Kejimkujik Calibrated Catchments: a benchmark dataset for long-term impacts of terrestrial acidification

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Abstract

Delays in forest recovery from terrestrial acidification combined with climate change is leading Acadian Forest ecosystems into new territory. Kejimkujik Calibrated Catchments (KCC) Study Program was established in an around Kejimkujik National Park and Historic Site (KNPHS) in Southwest Nova Scotia (SWNS) in the late 1970s to increase our understanding of the impacts of acid precipitation on relatively pristine ecosystems. KCC now have one of the longest continuously monitored water chemistry records in North America, with data collection beginning in 1980. Its infrastructure includes three gauged streams, twelve forest inventory plots,

an atmospheric deposition monitoring station, and three streams with continuous water quality monitoring and regular lab analysis of stream chemistry, and recent LiDAR coverage. The KCC fits into a wider network of monitored lakes. Data collected at the KCC form a key datapoint in comparisons of catchment response to terrestrial acidification in the context of a warming climate, due to their high and increasing DOC levels, highly dilute waters, lowland topography and extensive wetlands. KCC are also emerging as an important source of information for species at risk protection as SWNS was declared one of the 11 national priority places for biodiversity protection.

Keywords: acidification, catchment, Nova Scotia, stream chemistry, climate change, long-term research

1.0 Introduction and a brief history

The Acadian forests in and around Kejimkujik National Park and Historic Site (KNPHS) were the ancestral home to the Mi'kmaw people for thousands of years forming a culturally vital place for fishing, hunting and travel. Europeans settled the inland areas of KNPHS in the 1820s and logged much of the area for eastern white pine (*Pinus strobus*) and red spruce (*Picea rubens*). In the 19th and 20th centuries, KNPHS became a famous tourist destination for sports fisherman and hunters until terrestrial acidification reduced the productivity of this ecosystem in the 1960s and 70s. Southwest Nova Scotia was one of the most highly sensitive areas to acid precipitation in North America (Hindar, 2001; Kerekes, 1996) being downwind of major North American urban and industrial centres. The impacts to the region have been severe. In the mid-1990s, perch (*Perca flavescens*) and common loons (*Gavia immer*) from KNPHS had among the highest mercury concentrations across North America (Wyn et al., 2010). Adult abundance of wild Atlantic salmon (*Salmo salar*) populations plummeted 89-99% between 1980s and 2013 in the four monitored rivers (DFO, 2013). Current ionic monomeric aluminum concentrations exceed thresholds for aquatic health (Sterling et al., 2020). Recently, actions have been taken to help protect species at risk in and around KNPHS: a UNESCO Southwest Nova Biosphere Reserve was founded in 2001 and in 2018 Canada designated SWNS as a National Priority Place for species at risk.

2.0 Kejimkujik Calibrated Catchment Research Program

In 1978 the Government of Canada initiated the KCC in and around KNPHS in SWNS (Figure 1) to increase scientific knowledge of the potential impacts of long-range transportation of air pollutants (LRTAP) on terrestrial and freshwater ecosystems (Kerekes, 1996). KCC lies in and around KNPHS (Figure 1). KCC began as a multi-agency effort, encompassing federal government departments (wildlife, forestry, inland waters, atmospheric environment, fisheries and park departments). KCC thus has comprehensive baseline data on meteorology, hydrology, water chemistry, aquatic biology, and terrestrial biophysical characteristics (Kerekes, 1996). Monitoring continues today, although the monitoring and scientific staffing was markedly cutback in the 2010s. The KCC is the only region in Atlantic Canada where a consistent intensive effort has been made to produce quantitative, long-term data with which to assess catchment acidification processes (Clair et al., 2007). The KCC watersheds have particular advantages for research as they are not impacted by local industrial developments (Table 1) or other point sources of pollutants (Wyn et al., 2010).

