa's 2002 impaired waters list for not meeting the primary contact recreation use due to algae and nutrients. The lake was also added to the impaired waters list in 2004 due to E. coli bacteria. The Ventura Marsh, which is a large wetland complex located on the west edge of Clear Lake and flows directly into the lake is also on the INDR impaired water list for algae and turbidity [26]. This section describes the required steps to prepare a new watershed management plan or update an existing plan utilizing the Environmental Protection Agency (EPA) handbook for developing watershed plans [25]. The conceptual framework of this watershed management plan consists of the following steps, as shown in **Figure 1**:

Step 1: Define the Geographic Extension of the watershed: Clear Lake is located in north central Iowa, USA. The Clear Lake watershed extends in both Cerro Gordo County and Hancock County. The Hydrologic Unit Code (HUC) for this watershed is "Clear Creek - 070802030201". The Latitude is 43˚08'01"N, and the Longitude is 93˚22'57"W. The major communities within the watershed include: The City of Clear Lake (population: 7574); the City of Ventura (population: 687); and about 5000 people living in the developed areas. There are two major highways intersecting near the lake, Interstate 35, and Highway 18 as shown in **Figure 2**.

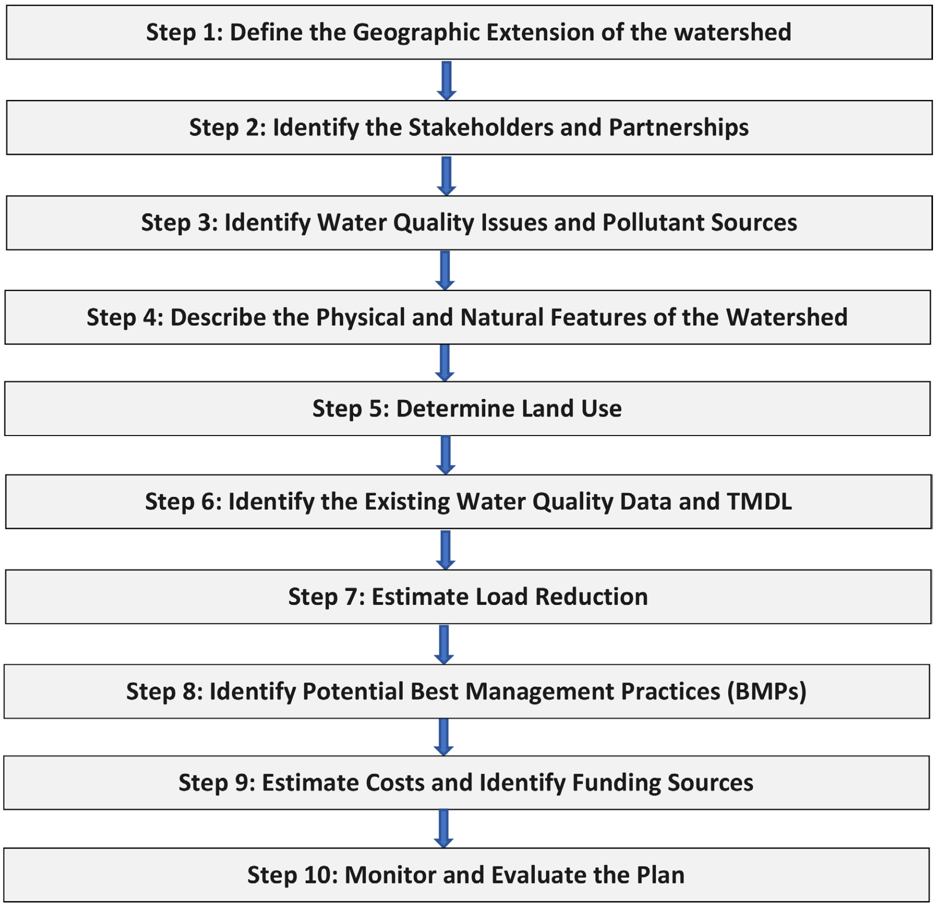

Figure 1. The conceptual framework of clear lake watershed management plan.

