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Determinants of Declining Water Quality

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1. Introduction

Freshwater makes up only 2.5 percent of the world's water. More than half is channeled to man-made uses (Uitto, 2001). Freshwaters sources are experiencing declines in quality and biodiversity far greater than those in the most affected terrestrial ecosystems (Dudgeon et al., 2006). Considerable effort has been made to understand processes that determine the variability of water in space and time. The relative ease of measuring water quality (by way of precipitation, snowfall, stream flow, water level), along with the pressing issues of water excess and shortage (floods and droughts), has necessitated a global focus on water quantity. In contrast, the complexity and diversity of water quality parameters and the challenge to accurately and frequently measure them have complicated the global monitoring of water quality. Recent developments in the use of remote sensing and the need to narrow the knowledge gap concerning the economic costs of water quality have provided a much-needed incentive to pay more attention to water quality assessments around the world.

This review examines determinants of poor water quality and natural and anthropomorphic factors determining water quality. It also discusses various water quality parameter measurement tools that can be applied in situ or remotely to assess water quality easily so measurements can be used to evaluate the economic impact of poor water quality. The correlation of water quality indicators to determinants (natural or anthropogenic) is also summarized based on the abundance of literature supporting the relationship. In doing so, this paper takes a thematic approach and applied the following search phrases to the literature review: "*determinants of (parameter) in surface water,*" "*drivers of (parameter) in surface water,*" and "*remote sensing techniques to estimate (parameter).*" Studies are listed chronologically. Table A.1 in the appendix summarizes the level of confidence concerning the impact of drivers on water quality indicators based on the corresponding literature.

2. Water Quality Indicators and Drivers

The physical, biological, and chemical characteristics of water, as well as aesthetic ones (in terms of appearance and smell) define water quality. Water quality parameters are often used to measure the condition of water relative to the requirements for a given purpose or functional use. This review covers 5 physical water quality indicators (chlorophyll-a, dissolved solids, temperature, total suspended matter, and turbidity); 4 biological indicators (total coliform, fecal coliform, *E. coli*, cyanobacteria); and 18 chemical indicators (alkalinity, ammonium, biochemical oxygen demand, calcium, chloride, chemical oxygen demand, colored dissolved organic matter (CDOM), conductivity, dissolved oxygen, magnesium, nitrate, nitrite, optical water type class, pH, phosphorus, potassium, sodium, sulfate).

Drivers are natural and/or anthropogenic factors that exhibit a strong relationship with a given water quality indicator. Five factors are especially important.

1. *Agriculture*. Agriculture involves extensive use of nitrogen-, phosphorus-, or potassium-based fertilizers which, when applied in excess, get washed into freshwater systems. Agriculture is the largest non-point source contributor to water pollution (Foley et al., 2005, Ribaudo et al., 1999). Land clearing for agricultural expansion (extensification) increases soil erosion, leading to higher sediment loads in streams (Foley et al., 2005). Forests protect the soil from washing away by reducing raindrop impact, breaking overland flow velocity, and facilitating percolation by delaying surface runoff. In areas dominated by forests, deforestation can lead to a decline in water quality in streams and other waterbodies in the watershed. Reforestation is encouraged by tree planting to yield forest products, as well as by economic development, which can create non-farm jobs that pull farmers off the land. These activities can induce the spontaneous regeneration of forests in old fields, which can eventually conserve the soil and hence improve stream water quality (Rudel et al. 2005).
2. *Climatic factors*. Climactic variables and climatic events affect water quality. Intense precipitation can erode soil. Extreme rainfall events (downpours) produce a very high runoff. Such runoff events create very large sediment plumes in freshwater systems (rivers and lakes) when they take place after a drought. Strong wind often creates strong water currents that force sediment to re-suspend and thus increase water turbidity.
3. *Geographic factors.* These include terrain slope, soil resistance to erosion, and presence of geologic features (such as karst escarpments) that alter the hydrologic characteristics of a watershed.
4. *Economic factors*. Mining, infrastructure, industrial expansion, and intensive agriculture are typical manifestations of economic growth. Waste from these sources can include chemical pollutants from industries and increase water temperature through the discharge of cooling water from thermal plants. In addition to the water quality degradation during construction, infrastructure often requires frequent maintenance that leads to increased salinity and turbidity in streams (such as dredging of dams and deicing of highways).

5. *Urban expansion*. The spread of urban and peri-urban areas modifies the runoff response of the altered landscape and the corresponding transportation of contaminants. Increased impervious area and higher population density characterize urban expansion. Urban areas may generate poorly treated sewage and detergents that wash into streams.

The discussion that follows discusses and describes the 5 physical water quality indicators, 4 biological indicators reviewed in this paper, and 18 chemical indicators. Table A.2 in the appendix summarizes threshold values for the various indicators.

Physical Water Quality Indicators

2.1. Chlorophyll-a (chl-a)

2.1.1. Description, Measuring Techniques, and Threshold Values

Chlorophyll-a (chl-a) is a photosynthetic pigment that enables green plants to undertake photosynthesis. Its presence in surface water serves as an indicator of an abundance of green vegetation, mainly phytoplankton or algae. Its ease of measurement using radiometric techniques makes it suitable to monitor the state of contamination of water bodies. The *Standard Methods for the Examination of Water and Wastewater* outlines spectrophotometry, high-performance liquid chromatography (HPLC), and fluorometry techniques to measure chlorophyll (APHA, 2005). Chlorophyll is measured in micrograms per liter (μg/l). Limited literature is available regarding threshold concentrations and these are very site-specific and cannot be used as recommended values.

2.1.2. Drivers, Linkages, and Degree of Drivers Influence

Agricultural runoff, poorly treated sewage discharge, and runoff from built-up areas lead to excessive fertilization (eutrophication) of natural water bodies (Yu et al., 2014, Ma et al., 2016, Yang et al., 2017, Shanmugam et al., 2018). This facilitates to the excessive growth of algae and cyanobacteria (Paerl et al., 2001, Elliott, 2010, Paerl and Paul, 2012, Ma et al., 2016, Boynton et al., 1982, Anderson et al., 2002b). A significant correlation between ammonia nitrogen, total nitrogen, total phosphorus, and suspended solids is also reported (Canfield Jr. et al., 1984, Prairie et al., 1989, Lehrter, 2008, Cai et al., 2012, Warner and Lesht, 2015). Precipitation, air temperature, water surface temperature, and discharge are among climatic and hydrologic drivers of chl-a (Warner and Lesht, 2015, Lehrter, 2008, Ji et al., 2018). A negative correlation between chl-a and the fraction of developed land is reported in the Tampa Bay area in Florida (United States) (McCarthy et al., 2018).

2.1.3. Chl-a as a Proxy for Other Water Quality Indicators

High concentrations of chl-a are indicative of high algal biomass and phytoplankton presence (Anderson et al., 2002b, Barbosa et al., 2010). A summertime maxima of chl-a due to phytoplankton is strongly related to annual loadings of nitrogen and phosphorus (Boynton et al., 1982, Elliott, 2010). Two-band (near infrared, red) algorithms are proven highly reliable for estimating chl-a concentration in turbid productive waters (Bagheri et al., 2012, Moses et al., 2012, Le et al., 2013, Tao et al., 2013). The strong correlation between chl-a and nitrogen and phosphorus can be exploited to estimate nutrient loadings (nitrogen and phosphorous) in turbid waters from remote sensing-based chl-a measurements. Chl-a is also considered a proxy of total phytoplankton biomass (Solidoro et al., 2010).

2.2. Total Dissolved Solids (TDS)

2.2.1. Description, Measuring Techniques, and Threshold Values

Total dissolved solids (TDS) comprise inorganic salts (principally calcium, magnesium, potassium, sodium, bicarbonates, chlorides, and sulfates) and small amounts of organic matter that are dissolved in water (Health Canada 1991). Salts used for road deicing in some countries may also contribute to the TDS content of drinking-water. Concentrations of TDS in water vary considerably in different geological regions because of differences in the solubility of minerals (WHO 2011a). No reliable data on possible health effects are available. High levels of TDS in drinking-water may be objectionable to consumers. It is recommended that water containing more than 500 mg/L of dissolved solids not be used if other less mineralized supplies are available (EPA 1995). Minimum and maximum TDS set by countries range from 200 mg/l to 2,500 mg/l (WHO 2018).

2.2.2. Drivers, Linkages, and Degree of Drivers Influence

Total dissolved solids in water supplies originate from natural sources, sewage, urban and agricultural runoff and industrial wastewater(Canada, 1991). Salts used for road deicing in some countries may also increase the TDS content of drinking-water. Contradictory results are reported on drivers of dissolved solids. Johnson et al. (1997) reports that dissolved solids were better explained by land use in summer than in other seasons. Hall (1970) reports better correlation between dissolved solids and stream discharge. In some watersheds, geology relates to the presence of higher dissolved solids due to higher solubility of minerals (Health Canada 1991). Total dissolved solids concentration increased markedly after dredging (Zhang et al., 2010).

2.2.3. Total Dissolved Solids as a Proxy for Other Water Quality Indicators

Total dissolved solids (TDS) is considered a proxy for inorganic salts (potassium, carbonate, bicarbonate, chloride, sulfate, phosphate, and nitrate) dissolved in water (Canada, 2006). TDS could be used to estimate electrical conductivity. However, it is often easy to measure electrical conductivity and then estimate the TDS using conversion factors.

2.3. Temperature

2.3.1. Description, Measuring Techniques, and Threshold Values

Water temperature is important because it affects the rates of biological and chemical processes. Temperature is measured in degrees Fahrenheit (180° between the freezing and boiling point of water) or degrees Celsius (100° between the freezing and boiling point of water). There is no health-related threshold value for temperature. However, cool water is generally more palatable than warm water, and temperature will have an impact on the acceptability of a number of other inorganic constituents and chemical contaminants that may affect taste. High water temperature enhances the growth of microorganisms and may increase problems related to taste, odor, color, and corrosion (WHO 2011a).

