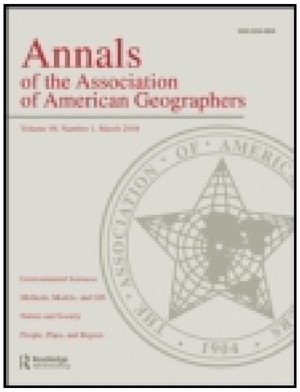

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Optical Water Quality of Inland Waters: A Landscape Perspective

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Optical water quality (OWQ) relates the composition of waters to their light transmission and thereby light availability for aquatic plants, visual range for aquatic animals, and suitability for recreational uses. This fundamental role of OWQ has led to numerous studies on the optical properties in rivers and lakes, which we overview here with a landscape perspective. International examples illustrate how the kinds and amounts of light-attenuating substances depend on landscape features on scales ranging from the river reach to the orientation of mountain ranges. OWQ is profoundly affected by increased nutrient discharges and sediment mobilization from human activities such as agriculture. Proper monitoring of OWQ is needed to fully understand and address these consequences. Remote sensing has potential for broad-scale surveys of OWQ, although currently its applications to inland waters are limited by low spatial resolution. A better understanding of OWQ will advance water management and remote sensing capabilities, as well as provide further insight into water quality impacts associated with global changes in climate, energy use, and land use. *Key Words: aquatic ecosystems, human–environment interactions, remote sensing, water resources, watershed science.*

光学水质 (OWQ) 将水的组成和其光线传播暨水生植物的光线可及性、水生动物的视觉范围, 以及休閒使用的可持续性相互连结。此一光学水质的重要角色, 引发诸多对于河川与湖泊光学性质的研究, 在此我们以地景视角概观之。国际的案例描绘出光衰物质的种赖和数量如何取决于自河流流域至山脉走向等规模的地景特徵。光学水质极度受到增加的营养物质排出和农业等人类活动的沉积物移动所影响。我们必须对光学水质进行适切的监控, 以更完整地理解并处理上述后果。遥测对于大尺度的光学水质调查而言具有潜能, 儘管目前在内陆水体的运用受到低空间解析度所局限。更佳的理解光学水质, 将可促进水资源管理和遥测能力, 并对全球气候、能源与土地使用变迁之于水质的影响提供更进一步的洞见。 *关键词: 水生生态系统, 人类—环境互动, 遥测, 水资源, 流域科学。*

La calidad óptica del agua (OWQ) relaciona la composición de las aguas con su transmisión de la luz y por consecuencia la disponibilidad de luz para las plantas acuáticas, el ámbito visual para los animales acuáticos y su propiedad para usos recreacionales. Este papel fundamental de la OWQ ha generado numerosos estudios sobre las propiedades ópticas de ríos y lagos, que aquí revisamos de pasada con una perspectiva paisajista. Ejemplos internacionales ilustran cómo los tipos y cantidades de sustancias atenuantes de la luz dependen de rasgos del paisaje a escalas que van desde el alcance del río hasta la orientación de las cadenas montañosas. La OWQ es afectada profundamente por las crecientes descargas de nutrientes y la movilización de sedimentos resultantes de actividades humanas como la agricultura. Se necesita un buen monitoreo de la OWQ para entender cabalmente estas consecuencias y para abocarlas. La percepción remota tiene potencial para estudios de la OWQ a escala amplia, aunque actualmente sus aplicaciones para las aguas interiores están limitadas por la baja resolución espacial. Con un mejor entendimiento de la OWQ se podrá avanzar en el manejo del agua y en las capacidades de las técnicas de percepción remota, lo mismo que en proveer mayor profundidad de conocimiento de los impactos de la calidad del agua asociados con los cambios globales de clima, uso de energía y uso del suelo. *Palabras clave: ecosistemas acuáticos, percepción remota, recursos hídricos, ciencia de las cuencas hidrográficas.*

Water quality is of increasing global concern because of changes in response to climate and land use (Foley et al. 2005). Among the many indicators of water quality, water color and clarity, turbidity, suspended solids, dissolved and particulate organics, and phytoplankton are all related to optical properties of water (Davies-Colley, Vant, and Smith 2003). Optical water quality (OWQ) has been defined as "the extent to which the suitability of water for its functional role in the biosphere or the human

