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Hydrologic processes and nutrient dynamics in a pristine mountain catchment

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Introduction

Nutrient dynamics in watersheds have been used as an ecosystem-level indicator of overall ecosystem function or response to disturbance (e.g. BORMANN et al. 1974, WEBSTER et al. 1992). The examination of nutrients has been evaluated to determine responses to logging practices or other changes in watershed land use. Nutrient dynamics have been related to changing physical and biological characteristics (MULHOLLAND 1992, CHESTNUT & MCDOWELL 2000). Herein, the concentrations and dynamics of nitrogen, phosphorus and particulate organic carbon were examined in a large pristine watershed because they are affected by changes in discharge directly from the catchment and after passage through a large oligotrophic lake.

Study site

McDonald Creek is a fourth-order stream draining ~443 km² of Glacier National Park in north-west Montana, USA. Basin and stream channel morphology are greatly influenced by the sedimentary bedrock and glacial history of the area. The maximum elevation in the drainage is 2912 m on the continental divide along the eastern border of the catchment. McDonald Creek, at its entry into McDonald Lake, has a drainage area of 279.4 km² and a mean annual discharge of 16.4 m³/s, annual maximum discharge of ~75–130 m³/s and a minimum discharge of ~1–3 m³/s. Lake McDonald, a glacial lake on the valley floor near the catchment terminus, is at an elevation of 961 m, has a surface area of 2.78 km² and a maximum depth of 486 m.

Methods

Discharges into and from Lake McDonald were measured continuously with in-situ pressure transducers attached to field data recorders. Pressure transducers measured stream depth, which was correlated with discharge to develop detailed depth-to-discharge rating curves for both lake input and lake outlet sites. To obtain virtually continuous measures of stream discharge, field data loggers recorded hourly average discharge from transducer readings obtained every 5 min from 1 October 1993 until 30 September 1997.

Water samples were collected bimonthly and biweekly from the stream thalweg at both sites during low flow and during snowmelt runoff, respectively. Water samples were analyzed for the major nutrient constituents: total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), nitrate plus nitrite ($NO_3 + NO_2$), particulate organic carbon (POC) and dissolved organic carbon (DOC). Soluble nutrient concentrations were determined following the methods of APHA (1985) with minor modifications (STANFORD et al. 1986). Total nitrogen was determined by persulfate digestion (D'ELIA et al. 1977). Dissolved and particulate organic carbon concentrations were determined by persulfate digestion and infrared CO_2 detection (MENZEL & VACCARO 1964).

Results and discussion

Stream discharge followed the pattern described for north-temperate snowmelt-driven streams (POFF & WARD 1989). Discharge generally remained <10 m³/s from mid-August until mid-March (Fig. 1). Accumulation of snow at high elevations within the upper catchment was observed at a long-term snow-monitoring site within the basin. Snow water equivalent (SWE) accumulation within the basin generally began in mid-October, with maximum SWE occurring in late April. Average SWE decreased rapidly between early May and late June (Fig. 1). Average discharge in both the stream above the lake and the outlet stream followed the pattern established by the melting snow pack, with peak average discharge each year occurring in late May, and a maximum discharge of

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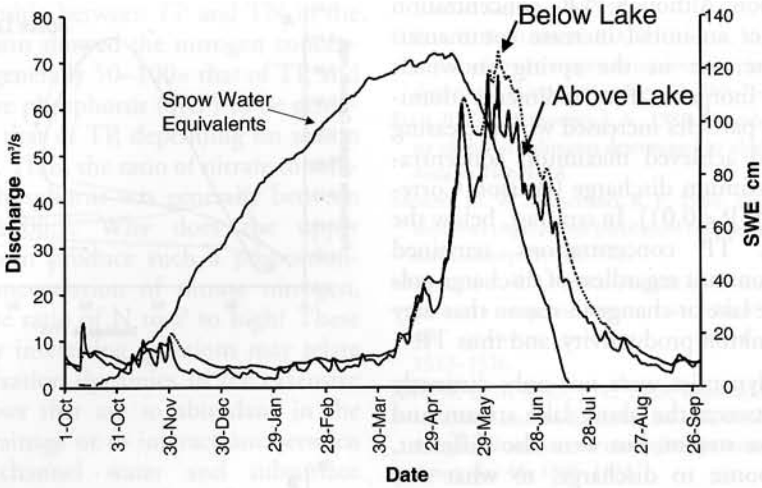

Fig. 1. Five-year average (1993–1997) discharge (m^3/s) of McDonald Creek above Lake McDonald, McDonald Creek below Lake McDonald, and average snow water equivalents (SWE in cm of water) at the Flattop Mountain SNOTEL monitoring site in the upper McDonald basin.

131.2 m^3/s in the inlet creek during the 5-year study. Although the hydrograph of the stream above the lake tended to fluctuate more rapidly than the stream below the lake, the general pattern of discharge was nearly identical, with <5% difference between the sites. The several small sub-basins that drain directly into Lake McDonald account for the stream below the lake having a slightly higher discharge.

Nutrient and carbon dynamics demonstrated fundamentally different patterns of response to change in discharge between nutrient constituents and between sites. The particulate organic carbon concentration in the stream above the lake demonstrated a distinctly positive, clockwise hysteresis (Fig. 2A). This pattern was driven by an increased POC concentration with the increasing discharge regime of spring snowmelt. However, as spring growth of periphyton and accumulations of detritus and other forms of organic matter from inundated channels and floodplain habitats were incorporated into the river seston, POC was exported from the upper basin and into the lake. Thus, as discharge increased to an annual maximum during spring snowmelt, the concentration of POC decreased by more than 50%. After spring snowmelt discharge, seston POC returned to levels similar to those observed prior to runoff. In contrast, the sestonic POC concentration in the stream downstream from the lake outlet decreased as spring snowmelt discharge into the lake increased lake depth and, consequently, lake outlet discharge, resulting in a slightly negative, yet clockwise hysteresis. The POC concentration did not increase in the outlet stream during summer, even though this might be anticipated with increased summer algal production. However, Lake McDonald is extremely oligotrophic, with Secchi disk depths of 15–20 m throughout the year.