2.3.2. Drivers, Linkages, and Degree of Drivers Influence

Dam operations and cooling water discharges have been found to modify thermal regimes by selectively releasing cold or warm water from thermally stratified reservoirs (Olden and Naiman, 2010, Verones et al., 2010). Urban land use, mainly imperviousness, is reported to be a major contributor to water temperature changes in storm water runoff draining to a natural stream (Hatt et al., 2004). A warming of the environment due to a changing climate has also been found to affect hydrologic and thermal regimes of rivers, having a direct impact on freshwater ecosystems (Van Vliet et al., 2013). Gross changes in stream temperature are reported to be driven by the annual cycle of incoming solar radiation and seasonal changes in hydrological and climatological changes. Riparian woodland in the lower catchment had a substantial impact on thermal regime, reducing the variability over the 24 hours and extremes (Malcolm et al., 2008). Groundwater inflow is also reported to drive stream water cooling by as much as 3°C (Story et al., 2003). The temperature regime of glacial streams in the northern hemisphere has been found to be characterized by rapidly increasing temperatures in April and May, a moderate decline from June to September (period of glacial melt), and a subsequent fast decline in autumn (Uehlinger et al., 2003).

2.3.3. Temperature as a Proxy for Other Water Quality Indicators

Phytoplankton abundance has been reported to have significant positive correlations with temperature (Gallina et al., 2013, Lv et al., 2014). A decline in dissolved oxygen could be associated with a rising temperature as water warming decreased dissolved oxygen (Ducharne, 2008). Temperature is one of the water surface physical parameters that can be observed using remote sensing techniques (Ahn et al., 2006, Sima et al., 2013, Handcock et al., 2006, Simon et al., 2014, Ding and Elmore, 2015).

2.4. Total Suspended Matter (TSM)

2.4.1. Description, Measuring Techniques, and Threshold Values

TSM (total suspended matter) is the portion of total solids retained by a filter. It is measured in the laboratory by filtering a known volume of sample through a preweighed glass fiber filter, drying it at 103°C–105 °C and weighing the sample (APHA, 2005). WHO, EPA, and the EU have not provided a standard for TSM in drinking water. The US National Academy of Sciences has recommended that TSM concentrations should not result in more than a 10 percent reduction of light penetration (EPA 2012b).

2.4.2. Drivers, Linkages, and Degree of Drivers Influence

In a Mediterranean watershed, multivariate analysis shows that total suspended load can be predicted by integrating rainfall and runoff variables (Tuset et al., 2016). Increased urbanization has been found to lead to increased risk of soil erosion, and thus TSM (Devereux et al., 2010). Higher suspended solids are reported to be associated with agricultural land (Fierro et al., 2017). Results of the study demonstrated that proximate drivers of changes in land use and land cover (LULC) accounted for 59% of the variation in total suspended solids (Wilson, 2015). In other watersheds, suspended sediment in the upper reaches of the streams have been found to originate largely from channel bank sources and from uncultivated topsoil (Carter et al., 2003). A comparison between two adjacent catchments with contrasting intensive agricultural and semi-natural land-use indicates that agricultural catchment exported a significantly higher suspended sediment concentrations on a storm-by-storm basis than the semi-natural catchment (Glendell and Brazier, 2014). In the Lake Victoria basin, an encroachment on papyrus wetlands was significantly related to increased sediment fluxes to the lake and is reported to be about three times larger than in catchments with intact papyrus vegetation (Ryken et al., 2015). In the Amazon, pasture streams exhibit higher concentrations of total suspended solids during the dry season, but not during the wet season (Neill et al., 2001). Total suspended matter concentration increased markedly after dredging (Zhang et al., 2010).

2.4.3. Total Suspended Matter as a Proxy for Other Water Quality Indicators

Total suspended matter in freshwater systems include chl-a, organic influents, and sediment, among others (Cai et al., 2012). Total suspended matter alters the turbidity characteristics of water (Mallin et al., 2009). Site-specific remote sensing techniques can be applied to estimate total suspended matter, turbidity, and chl-a (Onderka, 2008, Bhatti et al., 2010, Kaba et al., 2014, Shi et al., 2015, Shi et al., 2017).

2.5. Turbidity

2.5.1. Description, Measuring Techniques, and Threshold Values

Turbidity is a measure of the "cloudiness" of water (Davies-Colley and Smith, 2001). The term is often used to describe the level of clarity in water bodies (streams, rivers, lakes, and oceans). In scientific terms, turbidity describes the amount of light scattered or blocked by suspended particles (such as sediment, organic matter, colored dissolved matter, and phytoplankton) in a water sample. Turbidity is measured in Nephelometric Turbidity Units (NTU). The nephelometric method compares how light is scattered in a water sample against the amount of light scattered in a reference solution (Davies-Colley and Smith, 2001). WHO has set a turbidity of less than 1.0 NTU as acceptable (WHO 2011a). National guidelines generally agree with the stated threshold value (see, for example, EPA 2001).

2.5.2. Drivers, Linkages, and Degree of Drivers Influence

Complex processes of hydrological and human factors drive turbidity in natural water systems (Baker, 2005). Mixed results are reported regarding drivers of turbidity in streams. A recent study on the impact of land use change on turbidity in Florida indicates that turbidity was significantly negatively related to the percent cover of developed land and significantly positively related to the percent cover of agricultural land (McCarthy et al., 2018). Ouyang, Zhu, and Kuang (Yang et al., 2004) also report a reduction in turbidity with increased expansion in urban areas in the Pearl River delta in China. In contrast, Uriarte et al. (2011) and Ouyang et al. (2006) report an increase in turbidity with an increased extent of urban and pasture cover in larger watersheds. A census-based approach used to explore the relationship between water clarity and land use for lakes and rivers in the US state of Minnesota reveals that ecoregions with the largest proportion of forest exhibit the highest level of clarity (as measured in meters of Secchi disc depth), whereas lakes and rivers in agriculture dominant areas show the lowest clarity (Brezonik et al., 2007).

Climatic features, landscape characteristics, and soil properties are known to have complex interconnection with turbidity. It has long been established that the kinetic energy of raindrops, the resistance of the soil for detachment expressed as soil erodibility, and topography (expressed as slope length) have an impact on erosion and hence on turbidity (Wischmeier et al., 1978). Studies indicate that lakes exhibit shifting minimum turbidity levels after successive drought seasons. The driver is explained to be the longer water residence time in the lake, driven by reduced outflow from the lake's declining water level (Kaba et al., 2014, Whitehead et al., 2009). Peierls et al. (1991) report a very strong relationship between population density and annual nitrate concentration in 42 globally significant rivers. With nitrate facilitating algal growth that causes turbidity, an indirect link may exist between population density and turbidity. Wind is also reported to be significantly related to turbidity, as it leads to resuspension of sediments (McCarthy et al., 2018).

A number of site-specific empirical studies that relate remotely sensed water surface reflectance to turbidity have been undertaken. Some of the relationships found are single band (Chen et al., 2007, Kaba et al., 2014), while others are multiband (ratio, difference, or combination) (Petus et al., 2010). Dogliotti et al. (2015) have developed a single algorithm to retrieve turbidity from MODIS images in coastal and estuarine waters. The GEMStat water quality database (GEMStat.org) provides in situ turbidity observations to various water bodies worldwide. These observations may be used to establish the relationship between remote sensing reflectance and turbidity.

2.5.3. Turbidity as a Proxy for Other Water Quality Indicators

Turbidity is often used to estimate total suspended solids due to the strong relationship between the two (Gao et al., 2008). This relationship can be exploited to avoid the lengthy and costly procedure of estimating total suspended solids (TSS) using a gravimetric method. Caution should be taken given that the relationship could be complicated by the turbidity caused by inflow of color-causing materials dissolved organic matter—including colored dissolved organic matter (CDOM) and fluorescent dissolved organic matter (FDOM)—(Snyder et al., 2018). Turbidity levels are also often associated with total rainfall before samples are taken (Shi et al., 2017); the amount of runoff (Huey and Meyer, 2010); and higher levels of disease-causing microorganisms such as viruses, parasites, and some bacteria (EPA, 1995, Mallin et al., 2000).

Biological Water Quality Indicators

2.6. Total Coliform, Fecal Coliform, and *E. coli*

2.6.1. Description, Measuring Techniques, and Threshold Values

Total coliform is a collective name for different kinds of bacteria including *E. coli* (*Escherichia coli*) and fecal coliform (Noble et al., 2003). Total coliform presence in water bodies is an indicator of environmental contamination, not fecal contamination (Gruber et al., 2014). Fecal coliforms are types of total coliform that mostly exist in feces (Karp et al., 1999, Noble et al., 2003). The presence of total coliform in a water sample triggers a test for either fecal coliform or *E. coli*. *E. coli* is a subgroup of the fecal coliform group and thus is used as indicators for the presence of fecal material in drinking and recreational waters (Noble et al., 2003). Coliforms are measured in cfu (colony forming units), which are a number of viable bacterial cells in a sample per unit of volume (Elmund et al., 1999, Leclerc et al., 2001, Anderson et al., 2005). A common method is to pass 100 milliliters (mL) of water through a membrane filter to capture the bacteria. The filter is then placed in a petri dish with agar to grow the bacteria overnight. If bacteria are present, they appear as colonies on the filter paper that can be counted. The bacteria results are then reported as the number of colonies per 100 mL of water (APHA, 2005). The United States Environmental Protection Agency (EPA) recommends a single sample maximum *E. coli* standard of 235 cfu/100 ml and a geometric mean of 126 cfu/ 100 ml (a little less than half a cup). National water standards apply zero coliforms in a domestic water supply. Other coliform-bacteria testing methods rely on color changes to provide an estimate of the number of bacteria present. These are often referred to as "most probable number" (MPN) methods, which use a statistical relationship to estimate the number of bacteria in the sample based on color changes in multiple test tubes (Percival and Wyn-Jones, 2014).

2.6.2. Drivers, Linkages, and Degree of Drivers Influence

In an urbanized environment draining to an estuary, fecal coliform densities are strongly related with proximity to areas with septic tanks, rainfall, and runoff from urbanized areas (Kelsey et al., 2004, Bougeard et al., 2011). Other studies have reported that manure spreading, runoff from agricultural land use, and the runoff from forestry land use are also linked to elevated fecal coliforms. In forest-dominated urban landscape, the major sources of fecal pollution are wild animals, humans, and, to a lesser extent, dogs (Whitlock et al., 2002, Levy et al., 2009, Bougeard et al., 2011). Comparisons between restricted and unrestricted pasture system clearly show total coliform, fecal coliform, and *E. coli* densities reduced significantly downstream in the restricted pasture system, but not in the unrestricted system (Oliver et al., 2005, Wilkes et al., 2013). Mixed results are reported on the relationship between streamflow and rainfall and coliform densities (Crabill et al., 1999, Oliver et al., 2005, Schoonover and Lockaby, 2006, Sanders et al., 2013, Wilkes et al., 2013).