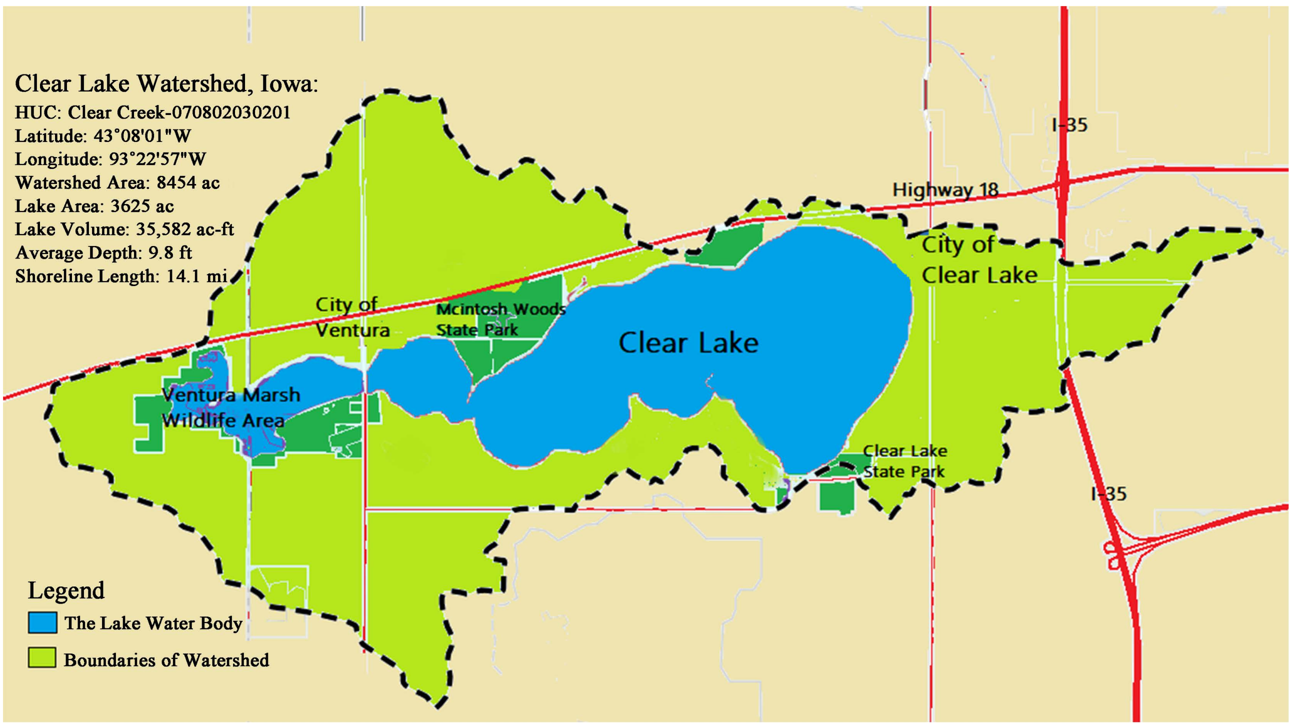

Figure 2. Map of the geographic extension of clear lake watershed, Iowa.

There are also two state parks along the shorelines that offer picnicking, wading, and swimming [26].

Step 2: Stakeholders and Partnerships: The stakeholders of the watershed include; local residents; landowners; Federal, state, and city officials; developers; and recreational users [26].

Step 3: Identify Water Quality Issues and Pollutant Sources: The water quality impairments of the lake include: algae, nutrients, E.coli bacteria, and turbidity as shown in Table 1. The pollutants originate from non-point sources, such as surface runoff, stormwater runoff from agricultural and developed areas, disturbed shorelines, internal loading of the lake, direct precipitation into the lake surface, and groundwater infiltration. There are no point sources for pollution. The bacteria impairment comes from septic systems, private and municipal sewer Lines, water birds, cattle, horses, and dogs [26].