Phosphorus dynamics were also distinctly different between the stream above the lake and the stream below the lake. Above the lake, total phosphorus (TP) increased approximately 10× between low flow discharge prior to spring snowmelt and the concentrations observed at higher discharge (Fig. 2B). However, unlike POC, TP concentrations maximized with maximum stream discharge. A very close correlation was found between total suspended particulate matter and TP concentration (Pearson Correlation = 0.946, $P < 0.001$). Ellis & Stanford (1988) demonstrated the relationship between phosphorus and fluvial sediments that explains this observation. Although POC concentration decreased after an initial increase commensurate with the rise in the spring snowmelt hydrograph, inorganic fine sediments dominated by clay particles increased with increasing discharge and achieved maximum concentration with maximum discharge (Pearson Correlation = 0.845, $P < 0.01$). In contrast, below the lake stream, TP concentrations remained remarkably constant regardless of discharge volume from the lake or change in season that may influence plankton productivity, and thus TP.

Nitrogen dynamics were not only distinctly dissimilar between the above-lake stream and the below-lake stream, but were also different, in their response to discharge, to what was observed as similar patterns for POC and TP. Nitrate nitrogen comprised >95% of the total nitrogen (TN) concentration transported into or from the lake during all seasons, resulting in an extremely close correlation (Pearson Correlation = 0.951, $P < 0.0001$). The pattern of TN concentration in the stream above the lake revealed a negative, but clockwise hysteresis (Fig. 2C). This was the result of relatively high TN concentrations during base flow coming from the upper basin that increased slightly during the onset of spring runoff but decreased precipitously as runoff continued, with the concentration of TN being lower during maximum discharge than during base flow. This pattern was probably the result of the relatively high nitrate concentration in ground waters that sustain stream discharge during base flow and the dominance of surface waters during snowmelt. Analyses of snow samples taken from 52 snow survey locations in the upper basin revealed a very low nitrate concentration in snow water (mean, 4.36 µg/L; S.D., 1.31). The concentration of TN in the stream above the lake was often 100× that found in snow, thus accounting for the decrease in the TN concentration with increased snowmelt. Similarly, the TN concentration in the stream below the lake had a neutral hysteresis (Fig. 2C). Some variation in TN occurred during low flow prior to the onset of spring snowmelt that may be due to increased low valley groundwater input to the lake during initial spring snowmelt.

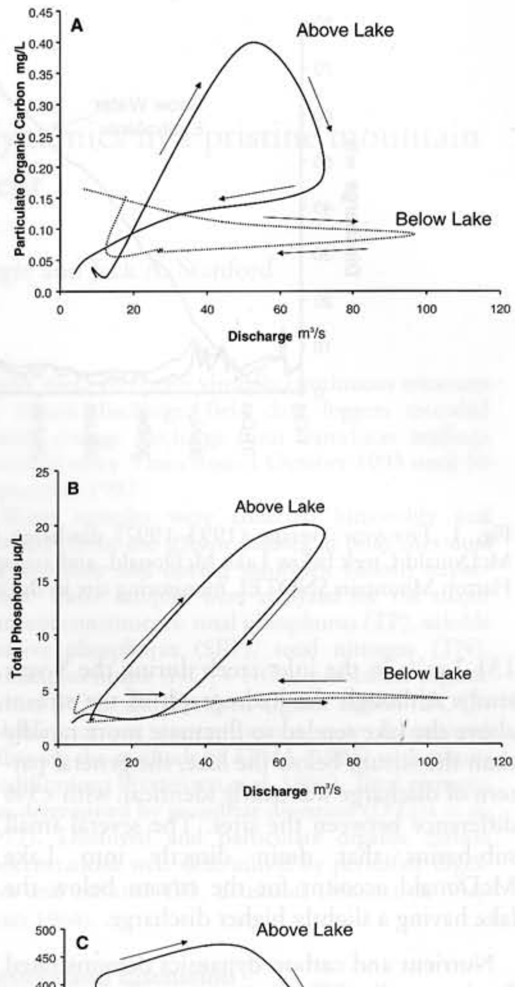

Fig. 2. Panel A – Hysteresis relationship of particulate organic carbon concentration (POC) to change in stream discharge over the annual hydrographic period in McDonald Creek above Lake McDonald and in McDonald Creek below Lake McDonald; Panel B – total phosphorus concentration (TP); Panel C – total nitrogen concentration (TN).

The relationship between TP and TN in the McDonald basin showed the nitrogen concentration to be generally 50–100× that of TP, and soluble reactive phosphorus (SRP) to be generally 0.5–0.1× that of TP, depending on season and discharge. Thus, the ratio of nitrate to soluble reactive phosphorus was generally between 100:1 and 1000:1. Why does the upper McDonald basin produce such a proportionately high concentration of nitrate nitrogen, and why is the ratio of N to P so high? These fundamentally interesting questions may relate to nitrogen fixation dynamics in the extensive alpine meadows that are so abundant in the McDonald drainage or to interactions between the stream channel water and subsurface hyporheic waters associated with upstream flood plains. TARDIFF & STANFORD (1998) showed that the nitrate nitrogen concentration in alpine meadow soils substantially increased following disturbance by bears, suggesting that further investigation of the cycling and mass flux of nitrogen at higher elevations will probably help explain the tendency of this pristine montane river system to export nitrogen.

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