2.6.3. Coliforms as a Proxy for Other Water Quality Indicators

Coliforms are usually washed into water bodies from upland wild life habitat, urban areas, and agricultural fields where grazing is a major land use (Oliver et al., 2005). The higher correlation between coliform count, suspended solid concentration, turbidity, and flow rate during storm flow conditions than during low flow conditions reveals the major carrying agents (Kim et al., 2005, Fries et al., 2006, Mallin et al., 2009, Sanders et al., 2013). In other regions, linear regression analysis has indicated that the percentage of watershed-impervious surface area alone can explain 95 percent of the variability in average estuarine fecal coliform abundance (Mallin et al., 2000). Such locally established relationships can be used to estimate coliform abundance in freshwater sources. Nevertheless, literature regarding the consistency of such relationships is unavailable.

2.7. Cyanobacteria

2.7.1. Description, Measuring Techniques, and Threshold Values

Cyanobacteria (also referred to as blue-green algae) are photosynthetic bacteria that share some properties with algae in that they possess chlorophyll a and release oxygen during photosynthesis. The decomposition of cyanobacteria consumes dissolved oxygen contained in the water and thus oxygen concentrations declines leading to hypoxic conditions (Brooks et al., 2016). Many cyanobacteria produce potent toxins that can cause liver damage and neurotoxicity and promote the growth of tumors. Cyanobacteria do not multiply in the human body and hence are not infectious (WHO 2011a). A World Health Organization (WHO) guideline recommends microcystin-LR of 1μg/L, while providing no guideline for other known cyanotoxins due to insufficient data to derive guideline values (WHO, 2008). A national or global list of thresholds is rarely available. However, a detailed recommended threshold is available for various states in the United States. These values range from 0.1 μg/L–1.6 μg/L of microcystin-LR and 0.1 μg/L–300 μg/L of anatoxin-a. Different maximum values are provided for children and adults.

2.7.2. Drivers, Linkages, and Degree of Drivers Influence

Globally, strong correlations have been demonstrated between nutrient enrichment (total phosphorus and total nitrogen) and some harmful species (Anderson, Gilbert, and Burkholder 2002; Michalak et al. 2013). Brookes and Carey (2011) show that cyanobacteria blooms are a product of high nutrient concentrations and lake water temperatures. Cyanobacteria have also been found to be related to the increasing annual average of air and water temperature gradient (Gallina et al., 2013). Poor circulation and longer residence time are also seen as facilitating factors for algal bloom (Michalak et al., 2013).

2.7.3. Cyanobacteria as a Proxy for Other Water Quality Indicators

Dense surface blooms of cyanobacteria is a typical characteristic of eutrophic lakes (Jöhnk et al., 2008). Cyanobacteria can be used as a proxy for phosphorus and nitrogen (Anderson et al., 2002a, Xu et al., 2010, Paerl et al., 2011, Lv et al., 2014, Doubek et al., 2015); changes in the thermal regime (Wagner and Adrian, 2009); and changes in temperature and phosphorus (Lv et al., 2014). While detecting algal blooms using remote sensing techniques is relatively straightforward, these techniques are not capable of separating waters dominated by cyanobacteria from waters dominated by other algae species. Some sensors (such as MERIS) have spectral bands suitable to detect cyanobacteria if they are present in relatively high quantities (Kutser et al., 2006, Matthews, 2014, Clark et al., 2017).

Chemical Water Quality Indicators

2.8. Alkalinity

2.8.1. Description, Measuring Techniques, and Threshold Values

Alkalinity is a measure of the capacity (also called "buffering capacity") of water to neutralize acids (Patil et al., 2012). Alkalinity is not considered detrimental to humans but is generally associated with high pH values, hardness, and excess dissolved solids. Highly alkaline waters may also have a distinctly flat, unpleasant taste (US EPA, 2009). Alkalinity is measured using a titrant and pH whereby the amount of carbonate (CO_3) involved in the reaction is determined and expressed as mg of $CaCO_3$/L. Health-based limits are not set for alkalinity.

2.8.2. Drivers, Linkages, and Degree of Drivers Influence

Alkalinity in surface waters is primarily a function of carbonate, bicarbonate, and hydroxide content and hence used as an indicator of the concentration of these constituents. Alkalinity is often related to hardness because the main source of alkalinity is usually from carbonate rocks (limestone), which are mostly $CaCO_3$ (APHA, 2000). In the Mekong River area, stream flow, air temperature, and precipitation, show strong positive correlations with alkalinity (Prathumratana et al., 2008). Stream water alkalinity show predictable fluctuations with the flow, with high flows exhibiting low and base flows high alkalinity (Soulsby et al., 2007). The alkalinity of water also plays an important role in daily pH levels. Photosynthesis by algae and plants uses hydrogen, thus increasing pH levels, while respiration and decomposition can lower pH levels. Most bodies of water are able to buffer these changes due to their alkalinity, so small or localized fluctuations are quickly modified and may be difficult to detect (Sheiham, 1981, USGS, 2016).

2.8.3. Alkalinity as a Proxy for Other Water Quality Indicators

Alkalinity is often used as a proxy for water hardness because the main source of alkalinity is usually from carbonate rocks (limestone), which are mostly $CaCO_3$(APHA, 2000). Alkalinity's sensitivity to temperature makes it a potential indicator for monitoring impacts of a changing climate (Prathumratana et al., 2008).

2.9. Ammonium

2.9.1. Description, Measuring Techniques, and Threshold Values

Ammonium (NH_4^+) is a chemical in water bodies resulting from the dissociation of nitrogen-containing compounds, mainly fertilizers containing ammonium sulfate or ammonium nitrate, washed into the water bodies. Ammonium (NH_4^+) is an ionized form of ammonia and total ammonia (NH_3) is what is measured analytically in water (ionized plus un-ionized). The un-ionized form is more toxic than the ionized form and thus measurements are focused on ammonia. Ammonia is analyzed by chemical titration. Threshold odor and taste concentrations of ammonia are respectively 1.5 mg/l and 35 mg/l (WHO 2011a).

2.9.2. Drivers, Linkages, and Degree of Drivers Influence

Sewage from industrial emission or leakage of manure and fertilizers from agricultural activities and urban land extent had higher positive relationship to ammonium (Shi et al., 2015, Du et al., 2017). A comparative study of ammonium dynamics in headwater streams from biomes throughout North America demonstrates that streams exert control over nutrient exports to rivers, lakes, and estuaries (Peterson et al., 2001). A meta-analysis of 240 experimental additions of ammonium shows statistically significant relationships between nutrient uptakes in restored streams. The size of the stream restoration (surface area), hydrologic connectivity, and hydrologic residence time have been found to be key drivers influencing ammonium retention at broader watershed scales and along the urban watershed continuum (Hatt et al., 2004, Newcomer Johnson et al., 2016). Higher ammonium level is also associated to the wet season (Berka et al., 2001, Shi et al., 2017).

2.9.3. Ammonium as a Proxy for Other Water Quality Indicators

The presence of ammonium in higher quantities in freshwater ecosystems facilitates higher algal growth. This triggers higher biochemical oxygen demand, which lowers dissolved oxygen levels and increases the amount of nitrification occurring (Webster et al., 2003). The presence of ammonium in surface water can be used to explain an abundance of cyanobacteria (Anderson et al., 2002a, Xu et al., 2010, Paerl et al., 2011, Lv et al., 2014, Doubek et al., 2015). Remote sensing approaches explained in section 2.1.3 can be used to establish a link between ammonium and chl-a as a proxy for cyanobacteria abundance (Shiomoto et al., 1994, Cai et al., 2012).

2.10. Biochemical Oxygen Demand (BOD)

2.10.1. Description, Measuring Techniques, and Threshold Values

BOD (biochemical oxygen demand) is a measure of the amount of oxygen that bacteria will consume in decomposing organic matter under aerobic conditions (Barnes et al., 1998). BOD is measured by determining the amount of oxygen consumed per liter of sample during five days of incubation at 20°C (Sawyer, 2003). Unpolluted, natural water has a BOD less than 5 mg/l. No health-based guideline value is recommended, but very high levels of dissolved oxygen may exacerbate corrosion of metal pipes (WHO 2011a).

2.10.2. Drivers, Linkages, and Degree of Drivers Influence

Strong correlations between the percentage of impervious area and BOD have been found (Kim et al., 2016). Urban land had a higher positive relationship with degraded water quality at small scales than at large scales, whereas agricultural land displayed the opposite scale effects(Shi et al., 2017). Conflicting results are reported on the seasonality of BOD in the dry season (Mallin et al., 2009, Shi et al., 2017).

2.10.3. BOD as a Proxy for Other Water Quality Indicators

Higher algal growth in water bodies triggers higher BOD, which lowers dissolved oxygen levels and increases the amount of nitrification occurring (Webster et al., 2003). Higher BOD and the associated decline in dissolved oxygen can be used to explain an abundance of phytoplankton (Xu et al., 2010, Paerl et al., 2011, Lv et al., 2014, Doubek et al., 2015). Elevated BOD can also be a proxy for ammonium and sulfate discharge from urban areas (Shi et al., 2017). Remote sensing approaches explained in section 2.1.3 can be used to establish a link between BOD and chl-a as a proxy for cyanobacteria abundance (Shiomoto et al., 1994, Cai et al., 2012).

2.11. Calcium

2.11.1. Description, Measuring Techniques, and Threshold Values

Calcium is an alkaline-earth metal essential to human health. Inadequate dietary intake of calcium can impair health (Talling, 2010). Calcium occurs in water naturally and is known to cause most of the hardness and scale-forming properties of water, which when consumed in industrial uses can result in costly breakdowns in boilers, cooling towers, and other equipment (LENNTECH, 2018a). Hardness is most commonly measured by titration with a solution of ethylenediaminetetraacetic acid (EDTA). A titration involves adding small amounts of a solution to a water sample until the sample changes color. Calcium can also be measured using a colorimeter by noting the difference between the amount of colored light transmitted by a colorless sample (blank) and the amount of colored light transmitted by a colored sample (APHA, 2005). The amount of colored light absorbed by the sample is directly proportional to the concentration. Upper levels of 2500 mg/day for calcium intake is recommended (IOM, 2008).

2.11.2. Drivers, Linkages, and Degree of Drivers Influence

Limited literature is available on drivers of calcium in surface/ground water sources. Studies in US watersheds have associated higher calcium concentration with mining (Zipper et al., 2016).

