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Review article

Synthesizing water quality indicators from standardized geospatial information to remedy water security challenges: A review

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ABSTRACT

Water is vital not only for food, energy and sanitation but also for ecosystem functioning, human health, socio-economic progress and poverty reduction. Water security exists when all people have physical and economical access to sufficient, safe, and clean water that meets basic needs. However, water security is threatened by growing human population, episodic environmental disasters, indiscriminate land management practices, contaminants, and escalation in geopolitical conflicts. < 3% of the estimated 1.4 billion cubic kilometers of water on earth is available for consumption. Although there exist a range of laboratory and field methods for measuring the chemical, physical and biological properties of water, the information available to the public remains inconsistent and patchy. To this end, we advance a new theory of a single-value objective water quality index (WQI) that considers the interaction between the above properties, to provide concise information for source water quality surveillance and monitoring. Although geospatial technologies such as remote sensing is credited as a high frequency spatiotemporal mapping tool, exiguous information is available on its application for constructing single-value WQIs. Besides, no remote sensing device exists that directly measures water quality, which must indirectly be inferred through modeling sensed remote sensing signals with measured water properties. This review not only highlights the water security conundrum but also provides an overview of methods for integrating geolocated qualitative (e.g., management data) with quantitative (i.e., measured water constituent properties) into a WQI.

1. Introduction

Other than climate change and the increasing population estimated at 80 million per year, global challenges include indiscriminate land use, rising economic disparities and anticipated deficiencies in food, energy and water (Esteban and Max, 2016; Gleick and Palaniappan, 2010; Lal, 2015b; UNU, 2013). Although water is one of the crucial resources for life on earth, defining a generic water quality standard that satisfies all water uses is challenging. This is because standards considered suitable for human consumption are different from those for industrial or even agricultural use (Haji Gholizadeh et al., 2016; Ritchie et al., 2003). Despite the diverse data processing platforms, water quality determination at field, watershed and even landscape scale is challenging because of spatiotemporal variation in the physical, chemical and biological water constituents (Table 1). Moreover, gleaning water quality information for routine management operations can be impeded by data scarcity and artifacts, nebulous baselines, and validation challenges (de Paul Obade et al., 2013, 2014). Indeed, incoherence in water quality information can contribute to feigned conclusions, poor regulatory enforcement, health risks, or even devalue environmental concerns (EPA, 2016b; Reif, 2011). To avoid catastrophic health ailments, diagnostic screening tools are required to ensure drinking water quality satisfies international standards, specified by World Health Organization (WHO), American Public Health Association (APHA), or Environmental Protection Agency (EPA), among others (EPA, 2016a; Kumar and Puri, 2012; WHO, 2011).

Water pollutants are categorized as point source (PS) and non-point source (NPS). PS pollutants are anthropogenic contaminants discharged via a discrete conveyance thus are traceable to single source (e.g., pipes discharging effluent of industrial or domestic wastewater). In contrast, NPS have diffuse origins, and are facilitated by: (a) infrastructure dysfunction (open/leaky sewer systems, landfill leakages, impervious urban surfaces), (b) land mismanagement (e.g., broadcasting fertilizer on soil surface, flood irrigation, agricultural and livestock waste, soil erosion), meteorological conditions (i.e., precipitation intensity, temperature and wind speed), (c) hydromodification and atmospheric deposition of industrial pollutants (Chipman et al., 2009; Kozlowski et al., 2016; Michalak et al., 2013; Selman et al., 2009; Swanson et al., 2015).

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Table 1
Overview of parameters for water quality surveillance and monitoring.