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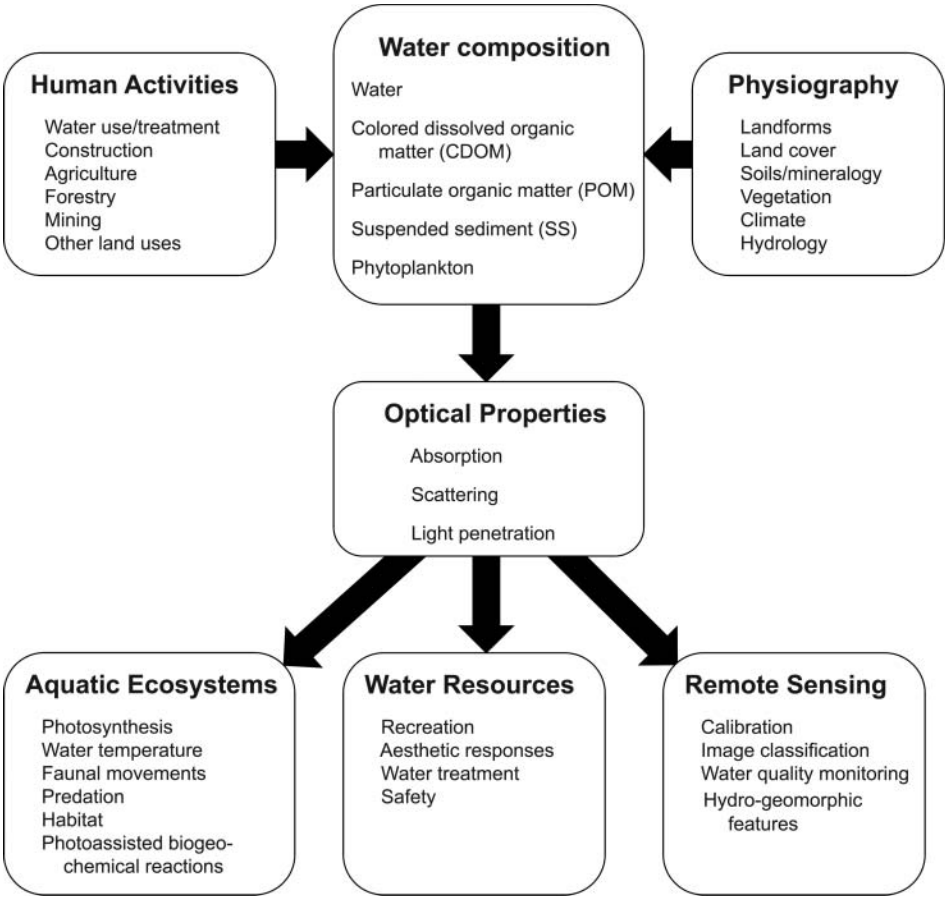

Figure 1. Relationships among landscape characteristics, optical water quality (OWQ), and water resources, including applications.

environment is determined by its optical properties" (Kirk 1988, 194). The behavior of light in water influences numerous ecosystem processes, water resources, and remote sensing capabilities (Figure 1). Accordingly, there is increasing appreciation of OWQ in inland waters, from both managers and scientists. Thus, we find it timely to provide a landscape perspective of OWQ of inland waters that assesses (1) spatial and temporal variability and (2) drivers and consequences of change. Because of limited space, this article is necessarily an introduction to a rapidly expanding topic rather than a comprehensive review.

Overview of Optical Water Quality

Light transmission in waters is controlled by its absorption and scattering properties (Kirk 2011). Absorption involves the conversion of light energy to another form, mostly heat, and scattering refers to the change in direction of light photons without change in energy. Scattering and absorption are quantified by an absorption coefficient (a) and a scattering coefficient (b), which, respectively, are the fraction of radiant flux that is absorbed or scattered along an infinitesimally small light path in water. Together, a and b establish the beam attenuation coefficient (c), which is the fraction of light flux that is reduced over an infinitesimally short path:

$$c = a + b \tag{1}$$

Visual clarity in waters is a simple inverse function of beam attenuation. For example, the visual range of a black body viewed horizontally (y), a valuable index of visual water clarity, is given by:

$$y = 4.8/c \tag{2}$$

(Davies-Colley 1988; Zanevald and Pegau 2003). A traditional index of visual water clarity, which is still commonly used in lakes, is the Secchi depth (z_{SD}), whereby a white disk is lowered until it is no longer visible. z_{SD} is also inversely related to beam attenuation but less precisely: $z_{SD} \sim 6/c$. Light penetration into waters for plant growth is quantified by the irradiance attenuation coefficient (K), defined as the fraction of irradiance removed per unit depth over an infinitesimally thin layer. The two aspects of water clarity—visual range and light penetration—are distinct optical properties that, although weakly related, cannot be calculated one from the other without further information.