2.11.3. Calcium as a Proxy for Other Water Quality Indicators

Calcium concentration in surface and ground water could be an indicator of the chemical alteration of water resulting from the underlying geological features (such as dolomite) (Thomas, 1970, Schmitt et al., 2003).

2.12. Chloride

2.12.1. Description, Measuring Techniques, and Threshold Values

Chloride is a widely distributed element in nature and occurs as salts of sodium (NaCl), potassium (KCl), and calcium ($CaCl_2$) (WHO 1996). Titration techniques are used to determine chloride in water (Clarke, 1950, WHO, 2011a). The US Environmental Protection Agency (EPA) has set a secondary maximum contaminant level (SMCL) of 250 mg/l for chloride in drinking water (US EPA, 2009). The World Health Organization (WHO) taste thresholds for sodium chloride and calcium chloride in water are in the range 200 mg/l -300 mg/l (Köster et al., 1981).

2.12.2. Drivers, Linkages, and Degree of Drivers Influence

Chlorides are leached from various rocks into soil and water by weathering. The major increase in the use of salt has been for deicing of roads, parking lots, and other impervious surfaces during the winter months (USGS, 2009). Higher chloride is observed on watersheds where forested land is converted to agriculture (Williamson et al. 1987). The use of deicing salt on roads applied during the winter season through salt applications has been found to cause increased chloride in direct proportion to the accumulated amounts (Zampella et al., 2007, Löfgren, 2001a, Kelly et al., 2007, Gutchess et al., 2018a). Various studies report a slight increase in chloride from sewage and water softeners associated with an increase in population (Löfgren, 2001b, Kelly et al., 2008, Gutchess et al., 2018b). Higher chloride is observed in watersheds where forested land is converted to agriculture (Williamson et al., 1987).

2.12.3. Chloride as a Proxy for Other Water Quality Indicators

Chloride in freshwater systems could be used as indicator of the inflow of sewage and its constituent impurities (Kelly et al., 2008). If the chloride is sourced from domestic sewage, this could lead to an increase in BOD and a decline in dissolved oxygen. Lower dissolved oxygen renders water acidic (Sheiham, 1981).

2.13. Chemical Oxygen Demand (COD)

2.13.1. Description, Measuring Techniques, and Threshold Values

COD (chemical oxygen demand) is a measure of the oxygen required to oxidize soluble and particulate organic pollutants in wastewater. It provides an index to assess the effect of discharged wastewater on the receiving environment (Yao et al., 2014). Higher COD levels imply higher amounts of oxidizable organic material in the water, which leads to reduced dissolved oxygen (DO) levels. Measuring COD involves the use of oxidizing chemical (potassium dichromate $Cr_2O_7^{2}$) to oxidize the organic matter in solution to carbon dioxide and water. The amount of chemical oxidant consumed by the sample in about 2 hours at 150°C is the COD of the water sample (APHA 2005). Sustainable Water Group water quality guidelines recommend the COD of wastewater be brought down to 200 mg/l or less before being discharged to any water body (bsr.org, 2010).

2.13.2. Drivers, Linkages, and Degree of Drivers Influence

Strong correlations between the percentage of impervious area and COD have been found (Kim et al. 2016). Residential areas have been reported to be major contributors of influent that elevate the COD in adjacent water bodies (Shao et al. 2006). Higher COD are found to be strongly associated with the dry season flow (Shi et al. 2017).

2.13.3. COD as a Proxy for Other Water Quality Indicators

Oxygen-demands (both BOD and COD) are generally indicators of non-point sources as a major source of contamination (Miltner and Rankin, 1998). Higher COD levels mean a greater amount of oxidizable organic material is present in the sample, which will reduce dissolved oxygen (DO) levels (Sheiham, 1981).

2.14. Colored Dissolved Organic Matter (CDOM)

2.14.1. Description, Measuring Techniques, and Threshold Values

CDOM (Colored dissolved organic matter) is the optically measurable component of the dissolved organic matter in water (Das et al., 2017). CDOM has a limiting effect on photosynthesis and can constrain phytoplankton population and consequently affect the aquatic food chain (Bidigare et al., 1993). The amount of CDOM in water is determined using the spectral absorption coefficients of the sample. This is done by comparing the absorption of the water sample to that of UV-oxidized water as the blank and reference (Mitchell et al., 2000). CDOM threshold values are not available.

2.14.2. Drivers, Linkages, and Degree of Drivers Influence

Calculated CDOM yields are also correlated with the percentage of wetlands in watersheds, providing a method for the estimation of CDOM export from ungauged watersheds (Spencer et al., 2013). Significant seasonal variability has been found to be most significant during the monsoon (Das et al., 2017). CDOM concentration has been shown to be negatively correlated with temperature, while elevated CDOM concentrations are reported at the depth of maximum chlorophyll-a, indicating production of new CDOM associated with the phytoplankton bloom (Coble et al., 1998).

2.14.3. CDOM as a Proxy for Other Water Quality Indicators

CDOM often exhibits a robust positive relationship with dissolved organic carbon (DOC) (Ferrari et al., 1996, Asmala et al., 2012, Spencer et al., 2013, Brezonik et al., 2015)and dissolved organic matter (DOM) (Brown, 1977, Helms et al., 2008), and an inverse relationship to surface salinity (Hu et al., 2004). Remote sensing-based CDOM algorithms are reported to be very robust (Joshi et al., 2017, Li et al., 2017).

2.15. Conductivity

2.15.1. Description, Measuring Techniques, and Threshold Values

The electrical conductivity of water is directly related to the concentration of dissolved solids in the water. Ions from the dissolved solids in water influence the ability of that water to conduct an electrical current, which can be measured using a conductivity meter. The drop in voltage between two electrodes in a probe immersed in the sample water caused by the resistance of the water is used to calculate the conductivity in a water sample (reported in micro Siemens per centimeter, μS/cm) (APHA, 2005). No recommended threshold values are available for drinking water. Conductivity in the range of 150 μS/cm to 500 μS/cm is considered to be ideal to support aquatic life (Behar, 1997).

2.15.2. Drivers, Linkages, and Degree of Drivers Influence

Higher specific conductance is reported downstream of mining-disturbed watersheds with increasing distance from mined areas (Zipper et al., 2016). Electrical conductivity increased markedly after dredging (Zhang et al., 2010). Among land cover types, urban land had a higher positive relationship with higher electrical conductivity at small scales than at large scales (Hatt et al., 2004, Shi et al., 2017). A study in the lower Mekong River indicated strong negative correlations between conductivity and hydrological precipitation, average air temperatures, and stream flow (Prathumratana et al., 2008).

2.15.3. Conductivity as a Proxy for Other Water Quality Indicators

When correlated with laboratory measurements, electrical conductivity can provide an accurate estimate of TDS concentration (Day and Nightingale, 1984, Atekwana et al., 2004).

2.16. Dissolved Oxygen (DO)

2.16.1. Description, Measuring Techniques, and Threshold Values

Dissolved oxygen (DO) refers to the amount of oxygen (O_2) dissolved in water expressed as milligrams of oxygen per liter of water. Because fish and other aquatic organisms cannot survive without oxygen, DO is one of the most important water quality parameters. In nature, dissolved oxygen comes from the atmosphere and green aquatic plants and algae during photosynthesis. DO can be measured either with a titrimetric method or using an electrochemical or optical sensor (Katznelson, 2004). While there is no threshold on the basis of human health, a concentration above 5.8 mg/l is considered essential for both cold water and warm water permanent fisheries (EPA, 2000).

2.16.2. Drivers, Linkages, and Degree of Drivers Influence

Blooms are reported to be a prime agent of deoxygenation of bottom waters (Paerl et al. 2001). The rate of gross primary production has been found to be strongly correlated with the amplitude of the diurnal dissolved oxygen deficit profile (Mulholland et al., 2005). Dissolved oxygen distributions in lake, especially the surface mixed-layer depth, are sensitive to changes in water transparency and temperature (Stefan et al., 1995). Higher turbidity is also associated with higher dissolved oxygen (Liao et al., 2011). Studies also indicate that managing nutrients results in positive feedback for recovering dissolved oxygen (Caballero-Alfonso et al., 2015).

2.16.3. Dissolved Oxygen as a Proxy for Other Water Quality Indicators

Lower DO is often associated with higher microorganism activity due to high presence of biodegradable material. The metabolic activity by these organisms in consuming the biodegradable matter lowers dissolved oxygen levels (Webster et al., 2003). Thus higher BOD and the associated decline in dissolved oxygen can be used to explain abundance of phytoplankton (Xu et al., 2010, Paerl et al., 2011, Lv et al., 2014, Doubek et al., 2015). However, dissolved oxygen is also produced as a waste product of photosynthesis from phytoplankton, algae, seaweed, and other aquatic plants and thus is replenished in the water.

2.17. Magnesium

2.17.1. Description, Measuring Techniques, and Threshold Values

Magnesium is a dietary mineral mainly present in watery solutions. Magnesium is a constituent of chlorophyll and activates a number of enzymatic reactions (Kirkby and Mengel, 1976, LENNTECH, 2018b). Given that calcium carbonate is one of the more common causes of hardness, magnesium hardness is usually reported in terms of calcium carbonate concentration (mg/L as $CaCO_3$) (Thomas, 2009, WHO, 2009). Literature recommends at least 6 mg/kg/day intake of dietary magnesium (Durlach, 1989). Both the EPA and European Union (EU) guideline recommend an upper intake limit of 250 mg/l-350 mg/l for humans. Magnesium concentrations greater than 125 mg/l may have a laxative effect on some people. Magnesium is one of the main contributors to water hardness along with calcium (WHO, 2009).

2.17.2. Drivers, Linkages, and Degree of Drivers Influence

Deposits of magnesium in Lake Symsar (Poland) revealed that pollutants received from an agricultural catchment and inadequately treated municipal wastewater influenced the magnesium concentrations (Potasznik and Szymczyk, 2015).

2.17.3. Magnesium as a Proxy for Other Water Quality Indicators

Higher total dissolved solids could signal presence of magnesium, among other inorganic salts (Canada, 1991).