Early aquatic chemistry research in the KCC (1980s) was dedicated to spatially delineating and measuring the deleterious effects of acid rain on aquatic ecosystems (Kerekes et al., 2002; Clair et al., 2007). Research changed to include geochemical modelling to determine if and how reductions in acid deposition might promote ecosystem recovery (Clair et al., 2007), such as dynamic modelling via the lumped-parameter Model of Acidification of Groundwaters (MAGIC) model (Dennis et al., 2005a). Paleolimnological studies were also conducted in the region in 2003-2004, where diatom and chrysophyte communities preserved in lake sediments were analysed for over 100 lakes in the region (Korosi et al., 2013).

3.0 Site Characteristics

Climate and Hydrology

Precipitation events in the KCC originate from both maritime air masses, via fog or tropical cyclone (hurricane) events and continental air masses moving southwesterly to westerly across North America producing frontal system precipitation events. Most of the anthropogenic acid precipitation that falls in the KCC is transported in frontal systems from the Great-Lakes region and Eastern US, particularly during the winter months (Beattie and Whelpdale, 1989). Mean annual precipitation in the KCC between 1966 and 1983 was 1430 mm with 18% of this falling as snow (Kerekes and Freedman 1989), and more recently 1352 mm, of which 10% fell as snow (Laudon et al., 2002). Temperatures in the KCC are relatively moderate compared to Eastern Canada, with mean temperatures at 7.6 +/-8.7 ºC (Rotteveel and Sterling, 2020) ranging between −10 °C during the winter to 25 °C during the summer. Annual river flow in the region typically peaks annually in early April with low-flow periods between mid-July to mid-September (Rotteveel and Sterling, 2020).

Surface Waters

KCC drainage waters are highly sensitive to acid deposition due to their unique combination of slowly weathering bedrock and thin soils with very low base cation concentrations, the lowest in Canada (Clair et al., 2007). This sensitivity to acid deposition is exacerbated by high organic acid inputs from extensive wetlands, and by acid anion (Cl^-) inputs from episodic sea salt deposition events (Clair et al, 2001; Freedman and Clair, 1987; Wright, 2008; Clair et al., 2011; Watt et al., 2000; Whitfield et al., 2007). Surface waters in the KCC have very low specific conductance (Clair et al., 2011). Surface water pH in the KCC and in the surrounding region is the lowest in Canada (outside of point source areas, such as Sudbury, Ontario) (Clair et al., 2007), chronically remaining below 5.5 with rapid further pH declines during runoff events. Dissolved organic matter (averaging to 15.5 ± 0.8 mgL^{-1} in the Mersey River in KCC; Rotteveel and Stelring 2020) increases natural acidity rates and is an important influence on biogeochemistry of freshwaters in the KCC (Clair et al., 2011).

Geology and Landscape

The KCC are found within the South Mountain and LaHave Drumlin Ecodistricts within Nova Scotia's Western Ecoregion (Neily et al., 2017). Bedrock geology consists mainly of granite family rock or a mix of greywacke and slate, all of which are acidic. Surficial geology is comprised of relatively thin, coarse, and often stony till deposits, except for drumlin deposits which are deeper and medium-textured. Climax forest cover on till-derived soils generally consist of red spruce and eastern hemlock (*Tsuga canadensis*), often with a component of eastern white pine and balsam fir (*Abies balsamea*). Associated deciduous species include red maple

(*Acer rubrum*), paper birch (*Betula papyrifera*), and red oak (*Quercus rubrum*). More fertile drumlin deposits can also support stands dominated by yellow birch (*B. allegheniensis*), sugar maple (*A. saccharum*), and red maple along with scattered American beech (*Fagus grandifolia*). Wetter sites are common and support peaty swamps containing black spruce (*P. mariana*), balsam fir, and red maple.The landscape is a complex mosaic of vegetation types, caused in part by variable topography and drainage, natural disturbance events (e.g., wind and fire, Taylor et al., 2020) and a long history of forest harvesting. Most forest soils in the area have seen little to no recovery from acid deposition impacts, with base saturation values often below 10% (Keys et al., 2016; Keys, 2018).