Step 4: Describe the Physical and Natural Features of the Watershed:

Hydrology: Clear Lake has a surface area of 3,625 acres, and the watershed has an area of 8454 acres, resulting in a watershed-to-lake ratio of (2.3 to 1). Clear Lake is relatively shallow, with a maximum depth of 30 feet and an average depth of 9.8 feet. The dimensions of the lake are 5 miles long with a maximum width of 2 miles in the eastern portion. The volume of the lake is 35,582 acre-ft. The length of the shoreline is 14.1 miles. The hydraulic residence time is estimated at 5.0 years. Many small tributaries drain the watershed, with the largest one passes through Ventura Marsh on its way to the lake. Clear Lake receives an average of 32.45 inches of precipitation annually. Also, groundwater inflows the lake from the north, west and south [26].

Soils: The most common types of soils found in the watershed are Clarion (25%), Webster (14%), and Canisteo (10%). The watershed soil is classified as 94% Group B. The other soil groups A, C, and D are rare due to the prevalence of field tile. Group B soils consist mainly of well-drained soils that have fine to coarse texture, with a moderate rate of water transition. The watershed lies in Des Moines Lobe within the Algona-Altamont moraine complex of the state of Iowa. The watershed is almost level with slopes ranging from 0 to 5%. The average high temperature in the winter is 26 degrees Fahrenheit while in the summer 81 degrees. June is considered the wettest month of the year. The water cycle of

Table 1. The current % of contaminated areas of impairments in the watershed.

Impairment Type	Percent of Contaminated Areas of the Watershed
Algae	17%
Nutrients	17%
Beach Bacteria (E.coli)	57%
Murky Water (Turbidity)	57%
% Total contaminated area of Watershed	75%

the watershed with anthropogenic components is shown in Figure 3.

Fish, Wildlife, and Recreation: There are about 30 species of fish that inhabit the lake, and substantial populations of predators. In addition, substantial numbers of carp, horses and buffalo exist in the area. Recreational use of the lake includes 44% camping; 28% boating; 19% swimming; 7% fishing; and 2% winter activities [26].

Step 5: Determine Land Use: The watershed lands consist mainly of row crop production (54%), urban areas and roads (16%), and wetlands (9%). About 24% of the Clear Lake watershed is in public ownership, and the remaining 76% of the watershed is in private ownership. Roughly, 1500 acres of the Clear Lake watershed are in public ownership. About half of these acres are comprised by the Ventura Marsh Wildlife Habitat. The rural portion of the watershed consists of approximately 50 farms and 125 landowners involved in row crop production [26].

Step 6: Identify the Existing Water Quality Data and TMDL: The main source of the existing water quality data is "The Clear Lake Diagnostic and Feasibility Study", completed by Iowa State University (ISU) in 2001, in which chemical and biological samples were taken twice a month from three sites on Clear Lake, and from one site on Ventura Marsh. This data is available from the Iowa DNR. A total maximum daily load (TMDL) plan was created for Clear Lake in 2005 to address algae and nutrients [27]. The TMDL showed that Phosphorus is the main cause of algal production at Clear Lake, and it comes from precipitation, groundwater, internal recycling, and watershed area, as shown in Table 2.