2.18. Nitrate

2.18.1. Description, Measuring Techniques, and Threshold Values

Nitrate in surface water is mainly sourced from inorganic fertilizers, manure, and liquid waste discharged from septic tanks (Behar, 1997). Nitrates occur naturally in plants, for which it is a key nutrient. If water containing nitrate levels greater than 10 mg NO_3^- nitrogen per liter is used to prepare infant formula, it can result in methemoglobinemia, a condition in which red blood cells are prevented from transporting oxygen throughout the body (WHO, 2011b). The US Public Health Service recommended a limit of 10 mg/L NO_3^-N (referred to as nitrate-nitrogen) in drinking water is used by the EPA as the maximum contaminant level for public water systems.

2.18.2. Drivers, Linkages, and Degree of Drivers Influence

Nitrogen pollution from anthropogenic sources enters bodies of water through agricultural runoff or percolation associated with nitrogen fertilization, livestock, precipitation, and effluents from industrial and human waste (van Kessel et al., 2009, Rouse et al., 1999). Land use and land cover across diverse watersheds have been correlated with nitrate loading(Binkley, 2001, Ahearn et al., 2005, Shi et al., 2017). The greatest annual loads of nitrogen are from less developed agricultural and low-density residential areas; the latter is the most rapidly growing land use in expanding metropolitan areas (Shields et al., 2008). Storm water event nutrient budgets indicate a substantial attenuation in nitrate loads where sediment retention structures are implemented as conservation structure (Richardson et al., 2011). Nitrate-contaminated groundwater contributed to high nitrates in major tributaries, lakes, and estuaries (Gärdenäs et al., 2005). Nitrate concentrations during the wet season have been positively correlated to surplus applications. Soil texture and drainage type have also been found to be significantly correlated with nitrate concentrations (Berka et al., 2001). In the Amazon, pasture streams has been reported to yield lower concentrations of nitrate than forest streams (Neill et al., 2001). Nitrate concentration increased markedly after dredging (Zhang et al., 2010). Subsurface tile drainage from row-crop agricultural production systems has been identified as a major source of nitrate entering surface waters in the Mississippi River basin (Randall and Mulla, 2001). Non-controllable factors such as precipitation and mineralization of soil organic matter have a tremendous effect on drainage losses, nitrate concentrations, and nitrate loadings in subsurface drainage water(Randall and Mulla, 2001).

2.18.3. Nitrate as a Proxy for Other Water Quality Indicators

Turbidity has been positively correlated with enteric bacterial abundance. Enteric bacterial abundance has been strongly correlated with nitrate and weakly correlated with orthophosphate concentrations (Mallin et al., 2000). In the warm season, a decline in nitrate with an associated phytoplankton growth as evidenced by increasing CHL is typical of a denitrification process (Eppley et al., 1979, Al-Qutob et al., 2002, McCarthy et al., 2007).

2.19. Nitrite

2.19.1. Description, Measuring Techniques, and Threshold Values

Nitrite is a naturally occurring inorganic form of nitrogen. Nitrite could also form by the reduction of ingested nitrate, which reacts with hemoglobin to form methemoglobin, which does not transport oxygen to the tissues (Powlson et al., 2008). Nitrite is relatively unstable given that it is the intermediate species between ammonia and nitrate. Manual colorimetry or ion chromatography is used to determine the nitrite-N concentration (Cox, 1980). Hence, it is usually found in very low concentrations in the environment—less than 0.1 mg/L. Its concentration should not exceed 1 mg/L in municipal wastewater.

2.19.2. Drivers, Linkages, and Degree of Drivers Influence

The presence and the type of vegetation, mainly due to changes in the sediment carbon and nitrogen content, have been found to be negatively correlated to the ratio between nitrate and nitrite reducers and positively correlated to the ratio between nitrite and nitrous oxide reducers. These results suggest that the potential for nitrous oxide emissions is higher in vegetated sediments (García-Lledó et al., 2011). Nitrite concentrations follow typical seasonal patterns, with the highest values in winter, and the lowest in the May-September period, when the discharge is lower (Pirrone et al., 2005). Nitrite excretion by phytoplankton is also reported to play a significant role in the formation of the deep nitrite maximum (DNM) during stratification in summer (Al-Qutob et al., 2002).

2.19.3. Nitrite as a Proxy for Other Water Quality Indicators

Phytoplankton community abundance and cyanobacterial blooms are strongly linked to excess nitrogen loading to a water body (Lv et al., 2014). Chl-a measurements show significantly correlation to nitrite, especially where algae with efficient nitrite conversion are present in the water body (Yang et al., 2004, Cai et al., 2012). Phytoplankton could also release nitrite when light is limited (Flynn and Flynn, 1998).

2.20. Optical Water Type Class

2.20.1. Description, Measuring Techniques, and Threshold Values

Optical water type is frequently used to characterize the spectral characteristics of water as affected by constituent impurities, which typically include chlorophyll-a (chl-a), suspended material (SPM), Secchi depth (SD), and colored dissolved organic matter (CDOM) (Arst et al., 2003). Reinart et al. (2000, 2003) introduced a widely accepted classification based on apparent optical properties, the amount of optically active substances (OAS), and the diffuse attenuation coefficient (Reinart et al., 2000, Reinart et al., 2003).

2.20.2. Drivers, Linkages, and Degree of Drivers Influence

Optical water type classification is mainly used to characterize lakes and oceans. This review focuses on lakes because they are mainly used as water sources for consumptive use. The five categories of levels used to classify lake water clarity are associated with the constituent parts found in the water and their interaction with light (Reinart et al. 2003). These categories labels lakes as *clear*, *moderate*, *turbid*, *very turbid* and *brown* lakes. Clear lakes are characterized by phytoplankton pigments. Lakes with moderate clarity have their water darkened by color-causing materials that dominantly favors absorption of light. Turbid lakes are characterized by higher suspended particles that scatter more light. Very turbid lakes are dominated by very high amount of chl-a. Very high amount of dissolved organic matter typically form brown lakes (Arst et al., 2003).

2.20.3. Optical Water Type Class as a Proxy for Other Water Quality Indicators

Optical water type class is mainly used as a proxy for turbidity and chl-a (Arst et al., 2003).

2.21. pH

2.21.1. Description, Measuring Techniques, and Threshold Values

pH describes how acidic or basic a solution is. The pH scale is used to represent hydrogen ion activity. Visual, photometric, and potentiometric methods can be used to measure the hydrogen ion activity of a solution. Visual and photometric methods rely on color changes of specific organic pigments in order to determine pH. pH values below 7 represent acidic solutions (hydrogen ion activity greater than hydroxide ion activity), while values above 7 represent basic solutions. A change on the pH scale of 1.0 pH unit indicates that hydrogen ion activity differs by an order of magnitude (that is, a factor of 10). For example, hydrogen ion activity at pH 4 is 10 times greater than at pH 5.

2.21.2. Drivers, Linkages, and Degree of Drivers Influence

Water-monitoring data collected by state and federal agencies demonstrate that pH is influenced by Appalachian mining. pH also exhibited spatial patterns that are consistent with dilution of mining influence with increasing distance from mined areas(Zipper et al., 2016). A substantial decrease over time in the magnitude of acidification per given quantity of antecedent rainfall is reported in lowland areas experiencing tidal inundation of coastal landscapes(Johnston et al., 2009). Photosynthesis by algae and plants uses hydrogen, thus increasing pH levels, whereas respiration and decomposition lower pH levels (Sheiham, 1981, USGS, 2016).

2.21.3. pH as a Proxy for Other Water Quality Indicators

The alkalinity of water also plays an important role in altering pH levels. The process of photosynthesis by algae and plants uses hydrogen, thus increasing pH levels, while respiration and decomposition lower pH levels. Laboratory experiments suggest that DOM is positively related to pH (Tipping and Hurley, 1988, Kennedy et al., 1996). A decline in pH could be an indicator of an increase in total organic carbon and sulfate. A decline of pH by up to 0.6 units is reported due to sulfate (Laudon and Bishop, 2002).

2.22. Phosphorus

2.22.1. Description, Measuring Techniques, and Threshold Values

Phosphorus is a critical nutrient required for life. The most common form of phosphorus used by biological organisms is phosphate (PO_4), which plays major roles in the formation of DNA, cellular energy, animal cell membranes, and plant cell walls. Phosphorus is a common ingredient in commercial fertilizers. Phosphorus tends to attach to soil particles and thus moves into surface-water bodies from runoff (Carpenter et al. 1998). Phosphorus occurs in water as orthophosphate, condensed phosphate, and organic phosphate (Berka et al., 2001, EPA, 2012b). Different techniques are applied to measure these different forms of phosphorus in water (Behar, 1997). A 0.10 μg/L of elemental phosphorus could lead to accelerated eutrophication of waters (EPA, 1996).

2.22.2. Drivers, Linkages, and Degree of Drivers Influence

Large quantities of phosphate present in wastewater is one of the main causes of eutrophication that negatively affects many natural water bodies, both freshwater and marine (De-Bashan and Bashan, 2004). Proximate drivers of changes in land use and land cover (LULC) are reported to account for about 42% of the variation in phosphorus impairment (Wilson, 2015). Changes in land use from forest to agriculture are typically associated with substantial increases in concentrations of phosphorus compounds (Binkley, 2001). Strong correlation between percentage of impervious area (urbanization) and total phosphorus are found (Shao et al., 2006, Kim et al., 2016). High livestock densities, excessive manure production, and excess fertilization and manure production cause a phosphorus surplus, which is transported to aquatic ecosystems, various studies show (Carpenter et al., 1998, McDowell and Sharpley, 2001, Alemu et al., 2017). A significant relationship between land use and phosphorus, and more specifically agricultural and impervious urban lands, is reported (Tong and Chen, 2002). The urban stream yielded the highest total phosphorus, and were significantly higher during rain events compared to non-rain periods. Total rainfall preceding sampling was positively correlated with total phosphorus (Shi et al., 2017). Conversion of tropical forest to actively grazed cattle pasture in the Brazilian Amazon increased phosphorus in stream water (Neill et al., 2001). In the Netherlands, areas with high livestock concentrations show high phosphorus concentrations in streams owing to leaching from phosphate-saturated soils (Breeuwsma et al., 1995). The rapid increase in the use of synthetic detergents during the past ten years has been accompanied by the presence of greater quantities of synthetic detergent compounds in sewage effluents and in surface waters (Engelbrecht and Morgan, 1959). In the Sahara, the concentration of phosphate was proportional to the amount of dust introduced and is associated with a significant amount of rain, as the main dissolution of phosphorus will occur in the air column (Ridame and Guieu, 2002).