Apparent optical properties (related to sunlight fields underwater; including K) are easily measured by profiling irradiance with depth. Measurement of the inherent optical properties (a, b, c) is more problematic because of the difficulty of separating light loss from scattering versus that from absorption. Methods have been developed, however, using special accessories and protocols with spectrophotometers (Davies-Colley, Vant, and Smith 2003; Julian et al. 2008). Light scattering is extremely difficult to measure and so is almost always estimated indirectly by subtracting absorption from beam attenuation (Equation 1). Turbidity measured by nephelometry (T_n) is often used as an index of light scattering and, although not a true physical quantity, has the virtue of being capable of continuous instrumental monitoring (Davies-Colley and Smith 2001).

There are four main natural constituents, broadly classified, that attenuate light besides water itself: colored dissolved organic matter (CDOM), mineral suspended sediment (SS), nonalgal particulate organic matter (POM), and phytoplankton (Davies-Colley, Vant, and Smith 2003). Assessing OWQ involves quantifying the behavior of light in waters as affected by these light-attenuating constituents. Spectral absorption by pure water follows an approximately parabolic trend whereby absorption is high for short (ultraviolet) and long (red–infrared) wavelengths and low for intermediate wavelengths (blue–green), such that pure water is blue-green in (transmission) color. The main dissolved light-attenuating constituent is CDOM, for which absorption rises exponentially with declining wavelength. CDOM is usefully indexed as the light absorption coefficient of a membrane filtrate at 440 nm (blue light; Kirk 2011). Particulate constituents that attenuate light include SS, POM, and phytoplankton (indexed by the main photosynthetic pigment, chlorophyll-a). SS scatters light strongly depending on particle size, shape, and composition. Absorption by mineral particulates is usually low. POM and phytoplankton both absorb and scatter light appreciably. The spectral absorption of POM is similar to that of CDOM and contrasts with absorption by phytoplankton, which has two distinct peaks at approximately 440 nm and 675 nm.

Landscape Perspectives

Rivers

An understanding of sources and variability in light-attenuating constituents is needed to predict general patterns of OWQ across diverse landscapes. CDOM originates mainly from the decomposition of plant tissue into dissolved humic substances that absorb light strongly. On a site-specific basis, CDOM concentrations correlate approximately with dissolved organic carbon (DOC) concentrations (Scott et al. 2006; Watanabe et al. 2011), so patterns in DOC illustrate those of CDOM and vice versa. Terrestrially derived DOM has a higher proportion of CDOM than in-stream sources (Wetzel 2001). High CDOM concentrations are found in rivers draining podzolized soils and wetlands (Aitkenhead and McDowell 2000). Conversely, rivers fed by lakes and reservoirs tend to have low CDOM concentrations because long water residence times allow decay, particularly by photooxidation (Larson et al. 2007).

CDOM concentrations tend to be higher in warmer and wetter climates and increase following storms that flush out humics from the catchment (Webster, Wallace, and Benfield 1995; Julian et al. 2008). Overall, the spatiotemporal variation of CDOM in rivers is largely dictated by the state of flow (Sedell and Dahm 1990; Smith et al. 1997). During baseflows, CDOM is often the main light-absorbing constituent (Davies-Colley, Vant, and Smith 2003; Julian et al. 2008), although POM typically dominates at higher flows.

SS in rivers originates from a range of sources including in-channel erosion (notably banks) and surface runoff (notably hillslopes). Suspended sediment concentrations (SSCs) largely depend on catchment geology, climate, topography, vegetation, impoundment, and land use. SSC increases strongly with increasing discharge (Q) and thus is highest during storm flows. Seasonal trends in SS occur in catchments with large ice and snow accumulations, but for most rivers, Q controls temporal distributions of SSC (Syvitski et al. 2000). Spatially, SSC should decrease in the downstream direction because overland sediment runoff decreases and contribution of sediment-free groundwater to total Q increases. Land-use disturbances such as deforestation, cultivation, and urbanization typically cause SSC to increase downstream in rivers, however (Walling and Webb 1992).

Temporal trends of POM, like SS, are governed by the river's hydrologic regime, with the highest concentrations occurring during storm flows due to increased surface runoff and suspension of benthic OM (Webster, Wallace, and Benfield 1995). Low-gradient rivers in humid environments with good floodplain connectivity tend to have high POM concentrations (Golladay 1997), as do rivers draining agriculturally dominated catchments (Julian et al. 2008). Typically, longitudinal trends of POM are weak, although some studies have found POM concentrations increasing slightly in the downstream direction (Webster, Wallace, and Benfield 1995; Julian et al. 2008).