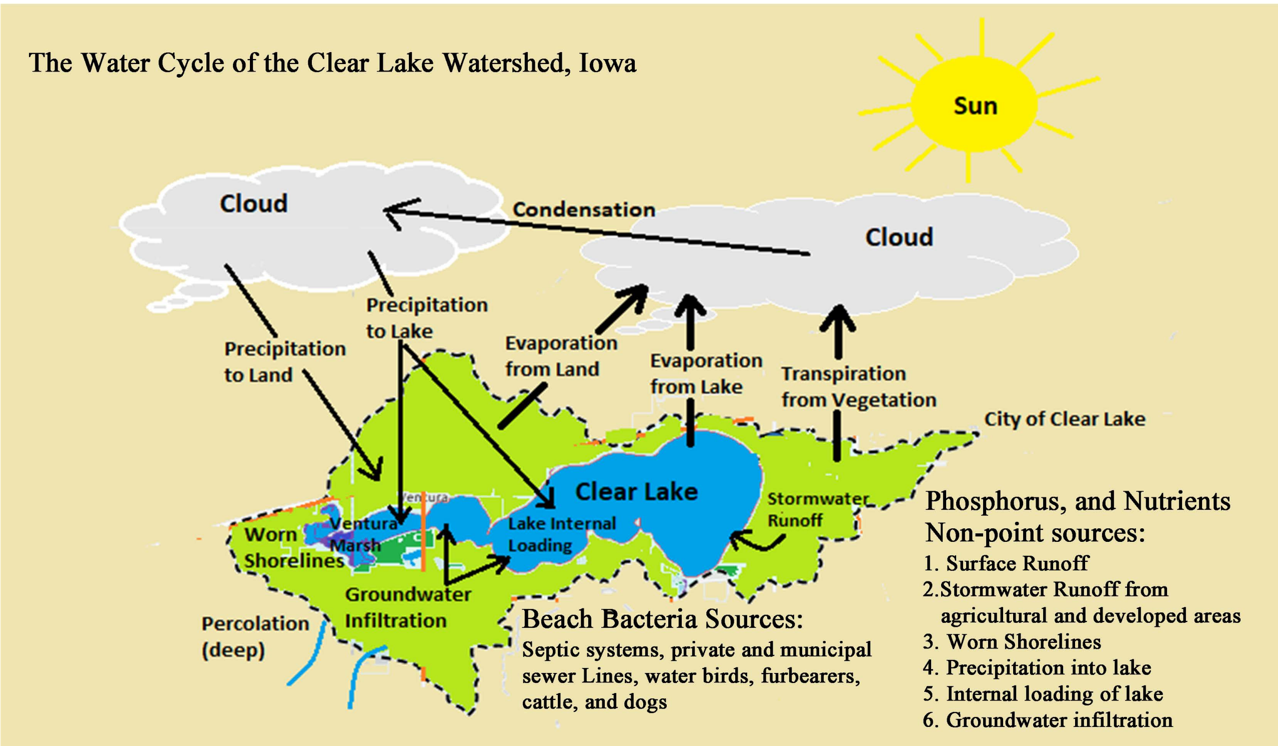

Figure 3. The water cycle of clear lake watershed, Iowa.

The TMDL was determined using the Vollenweider 1982 empirical model. The TMDL goal for total Phosphorus concentrations is 96 μg/L. Secchi disk depth is a measurement of water clarity or transparency. The goal set for water transparency is 0.7 m, but the community goal is 1.5 m. The beach bacteria (E.coli) is linked to high TSS, phosphorus, and turbidity. The existing bacteria at the lake beaches is regularly monitored by the INDR staff, but data showed that Clear Lake is still impaired for E. coli bacteria due to eight violations in the last several years [28] [29].

Step 7: Estimate Load Reduction: Although the TMDL targets have been met in recent years, however, the Clear Lake advisory team has created a restoration project called the "Clear Lake Enhancement and Restoration (CLEAR)" in coordination with landowners, the City of Clear Lake, and the IDNR to recommend best management practices (BMPs) and establish target values for pollutants load reduction by 2030. **Table 3** shows the recent load reduction for the lake as of 2022 and the CLEAR target goals by 2030. We can see from the table that a great amount of work is still required to achieve the goals set by the CLEAR project [26].

Step 8: Identify Potential Best Management Practices (BMPs): Since 2011, several management practices were implemented by CLEAR project in the watershed including 1030 ft of shoreline stabilization, 3 sites of permeable pavers, 4 units of rain gardens, 1 unit of soil quality restoration, and 2 acres of prairie restoration [26]. While good progress has been achieved, there remains some work to be implemented by applying additional BMPs in order to achieve the CLEAR goals by 2030. The load reduction estimate for the BMPs can be calculated

Table 2. Phosphorus loadings into clear lake.

Load Source	Phosphorus Allocation amount
Precipitation	4500 pounds per year
Groundwater	900 pounds per year
Internal Recycling and Watershed	3700 pounds per year
Total Load Allocation	9100 pounds per year

Table 3. The current load reduction and the CLEAR goals by 2030.

Pollutant	Current Load Reduction (2022)	CLEAR Load Reduction Goal 2030
Phosphorus	81 Ibs/year	335 Ibs/year
Nitrogen	124 Ibs/year	813 Ibs/year
Stormwater Volume	1303 Gallons per Day	4000 Gallons per Day
Total Suspended Solids	43 Ibs/year	150 Ibs/year
Sedimentation-Siltation	62 Tons/year	332 Tons/year
Beach Bacteria (*E. coli*)	88% Weekly Monitoring	>95% Weekly Monitoring

using the EPA's "Pollutant Load Estimation Tool (PLET)" regarding nutrients and sediment loads, and the EPA's "BASINS" for bacteria [30]. This updated plan suggests the following additional BMPs to be applied:

1) Use floating vegetated islands to eliminate nutrients and reduce the algae blooms [31].