4.0 Research infrastructure

Climate and Atmospheric Deposition data. Kejimkujik 1 climate station (WMO ID 71599), elevation 125 m, is located within KNP and has been in operation since 1994 measuring precipitation, air temperature, relative humidity, wind, and air pressure. Earlier data (1966-1994) were recorded at a nearby climate station in the KNPHS (Kejimkujik Park station, elevation 126 m). Data from both stations may be obtained at (https://climate.weather.gc.ca/historical_data/search_historic_data_e.html).

A Canadian Air and Precipitation Monitoring Network (CAPMoN) station was established in 1979 in KNPHS in the Mersey River drainage area, collecting data on wet and dry atmospheric pollutant deposition and atmospheric chemistry. Data can be accessed at http://data.ec.gc.ca/data/air/monitor/networks-and-studies/canadian-air-and-precipitation-monitoring-network-capmon/.

Surface Water Data. Arguably the most valuable asset in the KCC is its long-term surface water chemistry dataset. Weekly surface water chemistry measurements began in 1980 on the Mersey River at Mill Falls (draining a 295 km^2 catchment). A further three sites were added in 1983, Moose Pit Brook (17 km^2), Whitebourne Brook and Roger's Brook which (each ~ 9 km^2) (Clair and Freedman 1986). Sampling at Whitebourne and Roger's was discontinued in 1987, and replaced in 1990 by a smaller site, Pine Marten Brook (1.30 km^2) (Allen et al., 1992). Samples are measured for major ions, DOC, nutrients, metals and physical parameters, and analyzed at the Federal Laboratory in Moncton, New Brunswick. Data may be obtained at (http://data.ec.gc.ca/data/substances/monitor/national-long-term-water-quality-monitoring-data/maritime-coastal-basin-long-term-water-quality-monitoring-data/?lang=en). Detailed metadata for sites and chemical analysis methods are described in Rotteveel and Sterling (2020, Table S2). Sampling frequency was reduced from weekly from 1980s to 1997, to bi-weekly, then further reduced to monthly in the 2010s.

Lakes in the KCC form part the long-term regular lake monitoring network, where over 80 lakes in Atlantic Canada were sampled twice yearly during spring and fall overturns (Kerekes and Freedman, 1989). Sampling frequency in this program was cutback in the 2010s to once per year.

Terrestrial and Stream Ecology

In 1994 twelve permanent forest plots were established in KNP using the Smithsonian Institution/Man and the Biosphere (SI/MAB, now known as the Monitoring and Assessment of

Biodiversity Programme), with samples taken every five years (Data accessible at https://open.canada.ca/data/en/dataset/42de6c1a-6826-4197-bc35-3e099cc9a6f6).

The abiotic processes of atmospheric deposition, freshwater acidification, catchment-scale hydrological processes, and organic carbon cycling all affect downstream biotic ecosystems. The KCC provides an opportunity to pair these long-term abiotic datasets with a substantial amount of ecological research which has occurred immediately downstream of the KCC, particularly within Kejimkujik National Park. Some of this ecological data may serve as baseline 'acidified' conditions for long-term comparisons. For example, Kerekes and Freedman (1989) summarise detailed chemical and biological characteristics of Kejimkijik lake and two other nearby lakes including descriptions of phytoplankton, zooplankton, benthic invertebrates and fish communities. Macrophytes have also been extensively surveyed in the region (Catling et al. 1986). Finally, some indicators can be placed in more historical context such as changes in zooplankton as revealed by sediment coring of Kejimkujik lake where the outflow of KCC enters via the Mersey River (Korosi et al. 2003, Korosi and Smol 2012).
Additionally, there is a rich body of research describing freshwater mercury dynamics downstream of the KCC inclusing mercury in fish tissues (e.g., Edmonds et al., 2010; Drysdale et al. 2005, Burgess and Hobson 2006, Wyn et al. 2010) and piscivorous birds (Burgess et al. 2005, Burgess and Meyer 2008). Considering the presumed relationship between mercury and biogeochemical processes in this area (O'Driscoll et al. 2005), particularly those related to freshwater acidification, these data will continue to be relevant as the KCC recovers from freshwater acidification.