2.22.3. Phosphorus as a Proxy for Other Water Quality Indicators

Phytoplankton community abundance and cyanobacterial blooms are strongly linked to excess phosphorus loading to a water body (Wagner and Adrian, 2009, Paerl et al., 2011, Paerl and Paul, 2012, Lv et al., 2014, Doubek et al., 2015). This linkage is often used to establish a relationship between phosphorus and chl-a. In China, for example, studies report that phosphorus explained more than 98 percent of the variation in chl-a of freshwater lakes (Cai et al., 2012). Warner and Lesht (Warner and Lesht, 2015) and Lehrter (Lehrter, 2008) also indicated a strong relationship between phosphorus and chl-a.

2.23. Potassium

2.23.1. Description, Measuring Techniques, and Threshold Values

Potassium is an essential element in humans and is seldom found in drinking water at levels that could be a concern for human health. Potassium is measured based on the turbidity created when combining with sodium tetraphenyl borate (Clesceri et al., 2012). There are no health-based drinking water standards for potassium. Excessive intakes may have a laxative effect, but public health authorities have not established a maximum limit (EPA, 1996). The recommended daily dietary requirement is greater than 3000 mg (EPA, 2012b).

2.23.2. Drivers, Linkages, and Degree of Drivers Influence

Potassium is one of four cations that collectively account for most of total cataionic concentration in natural water systems. The growth of phytoplankton can deplete the concentration of potassium (Talling, 2010). Crop residue is a major source of potassium in agricultural fields. Nevertheless, it is lost from agricultural soil by crop harvesting and by leaching and runoff acting on organic residues (Hem, 1989).

2.23.3. Potassium as a Proxy for Other Water Quality Indicators

Potassium is one of the major positively charged ions and could be used as a potential proxy for higher conductivity, especially if it co-occurred with major negatively charged ions (such as chloride, sulfate, carbonate, and bicarbonate) (arroyoseco.org, 2010).

2.24. Sodium

2.24.1. Description, Measuring Techniques, and Threshold Values

Sodium occur naturally in freshwater sources. Elevated levels of sodium interfere with taste and the water intake of certain plants, and increase the corrosivity of water. Sodium concentrations can be determined by a method called direct aspiration atomic absorption spectroscopy (Andreae and Asmode 1981). No health-based guideline value has been derived because the contribution from drinking-water to daily intake is small. Nevertheless, WHO has set an average taste threshold of about 200 mg/l (WHO, 2011a).

2.24.2. Drivers, Linkages, and Degree of Drivers Influence

A major increase in the use of salt has been for deicing of roads, parking lots, and other impervious surfaces during the winter months (USGS, 2009). Salt used for deicing accounts for more than 90 percent of the sodium chloride input to the watershed, while sewage and water softeners account for less than 10 percent of the input (Kelly et al., 2008). Various studies report a slight increase in sodium and chloride from sewage and water softeners associated with an increase in population (Löfgren, 2001b, Kelly et al., 2008, Gutchess et al., 2018b). The use of deicing salt on roads applied during the winter season has been found to increase sodium in direct proportion to the accumulated amounts (Gutchess et al., 2018b, Löfgren, 2001b, Kelly et al., 2008).

2.24.3. Sodium as a Proxy for Other Water Quality Indicators

Sodium is an indicator of the inflow of sewage and its constituent impurities (Kelly et al., 2008). If the sodium is sourced from domestic sewage, this could lead to an increase in BOD and a decline in dissolved oxygen. Lower dissolved oxygen renders water acidic (Sheiham, 1981). When the source is salt used for deicing roads, sodium could be used as a proxy for higher chlorine (Kelly et al., 2008, Löfgren, 2001b, USGS, 2009, Gutchess et al., 2018b).

2.25. Sulfate

2.25.1. Description, Measuring Techniques, and Threshold Values

Sulfates occur naturally in numerous minerals forms. Sulfate in aqueous solutions may be determined by a gravimetric method in which sulfate is precipitated as barium sulfate (ISO, 1990). The presence of sulfate in drinking-water can cause a noticeable taste, and very high levels might have a laxative effect in unaccustomed consumers (WHO, 2011a). Taste threshold concentrations in drinking water are 350 mg/l for sodium sulfate, 525 mg/l for calcium sulfate, and 525 mg/l for magnesium sulfate (WHO, 2004).

2.25.2. Drivers, Linkages, and Degree of Drivers Influence

Annual sulfate flux follows a marked seasonal pattern (accumulation during summer and winter; washout during spring and autumn) resulting from increased leaching of base cations from the soil. The concentration of sulfate in stream water shows a characteristic pattern of high levels in the first stormflow following a dry summer period and low levels in baseflow (Christophersen and Wright, 1981). Other studies in US watersheds have associated higher sulfate concentration with mining (Zipper et al., 2016).

2.25.3. Sulfate as a Proxy for Other Water Quality Indicators

Sulfate in stream water results in an acidification of stream water (Christophersen and Wright, 1981). Higher sulfate concentrations can also increase the magnitude of phosphorus release from sediments washed into the water body and thus facilitates algal growth (Caraco et al., 1993).

2.26. Conclusion and Recommendations

Complex natural and anthropogenic factors drive processes that determine surface water quality. While the majority of reported studies tend to agree on the correlation between a water quality indicator and its driver, considerable literature reports otherwise. Some of the disparities in these studies may arise in defining and measuring “drivers.” A case in point is the correlation between urban expansion and turbidity. Various studies, mainly carried in developed regions of the world, report a decline in turbidity with the expansion of urbanization. The decline is often attributed to the extent of the impervious surface that protects the natural earth surface from getting washed to water bodies during rainstorms. Such studies correlate the impervious area with turbidity in determining the elasticity of turbidity as a function of urban expansion. In contrast, similar studies conducted in developing regions report a weak relationship between turbidity and the extent of urbanization (Hatt et al., 2004). Urban areas in developing regions may not necessarily have completely sealed, paved surfaces. Coarser satellite images used in developing urban areas often fail to represent the spatial heterogeneity in urban settings (de Colstoun et al., 2017). Various image processing methodologies have been developed to create a vegetation-impervious surface-soil (VIS) model of urban composition that enables distinctive densities of commercial, industrial, and residential zones within the city to be clearly defined, based on their relative amount of vegetation cover (Phinn et al., 2002). The Global Man-made Impervious Surface (GMIS) dataset built using 30m resolution Landsat imagery and other ancillary data sources is a pioneering effort to reveal the proportion of impervious areas around the world at considerably high resolution.

The following recommendations could lead to better estimates from water quality indicators using remote sensing techniques and cross-checking their reliability:

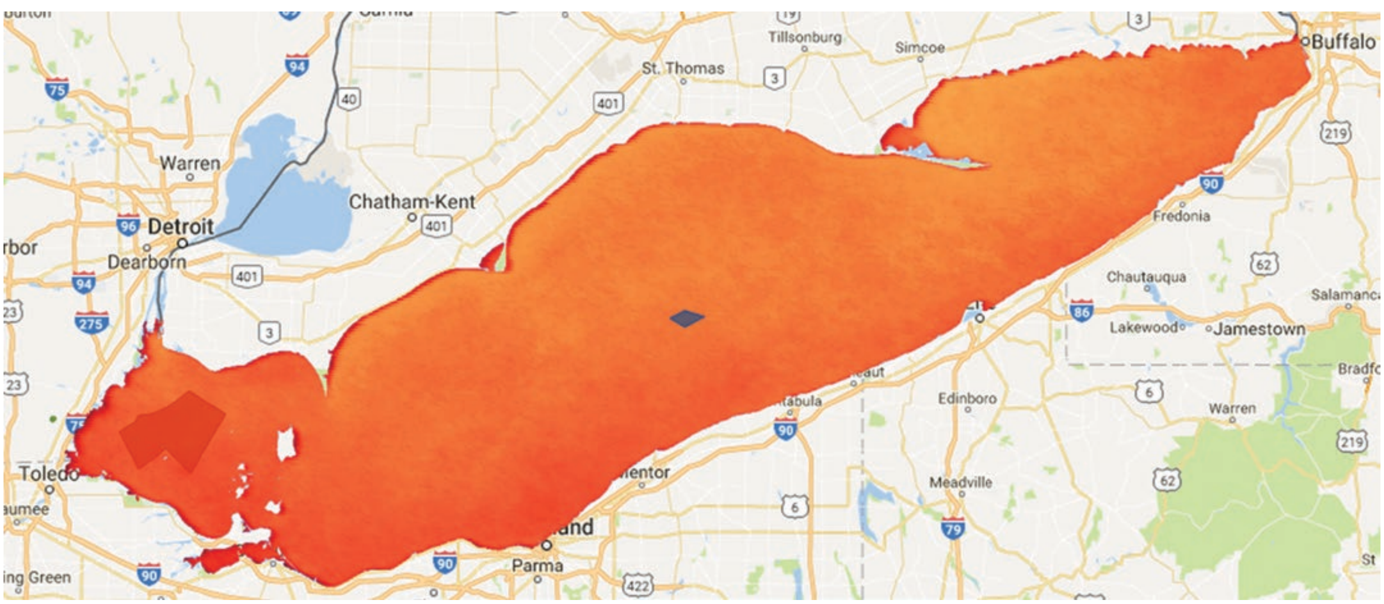
1. Physical water quality indicators—mainly turbidity, chl-a, total suspended solids, and temperature—can be measured relatively easily using remote sensing. While established relationships between these indicators and satellite-measured reflectance are site specific—except for temperature, which is often available at a global scale—they have been established for large lists of lakes globally. Moreover, globally applied techniques that help avoid local calibration are also established for specific remote sensing platforms (Nechad et al., 2010, Dogliotti et al., 2015).
2. The chemical and biological water quality indicators cannot be directly estimated using remote sensing methods. Instead, a strong relationship exists between some of the indicators (chemical and biological) and either turbidity, total suspended solids, or chl-a. These relationships can be used to extend the remote sensing approach to estimate chemical and biological water quality indicators. However, such cascading approaches could amplify uncertainty and render the estimates untrustworthy.
3. Among the three physical water quality indicators, turbidity and chl-a can ready be detected using remote sensing techniques. This is because turbid plumes often change the reflectance characteristics of water, and chlorophyll-bearing organisms can easily be detected using remote sensing, especially in the near-infrared spectrum. While the determination of these indicators is mostly straightforward, resolving between turbidity and chl-a could be tricky. This is because near-infrared sensors produce very similar responses in detecting turbidity and chl-a. Moreover, chl-a is one of the constituent parts in water that cause turbidity along with suspended sediment and color-causing dissolved matter. In reality, a turbid plume is often detected instantaneously from satellite images, whereas a detectable level of chl-a is reached once nutrients brought into the water body are consumed by phytoplankton and algae and aquatic vegetation subsequently expands across the

water body. In examining the impact of the expansion of agriculture on water turbidity or chl-a, the timing of occurrence of the peak near-infrared reflectance and chl-a in tandem with the amount of biomass at the plot can be used to verify whether the detected parameter using remote sensing is actually turbidity or chl-a.

