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Atmospheric Deposition Coupled Runoff Driven Shifts in Nutrients and Trophic Status of Two Fresh Water Tropical Lakes of India

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Abstract

The status of changing atmosphere-land-water linkages is not properly addressed in India despite recent global attention stressing its importance. The present study was an effort to investigate whether atmospheric deposition (AD) of nutrients, in addition to other sources enhances runoff nutrient flushing and primary productivity in fresh water lakes of Rajasthan India. Our data show that the region receives 2.65 to 21.85 Kg ha^{-1} of total N and 0.48 to 1.86 Kg ha^{-1} of total P as dry deposition annually. Wet deposition also adds these nutrients in similar order of magnitude. Intensive agriculture in catchment appeared most important non-point source contributing to Lake Udaisagar through runoff. Lake Baghdara although situated away from direct human interference, receives excessive AD-P through downwind influence of the air. AD-input enhanced nutrient flushing through runoff and contributed to raise chlorophyll ***a*** biomass, gross primary productivity (GPP) and dissolved organic carbon (DOC) as typically reflected through Lake Baghdara. The study further indicated a likely shift in N: P stoichiometric ratio with implications on ecological nutrient limitations and trophic cascades. The study has relevance from ecological as well as from integrated lake basin management (ILBM) perspective.

Keywords: atmospheric deposition, DOC, GPP, ILBM, nutrients, runoff, wet and dry inputs

INTRODUCTION

Increased human activities have dramatically altered the structure and functions of aquatic and terrestrial ecosystems globally. Rapidly growing human population and affluent life style coupled with extensive demand of resources are the main forcing factors for degrading the quality of natural and modified ecosystems. These activities have resulted in profound change in climate, vegetational characteristics, hydrological cycle as well as surface and marine water resources (Lovett and Kinsman, 1990; Puckett, 1995; Jickells, 1998; Kumar, 2003; Josipovic *et.al*., 2011; Antisari *et.al*., 2013). Surface water resources especially lakes and reservoirs being stagnant and under strong control of air and watershed drivers, are more prone to human modifications. In India, extensive deforestation, overgrazing, agricultural expansion, unprecedented urban-industrial growth and over extraction of biomass for fuel, fodder and timber have drastically changed the landscapes including freshwater resources (Pandey and Pandey, 2002; Pandey and Verma, 2004;)

Human-driven shifts in the quality of inland waters have received attention on two major issues: increased concentration of nutrients from air and watershed and nutrient driven autochthonous C build up which enhanced allocthonous C export and associated shift in carbon balance of water bodies (Lo and Chu, 2006; Monteith *et. al*., 2007; Cole *et al*, 2007). Regional scale studies have shown the importance of hydrologic flushing of carbon and nutrients and potential role of atmospheric deposition (AD) in Lake Eutrophication (Monteith *et al*., 2007; Bergstrom *et al*., 2008). Sensitivity of inland waters, both as sink or source of carbon and nutrients including their vulnerability to anthropogenic input, varies on spatial and temporal scales along with geographical location. They provide important information for regional budget of carbon and nutrients as well as for management of these resources. Studies indicate that apart from the point sources like urban-industrial inputs, non-point sources such as surface runoff and atmospheric deposition are important contributors of water quality degradation and shifts in carbon balance (Monteith *et al.*, 2007; Bergstrom *et.al.*, 2008). Studies on these issues in India especially for lakes of Rajasthan are very scarce.

The state of Rajasthan represents north western part of India. A major part of the state receives very low precipitation and includes Thar Desert of India. Udaipur region, where the present study was conducted, represents SE part of the state. This region also receives staggered precipitation and annual average rainfall generally remains below 625 mm and day time temperature in summer exceeds 46ºC. The region is characterized by a large number of small and large lakes and reservoirs. These inland freshwater bodies are generally rain fed and are the main source of drinking and irrigational water supply. During the last two decades, the region witnessed unprecedented urban-industrial growth and as a result, degradation of water quality of most of the lakes and reservoirs (Pandey and Verma, 2012). Along the other sources, the area is witnessing high input of nutrients through atmospheric deposition and lateral flow (surface runoff) from agricultural land. Despite these facts, systematic database on the role of AD-coupled surface runoff flushing in determining water quality of lakes in this region is very scarce. The present study is an effort to investigate the effect of AD-coupled surface runoff flushing on water quality of two fresh water lakes.