Non-Profit and Community Groups play a particularly large role in Nova Scotia in the gathering of ecosystem data (Sterling et al., 2014). Local groups such as the Mersey-Tobeatic Research Institute (MTRI) produce numerous reports on the status of the local ecosystems, particularly on terrestrial and stream biology. Annual reports of research conducted in the KCC and KNPHS region are also produced by MTRI (http://swnovabiosphere.ca/your-biosphere/science-and-research/kejimkujik-monitoring-reports/).

A 20 m enhanced digital elevation model is available for the entire KCC area (available at https://novascotia.ca/natr/meb/download/dp055.asp). Recently, leaf-on topographic LiDAR data have been collected over much of part the KCC area by the Nova Scotian provincial government (https://nsgi.novascotia.ca/datalocator/elevation/); increased LiDAR coverage over the KCC is planned in the next few years. Land cover data including a 1 m Digital Elevation Model are available at the Nova Scotian Provincial Geographic Data Directory (https://nsgi.novascotia.ca/gdd/).

5.0 Future outlook

The long-time series and rich baseline data from the KCC is extremely valuable in our understanding of processes and trends in high DOC, low pH, low ionic strength drainage waters draining low-relief, acidified maritime forest and peatland environments. The KCC have played an important role in regional syntheses and in placing SWNS in a global context. KCC scientists have contributed data and insights in a number of biogeochemical papers with other groups to produce large-scale trend and environmental process syntheses. KCC data contributed to regional synthesizes on acidification (Jeffries, 1995, Stoddard et al. 1999, Dupont et al. 2005, Clair et al.

2007), sulfate and cation catchment budgets (Watmough et al. 2005, Mitchell et al. 2020, Kerr et al. 2011), mercury in the environment (Dennis et al 2005b, Kamman et al. 2005, Evers et al 2007), freshwater carbon dynamics (Creed et al. 2008, Zhang et al. 2010) and catchment hydrological dynamics (Godsey et al. 2010).

Because current acid deposition rates still exceed critical load in SWNS (Clair et al., 2011), and because of lack of evidence of freshwater and soil recovery from acidification (Sterling et al., 2020; Keys, 2018), data collected at KCC are needed now as much as ever to understand the impacts of delays in acidification recovery in ecosystems in a warming climate.

