Turbidity of Shallow Prairie Lakes

Leland J. Jackson and Paul A. Moquin

Submerged Macrophytes Affect Turbidity of Shallow Prairie Lakes

Shallow Lakes of the Great Northern Plains

The Great Northern Plains are dotted with tens of thousands of shallow aquatic systems. Shallow prairie lakes are often called "sloughs," which conjures an image of a highly productive, turbid system that only a duck could love. And, while ducks do make extensive and essential use of these systems, the lakes are also critical habitat for other birds, amphibians, invertebrates, and even fish.

The view of a shallow prairie lake as an overly productive algal culture (Figure 1), while common, is only one form that shallow prairie lakes take. Another common form has abundant submerged macrophytes and relatively clear water. The clear/turbid dichotomy has been studied for nearly two decades and shallow lakes have been model ecological systems that exist in different states. The utility of shallow lakes as model systems is because their physical extent is relatively easy to define and many prairie shallow lakes are closed systems dominated by snowmelt inputs in the spring and by evaporation throughout the summer. The lack of a permanent inflow and outflow creates a closed system for many aquatic organisms. Many shallow prairie lakes are small, making them relatively easy to sample and experiments logistically possible.

Figure 1. Water samples from lakes classified as turbid (left cup) or clear (right cup) from two shallow Alberta lakes. The turbid water sample from Mushroom Lake is dominated by Aphanizomenon flos-aquae*, a blue-green alga, while the large particles in the clear sample from Barnett Lake are* Daphnia pulex.

Submerged macrophytes are thought to be a key component of shallow prairie lakes that allow them to remain in a relatively clear, low-phytoplankton state through a number of positive feedbacks. First, macrophytes compete with phytoplankton for nutrients and when abundant, macrophytes store nutrients in their tissues that might otherwise be available to phytoplankton. Second, macrophytes provide refuge to large-bodied zooplankton such as *Daphnia* that are the most effective algal grazers. Macrophytes provide structure, and possibly refuge from predation to invertebrates in shallow prairie lakes that contain fish (Rennie and Jackson 2005). Third, macrophytes produce a group of chemicals (called "allelopathic compounds") that reduce the growth rates of phytoplankton. When macrophytes are present and abundant, one or all of the mechanisms above may operate and shift the competitive arena to favour the growth of the macrophytes. Macrophytes also decrease water currents in shallow lakes by physically occupying the water column, reducing sediment resuspension and creating a clearer water column, once again favouring their light environment.

Is the study of the mechanisms that lead to turbid or clear states in shallow lakes merely an academic exercise? We suggest the answer is "no!" When shallow prairie lakes are highly productive and turbid, they often produce blue-green algal blooms, which may produce toxins (the summer 2009 issue of *LakeLine* provides a nice review of some of the nasty consequences of blue-green algal blooms). Therefore, there is a clear (pun intended) practical application to understanding factors that affect shallow lake state and ecosystem services they provide (critical habitat for numerous species, clean water for livestock, recreation, irrigation, etc.).

Different States of Shallow Lakes

Much of the theory regarding shallow lake states has been developed in Europe, which has a long history of their use for drinking water. A key paper was published by Scheffer et al. (1993), in which they identified clear and turbid contrasting states that depend on the presence or absence of submerged macrophytes across a range of nutrient concentrations. Turbidity was assumed to be due to phytoplankton resulting in a turbid, phytoplankton-dominated state or a clear, macrophyte-dominated state. Since this sentinel paper was published nearly two decades ago, other states have been identified and include floating plant, filamentous algae, *Chara* sp. or blue-green algae dominance (Scheffer and van Nes 2007). A significant difference between the Great Northern Plains and many areas of Europe concerns winter climate. Winters on the Great Northern Plains lead to extended periods of ice cover, and frequent winter anoxia in shallow prairie lakes (Meding and Jackson 2003), with the consequence that many shallow prairie systems are fishless (Jackson et al. 2007). In contrast, many European shallow lakes contain fish (roach, tench, and/or bream) that disturb sediments.

Here we present findings from ongoing studies of a number of shallow Alberta lakes. Data indicate that phytoplankton are only a minor component of turbidity in many of the shallow lakes sampled and relationships between turbidity, light penetration, and macrophytes are not linear. Sediment resuspension could present challenges to shallow lake management if a goal were to switch a lake from a turbid to clear state. Nutrient management alone, which targets phytoplankton, many not be sufficient to drive lakes between states – a situation that could occur if most of the turbidity was resuspended sediments and not phytoplankton.