Phytoplankton in rivers might originate from detached benthic populations and inflows from lake or wetland surface waters. The abundance of river phytoplankton is correlated to light, nutrients, temperature, and grazing pressure, but the typical control on algal growth in rivers is hydraulic residence time (Soballe and Kimmel 1987; Reynolds 2000). The generation rate of phytoplankton must be faster than downstream flushing for large biomasses to develop. Highest concentrations therefore tend to occur in impounded reaches and lower reaches of large rivers. Because of the two limitations of light availability and flushing, most rivers have limited length sustaining sufficient phytoplankton to significantly influence OWQ.

Although every river possesses a unique OWQ regime, the spatial and temporal trends of light-attenuating constituents allow for a few generalizations. Temporally, rivers have the highest OWQ (lowest c) during baseflow (Smith et al. 1997). Light attenuation increases as a power function of Q ($c = \alpha Q^{\beta}$) due primarily to suspended particulates (Julian et al. 2008). The coefficient (α) and exponent (β) are river dependent, but generally β is highest for rivers with large sources of readily available sediment or organic matter (Davies-Colley 1990). The source of sediment is influenced by catchment geology, topography, land use, and storm frequency (Syvitski et al. 2000). Julian et al. (2008) suggested that storm frequency is the dominant control on β because it expresses supplies of soil runoff. Temporal variations in OWQ can also be influenced by seasonal effects such as exposed soil surface in winter, crop harvesting, and vegetation senescence (catchment-wide and in-channel).

Many headwater streams have high OWQ owing to low CDOM, SS, POM, and phytoplankton. As rivers increase in size downstream and source areas of SS and POM are accessed, rivers tend to become more turbid. In the lowest reaches, the channel becomes more hydrologically connected to its floodplain and associated wetlands, thereby increasing CDOM. Slowing currents in the lower reaches might promote phytoplankton growth. The resulting trend of decreasing OWQ along the river continuum is an underlying tenet of stream ecosystem theory (Vannote et al. 1980); however, synthesis of longitudinal OWQ data sets by Julian et al. (2008) suggests two modifications. First, because tributaries are point sources for light-attenuating substances, the channel network configuration (density and location of tributaries) influences longitudinal trends in OWQ. Accordingly, the greatest spatial changes in OWQ usually occur at major tributary confluences of catchments with contrasting physiography or land use. Second, catchment shape also affects OWQ due to its influence on channel networks. Most catchments are pear shaped, where the distance between "geomorphically significant tributaries" increases with distance downstream due to the continually reduced drainage area available for major tributaries (Benda et al. 2004). The absence of major tributaries near the outlet of pear-shaped catchments, together with the increasing contribution of particulate-free groundwater and the increasing potential of sedimentation and hyporheic exchange processes in the downstream direction, results in a decrease in c over the lowest reaches (Figure 2). In rectangular-shaped catchments (with similar increments in drainage area in the downstream direction), c can increase in the downstream direction due to major tributaries occurring near the outlet of these catchments.

Although catchment shape and channel network configuration might influence longitudinal trends, land use will likely be the dominant control on magnitude of light attenuation (Figure 2). Forested catchments tend to have high OWQ (low c), whereas pastoral catchments tend to have lower OWQ owing to soil erosion and runoff (Davies-Colley 1990; Harding et al. 1999). Catchments in intensively used land (agricultural or urban) can be expected to produce very poor riverine OWQ, with c perhaps tenfold higher than comparable forested catchments (Julian, Stanley, and Doyle 2008). With approximately 40 percent of Earth's land surface under agriculture (Foley et al. 2005), degraded OWQ is probably globally abundant.

Lakes

The OWQ of lakes is heavily influenced by catchment physiography and land use (Davies-Colley, Vant, and Smith 2003). Given that rivers are the dominant inflows to lakes, the composition of lake waters might be expected to reflect inflowing rivers. There are some