STUDY AREA

The present study was conducted for three consecutive years (2000-2002) at two freshwater tropical lakes of Rajasthan India. The lakes considered for the study differ with respect to nutrient input sources. Lake Udaisagar (24º35´N latitude, 73º48´ longitude, 577 m above msl) receives nutrients from an urban stream and through vast agricultural catchment in addition to atmospheric deposition. Lake Baghdara (24º31´N latitude, 73º48´ longitude, 582 m above msl) is situated away from direct human disturbances.

MATERIAL AND METHODS

Sampling was done for atmospheric deposition, run-off water and stream flow being added in the catchment and directly to the study lakes. Surface runoff samples were obtained manually during rain event using pre-sterilized sampling bottles. The data presented here represent event mean concentration and flux.

Runoff samples were analyzed for nitrate-N using brucine-sulphanilic acid method (Voghel, 1971). For phosphate-P, Olsen's method was used (Mackereth, 1963) while DOC was quantified following $KMnO_4$ digestion method (Michel, 1984). Analysis of sediment quantity variables was performed as per Jackson (1973).

Atmospheric particulates were collected using deposition samplers placed at different sites at 3.0 m height for a known period of time. Atmospheric deposits were analyzed for N and P concentrations following standard methods. The values thus obtained were converted to AD-flux as Kg ha^{-1} yr^{-1}. For wet deposition, rain water samples were collected on event basis in plastic jars of known mouth area and concentrations of N, P were determined in these samples. The values were finally expressed as Kg ha^{-1} a^{-1}. Lake water samples were collected at monthly intervals at about 15-20 cm depth. Samples collected in triplicate were analyzed for nitrate-N, phosphate-P and dissolved organic carbon DOC as described for runoff waters. For presenting trophic status, phytoplankton biomass was measured in terms of chlorophyll ***a*** biomass and gross primary productivity. Chlorophyll ***a*** was extracted in acetone and measured spectrophotometrically (Maiti, 2001) and gross primary productivity was measured using dark and light bottle method (APHA, 1998).

RESULTS

Lake Udaisagar receives carbon and nutrients through stream flow as well as through surface runoff. Stream flow (Ahar river) mean concentrations of NO_3-N, PO_4-P and DOC were 0.065 mg L^{-1}, 0.027 mg L^{-1} and 5.180 mg L^{-1} respectively (Tab. 1). Their respective total fluxes were 153.48, 58.76 and 122.76 Kg/yr. Concentrations in runoff were 1.25 mg L^{-1} ($NO_3^{)}$, 0.562 mg L^{-1} (PO_4^{3-}) and 6.75 mg L^{-1} (DOC). Respective total flux of NO_3, $PO_4^{3-}$and DOC were 7.86×10^3, 3.53×10^3 and 42.45×10^3 Kg annually. For Udaisagar the total sediment transport (stream flow + runoff) was over eight folds higher than those transported in Baghdara. For the latter, the runoff transport of DOC and nutrients were significantly lower than those of Udaisagar (Tab. 1). Runoff concentrations for DOC, $NO_3^-$and $PO_4^{3-}$for Baghdara were 0.053, 0.033, and 6.63 mg L^{-1} and fluxes were 0.58×10^3, 0.36×10^3 and 7.36×10^3 Kg yr^{-1} respectively.

Lake Udaisagar receives 8.30 to 21.85 Kg ha^{-1} total N, 0.48 to 1.65 Kg ha^{-1} total P as dry deposition and 11.75-29.80 Kg ha^{-1} total N and 1.10-3.80 Kg ha^{-1} total P as wet deposition annually (Tab. 2). Atmospheric deposition input of total-N (AD-N) was significantly small for Baghdara with values ranging from 2.65 to 8.30 Kg ha^{-1} as dry deposition and 5.48 to 14.71 Kg ha^{-1} as wet deposition annually. However AD-P input for Baghdara lake was relatively higher than those recorded at Udaisagar Lake. For the later, AD-P inputs were 0.48 to 1.86 Kg ha^{-1} as dry deposition and 1.60 to 4.10 Kg ha^{-1} as wet deposition annually (Tab. 2). These trends were recorded uniformly throughout the study period.