Lake Descriptions and Sampling

Thirty shallow southern Alberta lakes were surveyed and in a subset there was evidence for turbid and clear states (Jackson 2003). Eight lakes were subsequently sampled during summer 2006 because they possessed a wide range of turbidity and macrophyte abundance. All lakes were shallow (maximum depth 1.2-2.6 m), mix frequently (judged by vertical profiles of temperature, pH, conductivity, and dissolved oxygen) and were sampled monthly from May to August, the period of rapid macrophyte growth. The lakes' watersheds have low slope and are primarily used to grow row crops (canola or barley) or hay (Figure 2). The underlying geology is limestone-rich and lake pH is alkaline (range 9.1-10.2). Productivity ranges from mesotrophic to hypereutrophic based on total phosphorus concentrations.

Each lake had three sampling stations that stayed consistent throughout the summer. Water for chlorophyll-a, total suspended solids, turbidity, and total phosphorous was sampled and analyzed with standard techniques (details in Jackson 2003). The above-sediment portion of rooted macrophytes within a 30.5 x 30.5 cm quadrat was collected by divers employing SCUBA. Two hundred to 700 ml of sample water were filtered through a pre-weighed PAL 0.45 µm quartz filter, dried and weighed. Organic carbon was estimated as loss on ignition at 550° C and carbonate as loss on ignition at 1000° C. Non-algal carbon was calculated by subtracting the algal carbon determined from chlorophyll-a from the organic carbon determined as loss on ignition. During sampling, light intensity was measured from lake surface to bottom.

Water Clarity

In many shallow lakes, Secchi disk depth is not a useful measure of water clarity because the disk is often visible on the sediment surface. A better measure of water clarity is the "light attenuation coefficient (λ)", the rate of light disappearance with each meter of water depth. In shallow, well-mixed lakes, it is possible to estimate λ from surface and bottom measurements. A positive linear relationship between λ and water column turbidity exists (Figure 3), yet the scatter in the relationship indicates that the correlation between the two measures is not high. Note that light extinction and turbidity are two different measures of the light environment in the water column – extinction estimates the disappearance of light with depth while turbidity measures light scattering and the two measures are affected by different components of the water column.

There was no significant relationship between l and algal carbon estimated from chlorophyll-a measurements, which

Figure 2. A typical shallow lake located near Strathmore, Alberta, approximately 50 km east of Calgary. Lakes typically have large, low-relief, agricultural watersheds. The eight shallow lakes, similar to the lake above, were selected to provide a range of macrophyte biomass and turbidity based upon 30 shallow lakes previously surveyed to determine whether or not there was evidence for clear and turbid states in shallow Alberta prairie lakes (Jackson 2003).