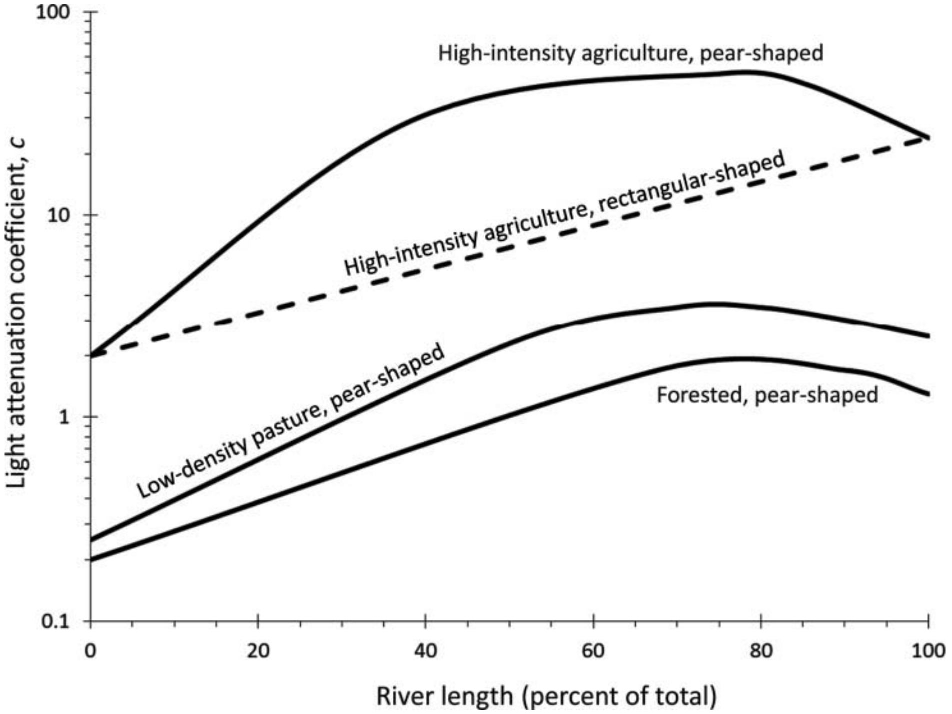

Figure 2. Longitudinal trends in optical water quality along a large river with different land uses and catchment shapes. Agriculture includes croplands and pasture. Adapted from Julian et al. (2008).

notable differences, however. The origin and consequent morphology of lakes has a major influence on mixing and productivity, which control quantities of SS, CDOM, POM, and especially phytoplankton (Wetzel 2001). In general, deep lakes (created by tectonic, volcanic, or glacial processes) tend to be oligotrophic with low concentrations of CDOM, POM, and phytoplankton. Furthermore, particulates are seldom disturbed from their bottom sediments. The clearest lakes globally (e.g., Crater Lake in the United States and Lake Baikal in Russia) are deep lakes created by endogenic processes.

Shallow lakes, in contrast, tend to be more eutrophic with higher concentrations of organically derived constituents. Furthermore, wind-exposed shallow lakes can experience frequent resuspension of particulates, which can mask phytoplankton (Van Duin et al. 2001). The effects of particle size on optical properties, settling velocity, and SSC means that normally there will be considerable variability in the relationships between light attenuation and SSC in shallow lakes (Sun et al. 2009). In most fresh waters, fine layer clays, which attenuate light more intensely than similarly sized spherical particles, might remain suspended almost indefinitely (Kirk and Oliver 1995).

Landscape position, referring to hydrologic connectivity to other water features (Kratz et al. 1997), influences lake OWQ. Landscape position of a lake is usefully indexed as lake order, the Strahler stream order of the outflow stream (Riera et al. 2000). z_{SD} does not typically display trends with lake order; however, certain other optical variables do. CDOM and chlorophyll-*a* in lakes generally increase with lake order for the same reason as they do in rivers (Riera et al. 2000; Martin and Soranno 2006). Unlike rivers, however, lake turbidity generally decreases with lake order because there is less particulate resuspension within larger and deeper lakes lower in the landscape. Lakes with catchments of high wetland coverage tend to have high concentrations of CDOM, depending on location of the wetlands relative to the lake (Gergel, Turner, and Kratz 1999).

Spatial patterns in lake OWQ have also been related to geologic features. In their study of two pairs of lakes on either side of the Southern Alps (South Island, New Zealand), Gallegos, Davies-Colley, and Gall (2008) found that optical properties of Lakes Brunner and Hochstetter, located on the perhumid (2,500-4,000 mm annual rainfall) western side of the range, were dominated by CDOM absorption. Their catchments have extensive wetlands, with organic and podzolized soils leached of the aluminum and iron oxides that would otherwise immobilize humic substances. In contrast, optical properties of Lakes Pukaki and Tekapo, located in the rain shadow of the Southern Alps and fed by glacial meltwater, are dominated by glacial flour. These lakes are known for their bright turquoise color