2) Use mechanical dredging by a dragline bucket equipment to remove sediments from the lake.

3) Increase water aeration of the lake by installing a bottom-diffused aeration system, which can increase the beneficial bacteria in the lake, reduce nutrients, and improve water quality.

4) Use ultrasonic control devices that create sound waves to kill the algae [32].

5) Implement a lake flocculent treatment program, which can purify clouding water from suspended particles and increase the water depth clarity to the required 1.5 m.

6) Implement a sludge remover treatment, which can reduce organic matter, and muck.

7) Reduce algae in the lake by adding clean-up species, such as fish and snails [33].

8) Apply riparian buffers around the lake banks that include trees and vegetation to prevent soil erosion and sedimentation, enhance wildlife, and improve flood retention [33].

9) Preserve open spaces around the lake to minimize impervious areas and reduce runoff [34].

10) Maintain topsoil quality to filter out stormwater, and erosion, and maximize water retention.

11) Use vegetated swales or wide channels around the lake. These devices can control stormwater peak rate, allow for pollutants to settle down, and improve water quality [34].

12) Increase constructed wetlands and wet ponds in the watershed to remove pollutants from stormwater, control peak flow rates, provide wildlife habitat, and enhance aesthetic beauty.

Step 9: Estimate Costs: The cost of construction and maintenance of all BMPs can be estimated using the EPA's "National Stormwater Calculator", utilizing the Storm Water Management Model [35].

Step 10: Monitor and Evaluate the Plan: The project schedule includes annual meetings of all partners, quarterly progress reports will be prepared, and partners will be informed. The monitoring program of the lake includes taking samples from three sites on Clear Lake and one site on Ventura Marsh each year from April through October. As soon as the water monitoring data is available, the plan will be reviewed and updated. Although this plan considers only the water quality concerns of Clear Lake, however, there are other concerns related to fish and wildlife, and the ecosystem that must be addressed in future plans. In addition, the effect of climate change must be considered by collecting data related to the extreme events of precipitation, increased drought or flooding, and changes to the volume of stormwater runoff and the timing of the peak flows.

7. Conclusion

Water scarcity is an increasing worldwide problem, with poorer communities most badly affected. Water can be scarce for many reasons: demand for water may exceed supply, water infrastructure may be inadequate, or mismanagement of water resources to balance the people's needs. As the global population increases, and resource-intensive economic development continues, water crisis becomes more severe. Besides, climate change affects the water crisis greatly. We feel its impacts through worsening floods, rising sea levels, shrinking ice fields, wildfires, and droughts. These impacts threaten sustainable development, biodiversity, and people's access to water and sanitation. In tackling these global water scarcity challenges, we must reinstall the principles of equity and justice into new international water arrangements we devise. Law and economics must both be reoriented to ensure universal access to clean drinking water, sanitation, hygiene, and to build more resilient and sustainable food systems. Incentives must be reinvented so that the private sector can do its part to provide access to technology and innovation to all poor and rich countries. This will require long-term finance and novel mechanisms to regulate how the public and private sectors work together for better water resources management. Human activities such as urbanization, irrigation, deforestation, agriculture expansion, and construction of dams have significantly impacted the water cycle. These impacts can have significant consequences, such as reducing the availability of freshwater resources, altering the flow of water in rivers and streams, and impacting aquatic ecosystems. It is essential that we manage our use of water and reduce our impact on the water cycle to ensure the sustainability of this vital natural resource. This paper presented a case study of the water quality concerns of the existing Clear Lake watershed plan in north central Iowa, USA. The lake is impaired for algae, nutrients, and bacteria. While significant progress has been made to reduce the amount of pollutants since 2011, there remains some work to be done to restore the water quality. Many BMPs are introduced in this proposed plan to be implemented in order to achieve the target goals of pollutant reduction by 2030.

Conflicts of Interest

The author declares no conflicts of interest.

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