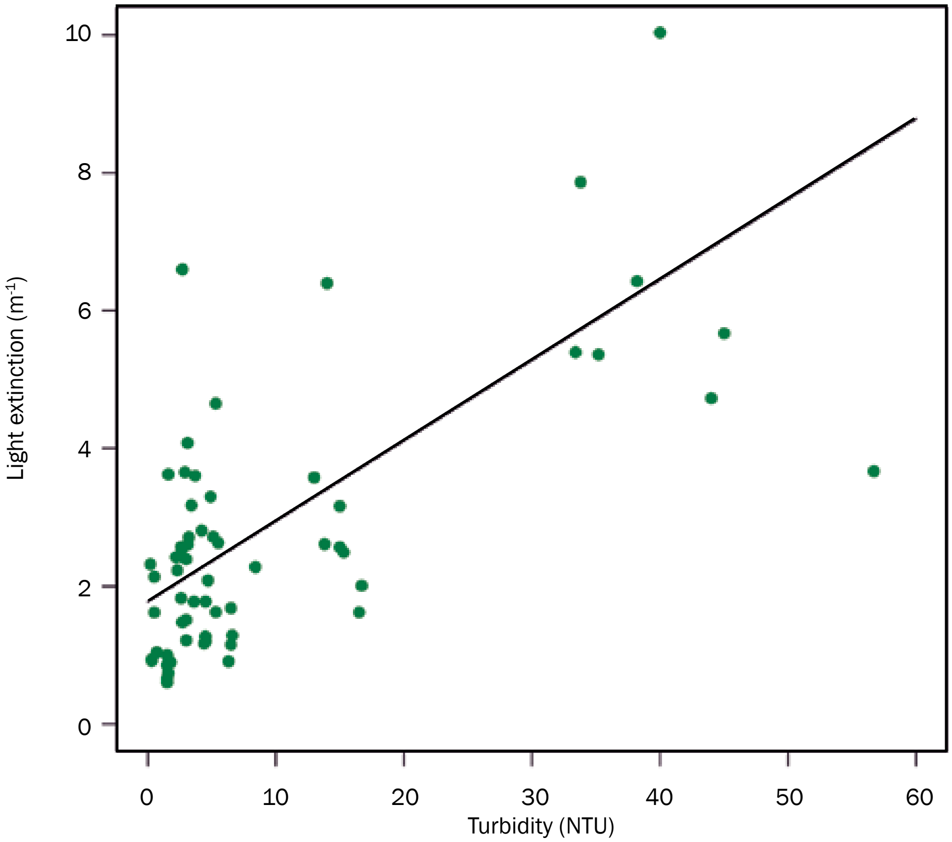


Figure 3. Relationship between the light extinction coefficient (λ), the rate at which light disappears with depth, and turbidity (nephlometric turbidity units,) in eight shallow prairie lakes throughout the summer, 2006 (Moquin, unpublished data).

strategies that reduce external nutrient loading would only directly affect a small portion of the suspended material that contributes to turbidity.

Water column clarity, as measured by λ increased in a non-linear fashion as a function of macrophyte biomass (Figure 5). The curved relationship suggests that at low macrophyte biomass, the plants have little ability to affect sediment resuspension; however, the turbidity decreases sharply once macrophyte biomass reaches about 0.3 kg/m^2 fresh weight. The lakes sampled here are relatively small. In lakes with much larger surface areas, a threshold between macrophyte biomass and water clarity might occur at a higher macrophyte biomass. The role of macrophytes as baffles that prevent sediment resuspension is most apparent in the most turbid lakes where their low biomass or absence is correlated with high turbidity from non-algal sources.

The timing of macrophyte and phytoplankton growth in the spring may be critical to the establishment and maintenance of a clear regime. At high nutrient availability, macrophytes may be

indicates that in these lakes variation in light attenuation is not related to different amounts of algae in the water. This is in contrast to deep, stratified lakes where algae would be expected to be the major component of particles in the water column that would affect light penetration (with exception of highly stained lakes).

Macrophytes and Suspended Matter in Shallow Lakes

Algal carbon estimated from chlorophyll-a measurements was a very small portion of water column seston, which was dominated by non-algal carbon and inorganic carbon (carbonates) in all lakes (Figure 4). The lakes sampled encompass a large range of turbidity, but high turbidity is not due to such lakes being "greener." In fact, we found an inverse relationship between turbidity and chlorophyll-a – the high turbidity lakes were actually the low chlorophyll-*a* lakes and water column turbidity is determined not by living phytoplankton, but rather by resuspended sediments. Why might this be important? Catchment-based management

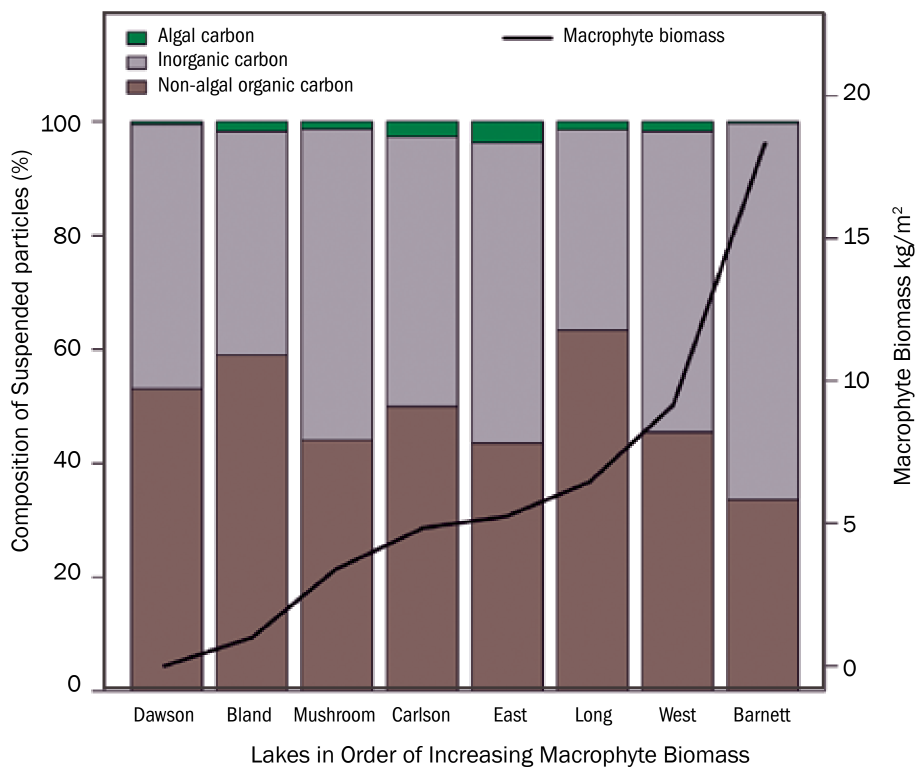


Figure 4. Relationship between macrophyte biomass (solid line) and the proportion of algal carbon, carbonates, and detrital carbon in eight shallow Alberta lakes that vary in turbidity and macrophyte biomass (Moquin, unpublished data).