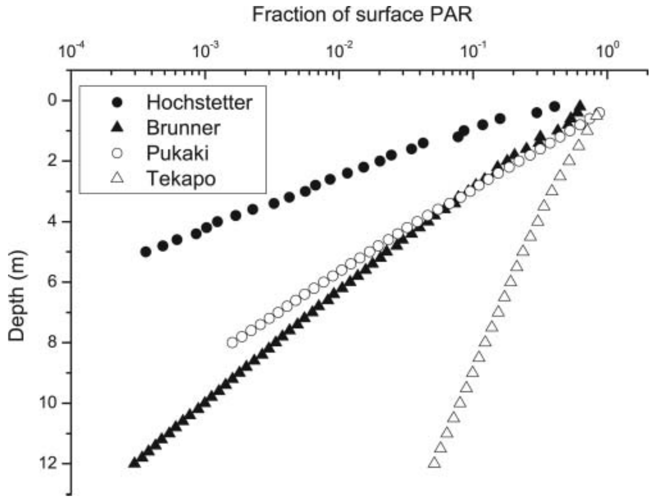

Figure 3. Vertical profiles of downwelling photosynthetically active radiation (PAR), normalized to surface-incident PAR, in four New Zealand lakes differing in amounts and kinds of light-attenuating substances: (filled symbols) Lakes Hochstetter (circles) and Brunner (triangles) are dominated by light-absorbing dissolved humic matter; (open symbols) Lakes Pukaki (circles) and Tekapo (triangles) are dominated by light-scattering glacial flour.

and low concentrations of CDOM and chlorophyll-*a*. The euphotic depth (1 percent irradiance level; Figure 3) of one of the colored lakes, Lake Brunner (7 m), was very similar to that of one of the turbid lakes, Lake Pukaki (5 m), despite upwelling light fields (and *b*/*a* ratios) differing a hundredfold. Thus, a geologic process (mountain building) results in lakes in close proximity with vastly different OWQ.

The OWQ of lakes responds to events that change the concentrations of light-attenuating components on a wide array of timescales. The spring phytoplankton bloom is a seasonally recurring event in temperate dimictic lakes that increases light attenuation as a result of the injection of limiting nutrients by winter deep mixing (Wetzel 2001). Episodic blooms might be triggered by other events that inject nutrients into the euphotic zone, such as storm-induced erosion of the thermocline or storm inflows. Phytoplankton require light to grow but themselves attenuate light (self-shading) such that phytoplankton blooms are ultimately self-limiting. Attenuation by phytoplankton of their own light field therefore limits the maximum phytoplankton standing crop in eutrophic waters.

Reservoirs have hydraulic characteristics associated with the transition from riverine to lacustrine conditions that affect OWQ rather differently from natural lakes (e.g., Figure 4). Effler, Perkins, and Johnson (1998) identified persistent but dynamic OWQ spatial gradients in a seasonal study of a reservoir in the northeastern United States. OWQ in the lacustrine zone, which occupied 80 percent of the reservoir when full, was dominated by phytoplankton, similar to lakes. Spatial and temporal patterns in light attenuation developed as a response to reservoir hydraulics and operation. z_{SD} was comparatively low in the riverine zone due to scattering by river-borne inorganic sediment, which decreased in concentration toward the dam. A gradual increase in light scattering during the summer was attributed to reservoir drawdown, exposing increasing bottom area to wave resuspension. As a reservoir fills with sediments, thereby reducing depth and residence time, the OWQ might increasingly resemble that of lower reaches of major rivers.

Land use is a major factor in lake OWQ. Agricultural land use tends to strongly mobilize nutrients, which promote increases in phytoplankton with reduced visual clarity and light penetration (Verburg et al. 2010). Urban effects on lake and river OWQ are largely unresolved due to the highly variable management strategies of urban environments and legacy effects from prior land uses (Brown et al. 2009), but likely consequences include eutrophication from suburban fertilizers and increased turbidity from greater surface runoff.

Consequences of Altered OWQ

Human-induced changes in OWQ can have profound effects on the functioning of aquatic ecosystems and water resources (Davies-Colley, Vant, and Smith 2003; Julian, Stanley, and Doyle 2008). Light-dependent photosynthesis is the primary production base in nearly all aquatic systems. Submerged rooted plants are particularly valued for their ecosystem services additional to photosynthesis, such as sediment stabilization, nutrient retention, and refuge habitat for invertebrates and juvenile fish. There are numerous examples of lakes that have lost their submerged macrophytes with vastly changed OWQ. For example, Davies-Colley, Vant, and Smith (2003) documented the disappearance of a rooted macrophyte in response to a positive feedback mechanism initiated by the discharge of turbid mining wastewaters into a lake. Loss of submerged vegetation in shallow lakes due to nutrient loading and associated algal turbidity has been particularly common in Europe (Körner 2002). Attempts to restore such systems have contributed to the development of a rich theory of alternative stable states (Scheffer and van Nes 2007) in which light penetration plays a central role. Light availability is likely to become an