A Google earth engine time series extract of MODIS image products—near-infrared (NIR) reflectance, chl-a, and enhanced vegetation index (EVI), along with global gridded precipitation product (CHIRPS)—can be used to demonstrate the similar sensor reaction for turbidity and chl-a over Lake Erie at the point where the Maumee River enters the lake at Toledo. Here, cyanobacteria bloom reached its peak in September 2011 (Michalak et al., 2013). The time series compare the EVI at an agriculture field near the river entry (labeled “a” in map 1) and chl-a of the water surface at entry (labeled “b”) and at the middle of the lake (labeled “c”), where the water is expected to be relatively clear. Figure 1 presents the corresponding data for vegetation at the agricultural field (panel a); chl-a levels at the entry of the Maumee River (panel b); and NIR reflectance at the entry of the Maumee River (panel c).

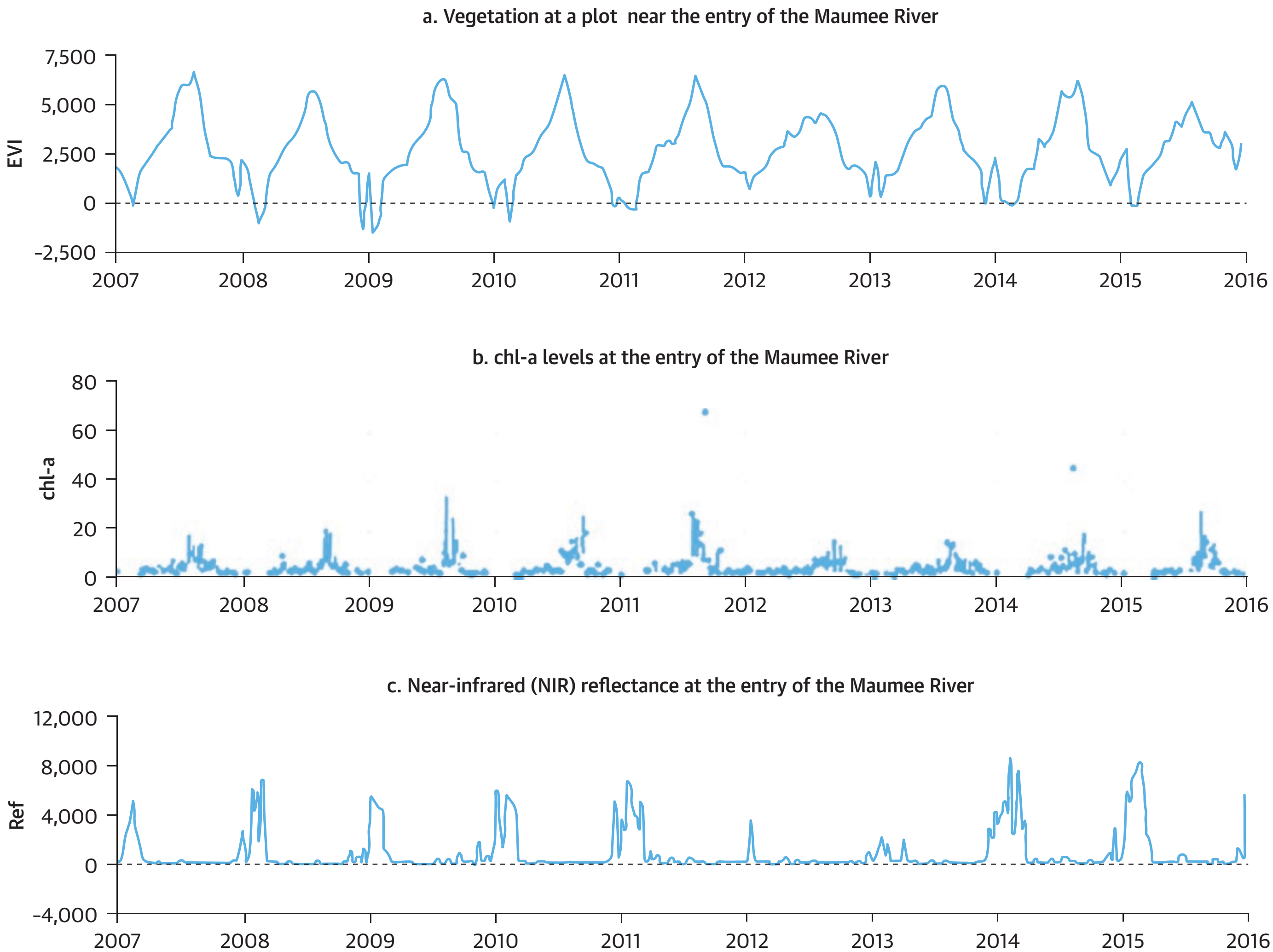
While turbidity peaks on January 25, chl-a peaks on September 3. The planting season is taken to start during the first week of March (EVI plot) (panel a of figure 1). Two rounds of fertilizer are applied before vegetation peaks (August 13). A September peak in chl-a is thus the lag time for the nutrient to be washed to the lake (figure 2, panel a), used up by the phytoplankton, and cover an area that can be detected by the imaging. The river water flowing into the lake—which is warmer in some spots than water from urban areas (panel b)—could have facilitated the growth of phytoplankton. High rainfall that year—50 percent higher compared to the median total annual precipitation of the 2007-15 period—could also be a driver (panel c).

MAP 1. Median Water Surface Temperature of Lake Erie, 2007-15



Source: Author's calculations.
Note: Point a = agricultural plot near the entry of the Manmee River; point b = river entry; point c = middle of the lake.

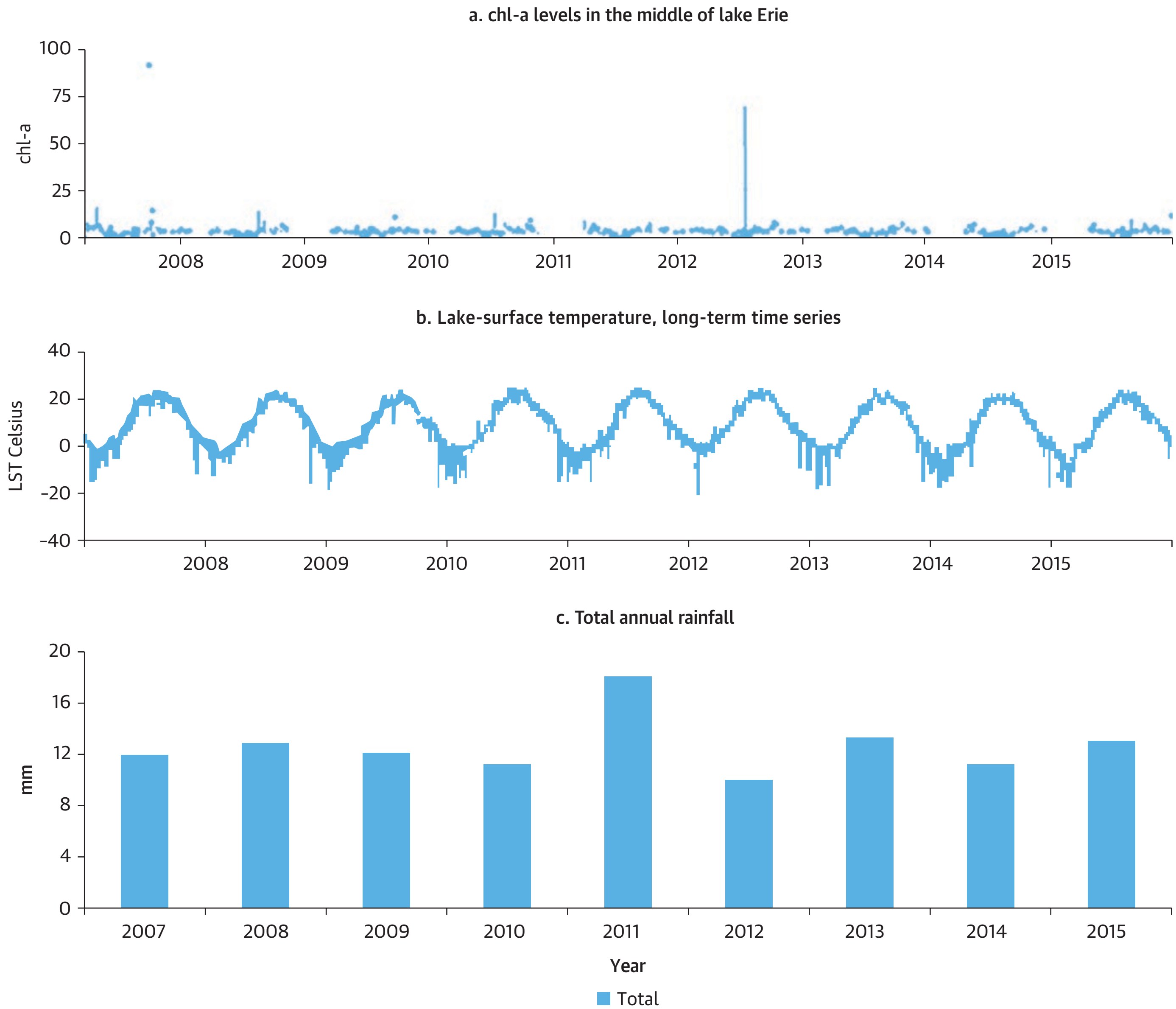
FIGURE 1. Comparing Vegetation, Chl-a Levels, and Near-Infrared Reflectance at and Near the Entry of the Maumee River



Source: Author's calculations.
Note: chl-a = chlorophyll-a; EVI = enhanced vegetation index; NIR = near-infrared; ref = reflectance.