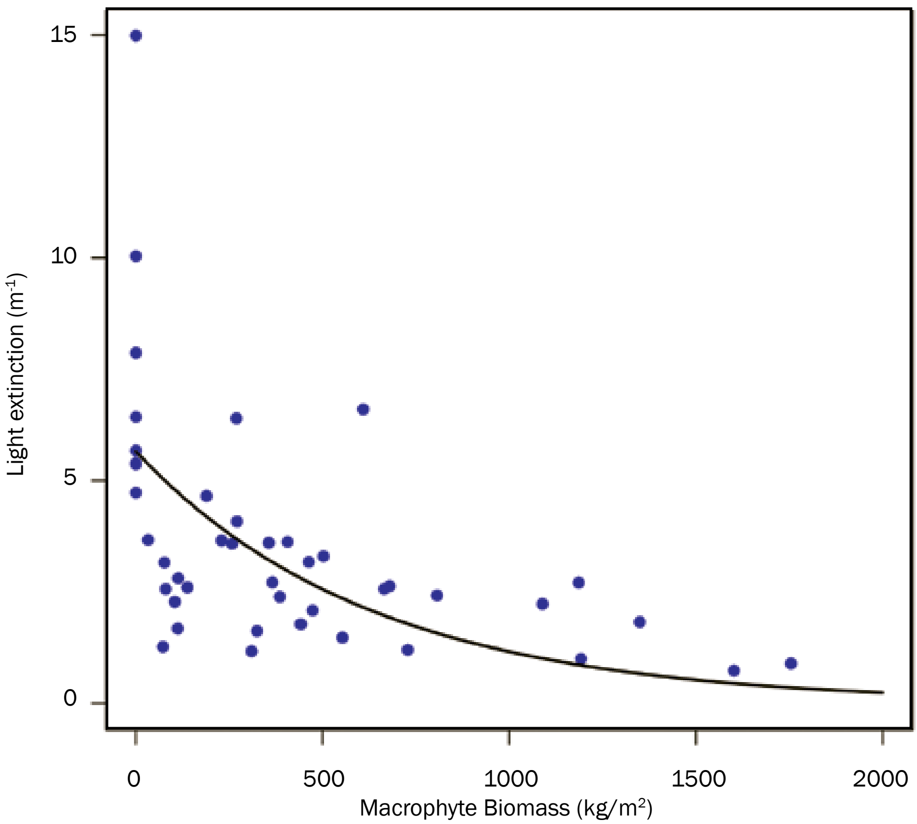


Figure 5. Relationship between the light extinction coefficient (λ) and submerged macrophyte biomass throughout summer, 2006 in eight lakes that vary in turbidity and macrophyte biomass (Moquin, unpublished data).

outcompeted by phytoplankton for light (Folke et al. 2004). Once the macrophytes and their baffling effects are lost, sediment resuspension maintains the turbid state, in part due to internal loading of nutrients to the water column. The threshold of macrophyte abundance required to maintain the clear state may depend primarily on macrophyte competition with phytoplankton for nutrients and light.

Sediment resuspension appears to be the dominant feedback mechanism that maintains the turbid state in these shallow lakes. The most turbid lakes had macrophyte abundance that was apparently below the abundance required to control sediment resuspension. Despite the increased available nutrients associated with resuspended sediments in the most turbid lakes, both macrophyte and phytoplankton abundance is lower and suggests that resuspended sediments create an environment where light limits growth. Sediment resuspension in shallow lakes is primarily wind-driven (Carper and Bachmann 1984) and would depend on physical parameters of the lake such as depth, basin shape, fetch, and alignment to predominant winds. Since very little of the particulate matter in the water column of these lakes is live phytoplankton, the drivers of the turbid state are primarily physical, and therefore the threshold of macrophytes needed to pass from the turbid to clear state would be governed by physical parameters. If physical conditions prevent the recolonization of macrophytes, turbid conditions may persist despite nutrient reductions. Because lake morphometry varies considerably between lakes, there is unlikely to be a single macrophyte biomass threshold that determines whether a clear or turbid lake occurs, a notion consistent with Zimmer et al.'s (2009) findings for a survey of a large number of shallow prairie and parkland lakes in Minnesota, USA.