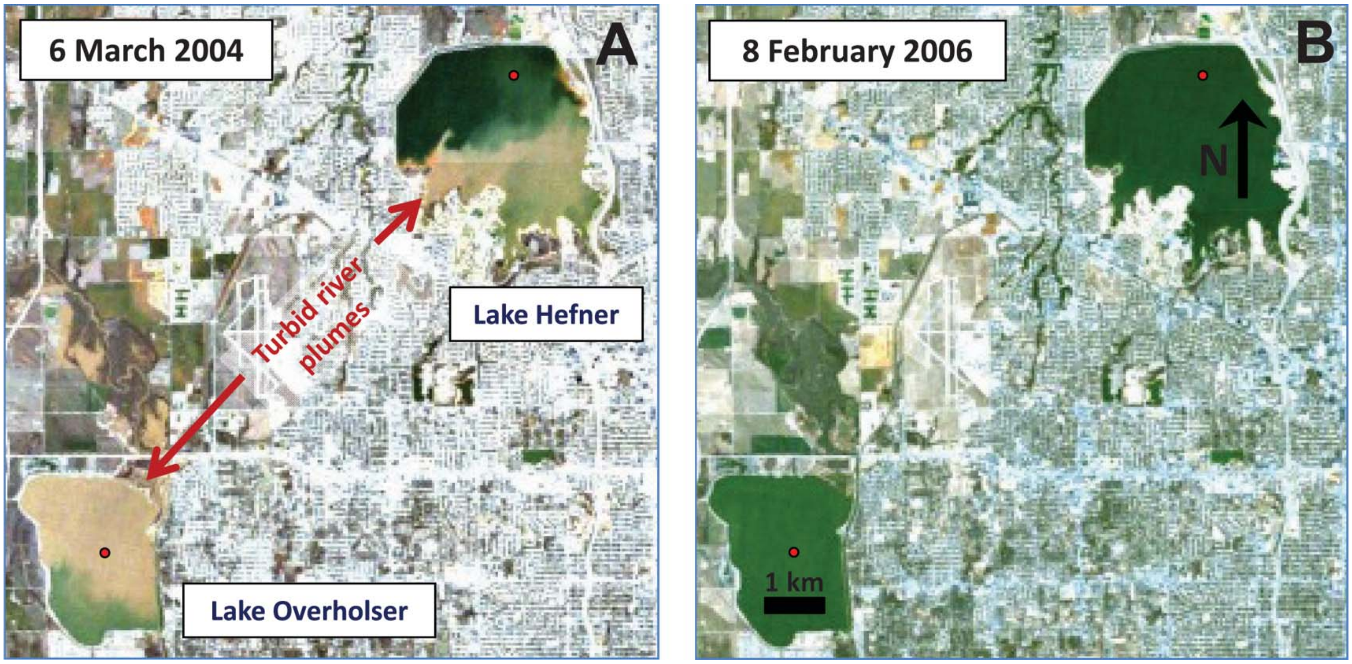

Figure 4. Spatiotemporal variation of water reflectance and color in two reservoirs in Oklahoma City, Oklahoma. These true color atmospheric-corrected Landsat 5 images depict Lake Overholser (mean depth = 2.7 m) and Lake Hefner (mean depth = 8.3 m) for (A) 6 March 2004 and (B) 8 February 2006. Optical water quality variables at sampling sites (red dots) for both lakes for both dates are listed in Table 1. Notice the spatial variability in rain-induced turbidity (via river inflows) in A, as well as the greater turbidity of the shallow lake on a moderately windy day (B; black map symbols within the lakes can be used for visual comparison). (Color figure available online.)

increasingly important regulator of primary production and species composition in rivers and lakes subject to greater human land use, soil runoff, and nutrient enrichment.

Future Challenges

Increasing numbers of OWQ studies by diverse groups of researchers testifies to the importance of OWQ to the management of water resources and aquatic ecosystems, as well as to remote sensing applications (Figure 1), but most OWQ studies are concentrated in specific regions (e.g., New Zealand) or cover only short periods (two to four years; the length of grants and dissertations). Thus, it is difficult to assess, globally, how changes in climate, energy use, and land use are altering inland OWQ over longer terms. We foresee two future challenges related to understanding impacts on inland OWQ: proper OWQ monitoring and improved remote sensing.