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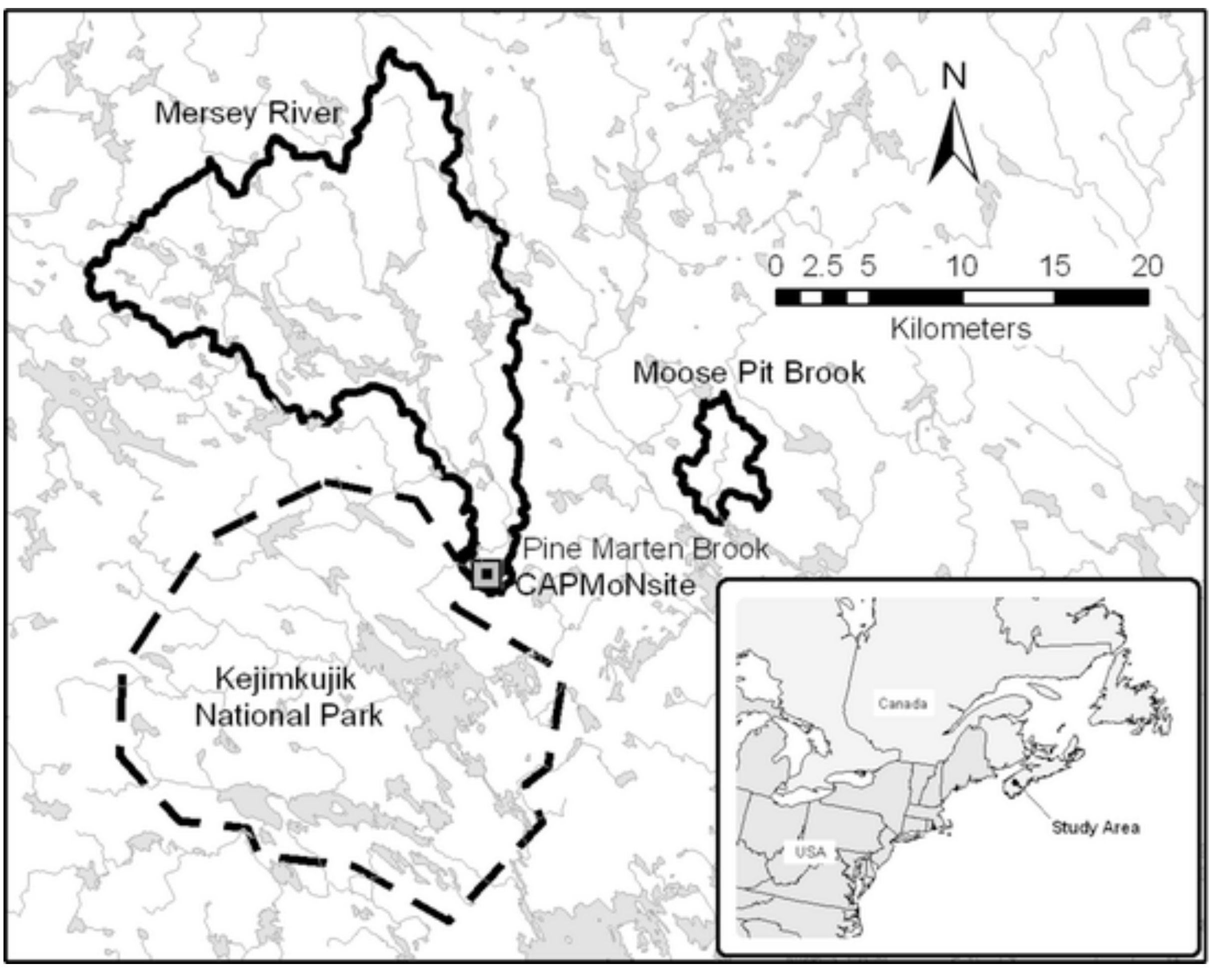

Figure 1. Kejimkujik Calibrated Catchments (KCC), adapted from Clair et al., 2008.

Table 1. Catchment characteristics of the three Kejimkujik Calibrated Catchments with the longest records, adapted from Clair et al., 2005, 2008; Rotteveel and Sterling, 2020; Yanni et al., 2000; Gimbarzevsky, 1975. Lat/long uses NAD83 datum.

Catchment	Lat/Long	Size (km^2)	Elevation (m)	Soil pH	Mean annnual surface water pH	Percent coverage[1]			Disturbance history[2]	Dominant soil type	Discharge information
						Forest	Wetland	Anthropogenic			
Mersey River (MR) (below Mill Falls)	44.4367, -65.2228	295	160-190	4-4.6	4.9	88.4	5.6	0.7	Small communities in upper	Sandy-loam, loamy-sand	Continuous discharge 1968-present (01ED007)

[1] Land use/land cover values may not sum to 100% due to overlap of features and presence of lakes, exposed bedrock, and harvested areas.

[2] Forest harvesting data is not publicly available in Nova Scotia (Sterling et al,. 2020)

NS01ED0005									watershed, forest harvesting in upper watershed		
Moose Pit Brook (MPB) NS01EE0014	44.4619, -65.0483	17	100-150	3.2-5	4.6	99.0	3.0	0.1	Forest harvesting in upper watershed		Continuous discharge 1981-present (01EE005)
Pine Marten Brook NS01ED0110	44.4264, -65.2128	1	120-190	n/a		96.2	3.8	0.0	No recent disturbance		Simulated using ForHyM (Yanni et al., 2000)