Implications to Management

Given the reduced ecosystem services and unpleasant esthetics of turbid, eutrophic lakes, restoration attempts have largely focused on reducing phosphorus concentrations. However, if a shallow lake is light limited due to resuspended sediments, then phosphorus reductions may do little to return the lake to a clear state. Jeppesen et al. (2003) have documented numerous cases where the reduction of nutrient concentrations alone proved unsuccessful to restore turbid lakes, yet found that transplanting macrophytes into them was effective in restoring them to a clear state. The physical presence of the macrophytes prevents or reduces sediment resuspension and creates a better light environment for macrophyte growth. Therefore, it may be that only when the physical limitations (sediment resuspension) are removed can macrophytes persist and feedbacks responsible for the maintenance of the clear state by biological means (nutrient control) be reestablished. Recognition of distinct steps that lead to successful restorations is likely to reveal more efficient ways to achieve shifts from turbid to clear regimes. Successful restorations of shallow prairie lakes from the turbid state by reduction of nutrients alone may be effective in situations where the majority of the light limitation is caused by live phytoplankton; however, in cases where high turbidity is caused by sediment resuspension, nutrient management alone may not be sufficient to generate a shift to a more desirable, clear state.

Literature Cited

Carper, G.L. and R.W. Bachmann. 1984. Wind resuspension of sediments in a prairie lake. *Can. J. Fish. Aquat. Sci.* 41(12):1763-1767.

Folke, C., S. Carpenter, B. Walker, M. Scheffer, T. Elmqvist, L. Gunderson and C.S. Holling. 2004. Regime shifts, resilience, and biodiversity in ecosystem management. *Ann. Rev. Ecol. Evol. System.* 35(1):557-581.

Jackson, L.J. 2003. Macrophyte-dominated and Turbid States of Shallow Lakes: Evidence from Alberta Lakes. *Ecosystems* 6(3): 213-223.

Jackson, L.J., T.L. Lauridsen, M. Sondergaard and E. Jeppesen. 2007. A comparison of shallow Danish and Canadian lakes, and implications of climate change. *Freshwat. Biol.* 52(9): 1782-1792.

Jeppesen, E., J.P. Jensen, M. Sondergaard, K.S. Hansen, P.H. Moller, H.U. Rasmussen, V. Norby and S.E. Larsen. 2003. Does resuspension prevent a shift to a clear state in shallow lakes during reoligotrophication? *Limnol. Oceanogr.* 48(5):1913-1919.

Meding, M.E. and L.J. Jackson. 2003. Biotic, chemical and morphometric factors contributing to winter anoxia in prairie lakes. *Limnol. Oceanogr.* 48(4): 1633-1642.

Moquin, P.A. 2007. BSc thesis, University of Calgary.

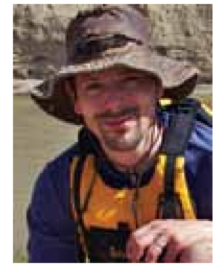
Rennie, M. and L.J. Jackson. 2005. The influence of habitat complexity on littoral invertebrate distributions: patterns differ in shallow prairie lakes with and without fish. *Can. J. Fish. Aquat. Sci.* 62(9):2088-2099.

Scheffer, M., S.H. Hosper, M.L. Meijer, B. Moss and E. Jeppesen. 1993. Alternative equilibria in shallow lakes. *Trends in Ecology & Evolution* 8(8):275-279.

Scheffer, M. and E.H. van Nes. 2007. Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size. *Hydrobiologia* 584(1):455-466.

Zimmer, K.D., M.A. Hanson, B.R. Herwig and M.L. Konsti. 2009. Thresholds and stability of alternative regimes in shallow prairie – parkland lakes of central North America. *Ecosystems* 12(5):843-852.

Lee Jackson is a professor in the Department of Biological Sciences at the University of Calgary. His research interests consider how physical, chemical and biological structure affect ecosystem function, including the structuring role of macrophytes in shallow prairie lakes. Other research areas include the effects of endocrine disrupting compounds on field-based fish populations, and the bloom ecology of “Didymo” (*Didymosphenia geminata*). He co-organized the scientific program for the 2008 NALMS meeting in Lake Louise.



Paul Moquin recently completed his MSc in the Water and Climate Impacts Centre at the University of Victoria, where his thesis research took an experimental approach to understand the effects of shoreline retrogressive thermokarst slumping on the productivity and food web structure of upland arctic lakes.