Nutrients and primary productivity variables did show significant between-lake variations (Tab. 3). Chlorophyll ***a*** biomass and gross primary productivity (GPP) both were almost 1.5 folds higher in Udaisagar than those recorded in Baghdara, although the concentration of dissolved organic carbon (DOC) did show only marginal difference (Tab. 3). Concentration of nutrients differed significantly between the study lakes. Concentrations of $NO_3^-$and NH_4^+ were 0.82 and 0.052 mg L^{-1} respectively in Udaisagar while in Baghdara respective values were 0.511 and 0.041 mg L^{-1}. The mean concentration of PO_4^{3-}in Udaisagar was 87.50 mg L^{-1} and in Baghdara it was 65.40 µg L^{-1} (Tab. 3).

DISCUSSION

Inland waters, especially lakes are prone to nutrient inputs both from air shed as well as from water shed. Human modifications in the drainage basin, therefore, induces proportionate shift in the concentration of nutrients and in the trophic status. Similar is the case with increased atmospheric loading and deposition. In particular, atmospheric deposition (AD) may add nutrients even in water bodies situated away from direct human interferences. In this study, we have compared an anthropogenically impacted lake (Udaisagar) with a lake situated away from direct human interference. This has relevance validating data comparison and demarcating human induced changes in air shed and in watershed.

Nutrient concentrations in surface runoff indicated the combined effect of variations in catchment characteristics and atmospheric deposition. Depending upon the water volume such addition could alter the water quality of study lakes significantly

(Cooper and Thomsen, 1988; Dillon *et. al.*, 1991; Johnes and Heathwaite, 1997; Baumler and Zech, 1998; Wetzel, 2001; Lau and Lane, 2002, Bergstrom *et. al*., 2008). In addition Ahar river also add sizeable amount of nutrients and organic waste to Udaisagar. In earlier studies, it has been shown that dissolved inorganic nitrogen, where NO_3^-assumes predominance is the principal nitrogen species in runoff flushing in polluted areas (Perakis and Hedin, 2002; Lo and Chu, 2006). High flux of $NO_3^-$and $PO_4^{3-}$from Udaisagar was expected as major part of the catchment of this lake witness agricultural activities. This indicates anthropogenic control as well as role of hydrological flushing in lake N and P loading. NO_3 flushed from agricultural catchment was almost seven times higher than from barren and rocky catchment. The vast stretch of arable land on two sides could add significantly high amount of N to Udaisagar. Similar observations have been made in other studies (Fleischer and Hamrin, 1988; Downing *et. al.*, 1999; Andersson and Lepisto, 2000; Arbuckle and Downing, 2001; Josipovic *et.al*., 2011). The catchment with extensive agricultural activity receives 30 to 125 Kg N $ha^{-1}a^{-1}$ and 15 to 75 Kg P ha^{-1} $a^{-1.}$ This was reflected also through substantially high run-off transport of P from agricultural catchment. Agriculture is an important non-point source of nutrient addition to downstream ecosystems (Williams, 2000; Tilman *et. al.*, 2001; Antisari *et.al*., 2013). Runoff draining from woodland catchment, as in the case of Baghdara, flushed relatively small quantities of sediment as well as nutrients. In contrast, however, runoff flushing of DOC was almost similar in magnitude with Udaisagar. This indicates that woodland catchment could be an important source of allocthonous organic input to downstream lakes and reservoirs.