Physical	Chemical	Biological
Temperature -Water temperature determines the amount of oxygen dissolved in the water, the photosynthesis rate of aquatic plants and metabolism of aquatic organisms. -Causes of temperature change include weather, removal of shading streambank vegetation, impoundments, discharge of cooling water, urban storm water, and groundwater inflows to the stream.	**Chlorophyll** -Chlorophyll pigment is useful for photosynthesis, whereby green plants and algae convert sunlight energy into chemical energy by taking in CO_2, H_2O and producing carbohydrates and O_2. Chlorophyll measures plant and algae pigments, and can be used as proxy biomass estimate. Chlorophyll absorbs blue and red light and reflects green (thus healthy plants appear green). -Algal blooms make water unsuitable for swimming, toxic and unpalatable to the aquatic food chain. Besides, unconsumed algae sink and decay, depleting deeper water of oxygen.	**Benthic macroinvertebrates**: -Macroinvertebrates are organisms large (macro) enough to be seen through the naked eye; and lack a backbone (invertebrate). Benthic refers to the bottom of a waterway. Examples of benthic macroinvertebrates include insects in their larval or nymph form, crayfish, clams, snails, and worms. Most are attached to submerged rocks, logs, and vegetation. -Some macro invertebrates are more sensitive to pollution than others.
pH -pH indicates the alkalinity or acidity of a substance, ranked on a scale from 1 to 14. pH $<$ 7 is acidic whereas pH $>$ 7 is alkaline. A pH of 7.0 is neutral. -Aquatic organisms differ as to the range of pH in which they flourish.	**Suspended solids/minerals** -Suspended minerals or sediments move along in a stream, thus are dependent on water flow and rainfall. -sediments obstruct light and may harbor pathogens. -suspended particles/algae pigments affect how ambient light is absorbed and reflected.	
Streamflow -Streamflow, or discharge, is the volume of water that moves over a designated point over a fixed period of time. -It is affected by weather as it increases during rainstorms and decreases during dry periods; and varies by season.	**Colored Dissolved Organic Carbon** contains fulvic or humic acid, which makes water-bodies to have brownish tan color. Turbidity estimates particulate matter suspended in water. Water with high turbidity is cloudy or opaque. High turbidity increases water temperatures because suspended particles absorb heat, and reduce penetration of light into water. Murky water is unsafe for recreational purposes because hazardous materials/objects are obscured. **Secchi Disk Transparency** measures water clarity. This measurement is done by lowering a black and white disk into the water and recording the depth at which the disk is invisible. Clear water signifies environmental health. **Dissolved Oxygen**: Respiration of most aquatic organisms requires Oxygen dissolved in water. Rapidly moving water dissolves more Oxygen than stagnant water. Colder water dissolves more oxygen than warmer water. -An oxygen-deficient aquatic environment results in water bodies with excess organic material, which cause death to aquatic life.	**Submerged Aquatic Vegetation**: Submerged aquatic vegetation (SAV) provides invaluable benefits to aquatic ecosystems. It not only provides food and shelter to fish and invertebrates but also produces oxygen, traps sediment and absorbs nutrients such as nitrogen and phosphorus. Whereas SAV are dependent upon the transmission of sunlight through the water, the location of individual species depends upon a variety of factors such as salinity, depth and bottom sediment. -plankton include bacteria, archaea, algae, protozoa and drifting or floating animals that inhabit oceans, seas, lakes, ponds

Phosphates which are largely lost through runoff and erosion are major NPS pollutants; compared with nitrates which being soluble are leached and recyclable depending on climate and bioactivity (Causse et al., 2015; de Paul Obade et al., 2013). In essence, high quality soils are natural buffers against contaminants (Adhikari and Hartemink, 2016; Lal, 2018). For brevity, soil organic Carbon (SOC), a proxy of soil quality plays a key role in: (i) water purification and retention, thereby preventing indiscriminately managed nutrients (e.g., nitrogen and phosphorus) from contaminating surface or ground water, (ii) food, fuel, and fibre production, (iii) biodiversity conservation, (iv) climate regulation, and (v) nutrient cycling (de Paul Obade, 2017)

Conceptually, a water quality index (WQI) synthesizes complex water characteristic properties into more interpretable and informative format to support decision-making (Chaturvedi and Bassin, 2010; Khan et al., 2003; Liou et al., 2004; Mohebbi et al., 2013). In essence, WQIs should integrate water quality parameters using techniques that: (i) are simple to develop and use, (ii) correlate well with water constituent properties, and (iii) are replicable and accurate at variable scales (Cobbina et al., 2010; House, 1990; Mohebbi et al., 2013). Although guidelines exist for water quality determination (Ashbolt et al., 2001; WHO, 2011), no universal comprehensive single-value WQI has been conclusively determined. Here, the feasibility of integrating field and remote sensing data to generate a concise objective WQI is explored. Remote sensing technologies acquire data even from inaccessible field locations; is rapid, non-destructive, reproducible, durable and provides both analog and digital data to support automated processing. However, no remote sensing device exists that directly measures water quality, which can instead be indirectly inferred by modeling sensed remote sensing signals with measured water properties. Because, water management decisions determine ecosystem health and productivity, other reviewed priorities include: (i) evaluating consequences of anthropogenic activities on water security, (ii) which strategies ensure sustainable freshwater ecosystems? and (iii) what tools, models, and information are required for cost-effective monitoring of water quality?

2. Risks and impacts of water insecurity

Although 71% of the earth's total surface area ($51 \times 10^7\,km^2$) is water, only 2.5% (3.5 million cubic kilometers out of a total 1.4 billion cubic kilometers) is renewable freshwater (Lal, 2015a). Approximately 70% of this freshwater is contained in ice caps, glaciers, permanent snow, ground ice, permafrost, or ground water, and only 1.2% is available for direct consumption by living organisms (Gleick and Palaniappan, 2010). Consumptive water refers to water unavailable for use after being evapotranspired, ground infiltrated or incorporated into plant or animal tissue, whereas, non-consumptive returns to surface runoff and is reusable after treatment. Blue water refers to fresh surface or ground water and includes precipitation, whereas green water is the