In summary, while literature provides ample evidence concerning the factors that determine water quality, not all evidence is equally strong. In some cases, evidence is contradictory. Remote sensing techniques provide ample opportunities to easily estimate the most important physical water quality indicators that can be used as a proxy for other chemical and biological water qualities. A major challenge is establishing these relationships and quantifying the uncertainties associated with such estimates. Establishing a tailored water quality index that uses the readily measurable indicators could be a viable approach to make a rapid assessment of the water quality status of a water source. An approach that incorporates some of this indicators is outlined by Akkoyunlu and Akiner(Akkoyunlu and Akiner, 2012).

FIGURE 2. Possible Drivers for the Phytoplankton Bloom



Source: Author's calculations.
Note: chl-a = chlorophyll-a; LST = lkae surface temperature.

Appendix A

TABLE A.1. Summary Table: Impact of Different Drivers on Water Quality Indicators, as Reported in the Reviewed Literature

Indicator	Driver	Number of papers: Negative impact	Number of papers: Positive impact	Remarks	Literature
Chlorophyll-a	Agriculture			Fertilizer	Boynton, Kemp, and Keefe (1982); Canfield Jr. et al. (1984); Prairie, Duarte, and Kalff (1989); Anderson Gilbert, and Burkholder (2002); Lehrter (2008); Elliott (2010); Cai et al. (2012); Paerl and Paul (2012); Warner and Lesht (2015); Ji et al. (2018); McCarthy et al. (2018)
	Climatic factors			Precipitation, temperature	
	Geographic factors			Residence time	
	Urban expansion			Population growth	
Coliforms	Agriculture			Livestock	Crabill et al. (1999); Whitlock, Jones, and Harwood (2002); Kelsey et al. (2004); Ahn et al. (2005); Oliver et al. (2005); Schoonover and Lockaby (2006); Levy et al. (2009); Bougeard et al. (2011); Sanders, Yuan, and Pitchford (2013); Wilkes et al. (2013)
	Climatic factors			Precipitation	
	Geographic factors			Forested areas	
	Economic factors			Recreation	
Cyanobacteria	Agriculture				Anderson Gilbert, and Burkholder (2002); Brookes and Carey(2011); Gallina et al. (201)3; Michalak et al. (2013)
	Climatic factors			Precipitation, temperature	
	Economic factors			Urban expansion	
Alkalinity	Climatic factors			Precipitation, temperature	Sheiham (1981); APHA (2000); Soulsby et al. (2007); Prathumratana, Sthiannopkao, and Kim (2008)
	Geographic factors			Rocks	
Ammonium	Agriculture			Fertilizer	Berka, Schreier, and Hall (2001); Hatt et al. (2004); Shi et al. (2015, 2017); Newcomer Johnson et al. (2016); Du et al. (2017)
	Climatic factors				
	Geographic factors				
	Urban expansion			Population growth	
BOD	Climatic factors			Precipitation, temperature	Mallin, Johnson, and Ensign (2009); Kim et al. (2016); Shi et al. (2017)
	Urban expansion			Impervious surface	
Chloride	Agriculture				Williamson et al. (1987); Löfgren (2001); Zampella et al. (2007); Kelly et al. (2008); USGS (2009); Gutchess et al. (2018)
	Economic factors			Dicing	
Calcium	Geographic factors			Limestone rocks	Thomas (1970); Schmitt, Chabaux, and Stille (2003)
COD	Climatic factors			Precipitation	Shao et al. (2006); Kim et al. (2016); Shi et al. (2017)
	Urban expansion			Impervious surface	
CDOM	Climactic variables			Precipitation	Spencer et al. (2013); Das et al. (2017)
	Geographic factors			Wetland loss	
Conductivity	Climatic factors			Precipitation, temperature	Hatt et al. (2004); Prathumratana, Sthiannopkao, and Kim (2008); Zhang et al. (2010); Zipper et al. (2016); Shi et al. (2017)
	Urban expansion			Urban	
	Economic factors			Dredging, mining	

table continues next page

TABLE A.1. continued

Indicator	Driver	Number of papers		Remarks	Literature
		Negative impact	Positive impact		
Dissolved solids	Climatic factors			Precipitation	Hall (1970); Johnson et al. (1997); Zhang et al. (2010)
	Economic factors			Dredging	
Dissolved oxygen	Agriculture			Fertilizer	Stefan et al. (1995); Paerl et al. (2001); Caballero-Alfonso, Cartensen, and Conley (2015)
	Climatic factors			Temperature	
	Geographic factors			Blooms	
Magnesium	Urban expansion			Waste water	Potasznik and Szymczyk (2015)
Nitrate	Agriculture			Pasture	Berka et al. (2001); Neill et al. (2001); Randall and Mulla (2001); Shields et al. (2008); Zhang et al. (2010); Richardson et al. (2011)
	Climatic factors			Precipitation	
	Economic factors			Dredging, urbanization	
Nitrite	Agriculture			Fertilizer	Al-Qutob et al. (2002); Pirrone et al. (2005); Zampella et al. (2007)
	Climatic factors			Precipitation	
	Economic factors			Urban	
pH	Agriculture			Fertilizer	Sheiham (1981); Johnston et al. (2009); USGS (2016); Zipper et al. (2016)
	Geographic factors			Tide	
	Economic factors			Mining	
Phosphorus	Agriculture			Livestock	Engelbrecht and Morgan (1959); Breeuwsma, Reijerink, and Schoumans 5); Carpenter et al. (1998); Binkley (2001); McDowell and Sharpley (2001); Neill et al. (2001); Tong and Chen (2002); Ridame and Guieu (2002); De-Bashan and Bashan (2004); Shao et al. (2006); Kim et al. (2016); Alemu et al. (2017); Shi et al. (2017)
	Climatic factors			Precipitation	
	Geographic factors			Dust	
	Urban expansion			Detergent	
Sodium	Urban expansion			Sewage	Löfgren (2001); Kelly et al. (2008); USGS (2009); Gutchess et al. (2018)
	Economic factors			Deicing, sewage	
Sulfate	Climatic factors			Precipitation	Christophersen and Wright (1981); Zipper et al. (2016)
	Economic factors			Mining	
Temperature	Climatic factors			Glacial streams, warming climate	Uehlinger, Malard, and Ward (2003); Hatt et al. (2004); Malcolm et al. (2008); Olden and Naiman (2010); Verones et al. (2010); Van Vliet et al. (2013)
	Geographic factors			Riparian woodland	
	Economic factors			Dam release, cooling	
TSM	Agriculture			Fertilizer	Devereux et al. (2010); Zhang et al. (2010); Glendell and Brazier (2014); Ryken et al. (2015); Wilson (2015); Tuset, Vericat, and Batalla (2016); Fierro et al. (2017)
	Climatic factors			Precipitation	
	Geographic factors			Wetland loss	
	Urban expansion			Urban expansion, dredging	
Turbidity	Agriculture			Pasture	Wischmeier and Smith (1978); Peierls et al. (1991); Baker (2005); Ouyang, Zhu, and Kuang (2006); Brezonik et al. (2007); Chen, Hu, and Muller-Karger (2007); Whitehead et al. (2009); Petus et al. (2010); Uriarte et al. (2011); Kaba, Philpot, and Steenhuis (2014); McCarthy et al. (2018)
	Climatic factors			Precipitation, wind	
	Geographic factors			Forest	
	Urban expansion			Population growth	

TABLE A.2. Threshold Concentrations for Various Water Quality Indicators, Unless Specified Units are in Milligrams per Liter

Indicator	WHO	EPA	EU	Normally found in freshwater
Chlorophyll - a	—	—	—	
E. coli	0	0	0	Drinking: Zero. Surface water used for swimming (full-body contact): 235 cfu/100 mL. Fishing, boating, etc. (partial-body contact): 575 cfu/100 mL. Wastewater used for irrigation: < 2.2cfu/mL 100. Wastewater discharge: < 1.0 cfu/100 mL (EPA 1996, 2012a).
Fecal coliform	0	0	0	
Cyanobacteria				
Total coliform	0	0	0	
Alkalinity	—	—	—	Wildlife propagation and stock-watering waters (230-day average): daily maximum 750/1,313.
Ammonium			0.5	
BOD				
Calcium		2500	2500	Upper levels for calcium intake.
Chloride[a]	250	250	250	
COD				
CDOM				
Conductivity	—	—	2500 µS/cm at 20°C	Wildlife propagation and stock-watering waters: 4,000/7,000. Irrigation waters: 2,500/4,375.
Dissolved solids	—	500 mg/l	—	No reliable data on possible health effects. High levels of TDS in drinking-water may be objectionable to consumers. Maximum and minimum set by specific countries are 2,500 mg/l and 200 mg/l, respectively.
Dissolved oxygen	—	—	—	>6.0 in both cold water and warm water permanent fisheries.
Magnesium	—	250–350	250–350	Upper levels for magnesium intake.
Nitrate[b]	50	10	50	The sum of the ratios of the concentrations of each of nitrate and nitrite to its guideline value should not exceed one.
Nitrite	3	1	0.5	
pH		6.5–8.5	6.5–9.5	
Phosphorus				
Potassium	—	—		Not established because no evidence that it poses health risk at current levels, also no information available on threshold of potassium in water ecosystem.
Sodium	200 mg/l	—	200 mg/l	No health based guideline value is available. Concentrations in excess of 200 mg/l may give rise to unacceptable taste.
Sulfate	500	250	250	No health based guideline is available. It is recommended that sulfate concentrations in excess of the proposed value be reported.
Temperature				None set.
TSM	—	—		Average/daily maximum in cold water: 30/53. Average/daily maximum in warm water: 90/158.
Turbidity	None	1 NTU		Conventional or direct filtration must follow state limits, which must include turbidity at no time exceeding 5 NTUs. Maximum and minimum values set by countries are 25 NTU and 0.3 NTU.

Source: EPA 1995, 2012a; EEC 1998; WHO, 1998

Note: — = not available; no threshold established. BOD = biochemical oxygen demand; cfu = colony forming units; COD = chemical oxygen demand; CDOM = chromophoric dissolved organic matter; EPA = United States Environmental Protection Agency; EU = European Union; mg/l = milligrams per liter; mL = milliliters; NTU = Nephelometric Turbidity Units; TDS = total dissolved solids; TSM = total suspended matter; WHO = World Health Organization; µS/cm = microsiemens per centimeter.

a. https://www.epa.gov/dwstandardsregulations/secondary-drinking-water-standards-guidance-nuisance-chemicals.

b. https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations#one.

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