Monitoring OWQ

Typically OWQ of inland waters is not systematically monitored, with the exception of z_{SD} in lakes and T_n in rivers. If standards protecting OWQ were more widely promulgated, more effort would undoubtedly be put into OWQ monitoring. The New Zealand Resource Management Act (1991) specifically protects OWQ,

Table 1. Optical water quality characteristics for Lake Hefner and Lake Overholser on 9 March 2004 (A) and 21 February 2006 (B)

		Lake Hefner (M depth = 8.3 m)	Lake Overholser (M depth = 2.7 m)
Mean wind speed (m/s); Azimuthal direction (degrees) in parentheses	A	7.5 (200°)	
	B	6.0 (351°)	
72-hour precipitation (mm)	A	34.5	
	B	0	
Turbidity (NTU)	A	87	664
	B	4	13
Chlorophyll-*a* (mg/m^3)	A	12.5	9.7
	B	11	18
Secchi depth (m)	A	N/A	0.05
	B	N/A	0.52

Note: Weather data obtained from Oklahoma Mesonet for imagery dates. Water quality data obtained from Oklahoma Water Resources Board for closest date to imagery. NTU = nephlelometric turbidity units.

and consequently the National Rivers Water Quality Network (including monthly sampling of seventy-seven river sites; Davies-Colley et al. 2011) measures visual clarity, turbidity, and CDOM, among other water quality variables. In situ sensors can also usefully monitor OWQ: optical back-scatter sensors for T_n, beam transmissometers for c, absorptiometers for CDOM, and fluorometers for phytoplankton. To assess broad-scale, long-term changes in OWQ and their associated consequences, more routine OWQ monitoring is needed.

Remote Sensing of Inland OWQ

Although in situ and laboratory approaches provide valuable OWQ data over time, they do not provide a broad view of spatial patterns. Satellite remote sensing, anchored by "water truthing" data obtained by more traditional means, has the potential to greatly improve our understanding of aquatic systems (Schmugge et al. 2002). There are several obstacles that must be overcome, however. First is the trade-off between spectral and spatial resolution, whereby high-spectral-resolution imagery currently has low spatial resolution and vice versa. This trade-off is the primary reason why remote sensing of inland OWQ has been limited compared to ocean and coastal OWQ; that is, most rivers and lakes are too small to image with high spectral resolution. New platforms with higher spatial, spectral, and temporal resolution scheduled to deploy soon have the potential to improve remote sensing capabilities for inland waters. For now, hyperspectral sensors mounted on aircraft provide the best option for remote sensing of OWQ in small water bodies, although with the disadvantage that repeating imagery to follow temporal changes becomes very expensive.

A second obstacle is correcting satellite imagery for atmospheric, illumination, and sensor errors. Such errors are ideally removed by absolute radiometric correction procedures so that data extracted from multiple images are comparable (Figure 4). Because a priori knowledge of both the sensor spectral profile and atmospheric properties are often not available, relative radiometric normalizations (RRNs) are an alternative approach, whereby images are normalized to reference pixels (Du, Teillet, and Cihlar 2002). The pseudo invariant feature (PIF) approach (Schott, Salvaggio, and Volchok 1988) has become the most popular RRN, where dark (water) and bright (concrete) pixels are used for radiometric (ground) control points under the assumption that their reflectance is constant. As we have illustrated (Figure 4) and others have demonstrated (Elvidge et al. 1995), however, the assumption that water reflectance is invariant is seldom valid due to both spatial and temporal variability in OWQ, even over small areas. Further, water close to lake shorelines or riverbanks usually has boundary reflectance contamination (Olmanson, Bauer, and Brezonik 2008). Thus, for remote sensing to be broadly applicable, new methods (or models) must be developed that can account for OWQ spatiotemporal variability.

Closing Remarks

In this landscape perspective of OWQ, we have emphasized inland waters, but rivers are hydrological conduits that deliver contaminants and light-attenuating substances to downstream waters such as estuaries and deltas. The OWQ of inland waters thus has considerable influence on coastal environments, whose biota, including coral, fish, birds, and aquatic vegetation, greatly depend on light availability and visual clarity. Indeed, tracing and assessing the effects of river plumes in coastal waters is an important and rapidly developing research theme. Unfortunately, optical remote sensing of river plumes in coastal waters is sometimes confounded by nonunique optical signatures. CDOM detection using scheduled satellite remote sensing systems might prove to be a valuable tracer of river plumes and an inverse tracer of salinity. We forecast an increasingly important role for OWQ studies driven by increased awareness of the need to protect ecosystems, manage water resources, and advance remote sensing capabilities.

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