Study further indicated that nutrients in lakes as well as in runoff were well correlated ($p<0.01$) with nutrients added through AD inputs. During recent years, the region witnessed unprecedented growth of urban-industrial sector (Verma, 2004). These coupled with other human activities could enhance atmospheric loading and deposition. More recent studies have shown that many parts of India is receiving massive amount of N and P through atmospheric deposition (Pandey *et. al*., 2016). The study region also receives substantially high amount of AD-N and P (Table 2) almost similar in order of magnitude observed in other parts of the country (Pandey *et al*., 2016). This amount could be sufficient to raise concentrations of nutrients in runoff as evidenced through Baghdara lake although woodland catchment can substantially absorb the air-borne nutrients. Global data on AD-P show highly variable results. Most reports of total P deposition show values ranging from 0.07 to 1.7 kg P ha^{-1} a^{-1}, although exceptional values as high as >5 Kg P ha^{-1} a^{-1} have been reported (Newman, 1995). Previous studies conducted in the study region have shown high input of AD-P (Verma, 2004). In the present study AD-P input was substantially high. In particular lake Baghdara although situated away from direct human interference receives sizably high input of P through atmospheric deposition. This could be due to downwind influence of phosphate fertilizer factories through aerial catchment (Pandey and Nagda, 2002). As expected, however, atmospheric deposition of N at Udaisagar lake was three times higher than those recorded at Baghdara. The reason behind can be emissions from nearby industrial sources and highways. Effects of increased atmospheric deposition and other human activities were clearly reflected through increased concentrations of such elements in surface run-off.

Concentrations of nutrients were sizably high in Udaisagar (Tab. 3) indicating the effects of human activities. Apart from vast agricultural catchment and pasturelands, the lake receives input of urban release through Ahar stream. The data presented here indicate that the lake receives about 153.48 Kg NO_3, 58.76 Kg PO_4 and 122.30 Kg DOC annually as stream flow. These inputs can substantially elevate concentrations of N, P and C in Udaisagar lake. High concentrations of nutrients were reflected also through enhanced phytoplankton development in Udaisagar. Chlorophyll ***a*** biomass and GPP in Udaisagar were almost 1.5 folds higher than those recorded for Baghdara. Despite this fact primary productivity measured in Baghdara lake could be considered high because it is situated away from direct human perturbation. It seems and as could be expected that phytoplankton development (measured in terms of chlorophyll ***a*** biomass and GPP) in Baghdara lake was regulated in a major way by atmospheric input of N and P. Earlier studies have shown that atmospheric deposition can be an important factor changing the trophic status of lakes situated even in remote areas (Bergstrom *et. al*, 2008; Verma, 2015). Further, lake Baghdara is receiving high input of AD-P with rate of increase proportionately higher than N deposition. If this trend continued, the lake would witness a shift in N:P stoichiometric ratio. This has long-term implications and need scientific attention because a shift in N:P stoichiometry towards P will lead P limitation to shift to N limitations and consequently a change in phytoplankton composition and trophic cascades. Previous studies have shown stoichiometric shifts in lake nutrient limitation driven by atmospheric deposition (Elser *et. al*., 2009; Verma, 2015). In India also a similar shift is expected as AD-P inputs is more consistently rising than D-N input (Pandey *et. al.*, 2016).

Table 1: Influx of sediment, dissolved organic carbon (DOC) and nutrients in Udaisagar and Baghdara lakes through stream flow and surface runoff (values are mean ± 1SD)

Variable	Udaisagar lake		Baghdara lake	
	Concentration*	Flux**	Concentration*	Flux**
STREAM FLOW				
Sediment	46.50±5.60	107528.0±9415.0	-	-
NO_{3-}	0.065±0.08	153.48±11.57	-	-
PO_4^{3-}	0.027±0.03	58.76±5.48	-	-
DOC	5.180±0.68	122.30±11.62	-	-
RUNOFF				
Sediment	18.65±2.30	117.30×10^3 ±4368	8.10±0.62	8.99×10^3 ±667
NO_{3-}	1.250±0.22	7.86×10^3 ±625	0.053±0.004	0.58×10^3 ±61
PO_4^{3-}	0.562±0.07	3.53×10^3 ±286.40	0.033±0.002	0.36×10^3 ±29
DOC	6.75±0.87	42.45×10^3 ±745.60	6.63±0.38	7.36×10^3 ±805

**values except sediment (gmL^{-1}), are in mg L^{-1}*
***values except sediment (tonnes) are in Kg yr^{-1}*

Table 2: Atmospheric deposition of N and P at Udaisagar and Baghdara lakes (values are mean ±1SD) Values in parenthesis represent the range of deposition

Variable	Udaisagar	Baghdara
Dry deposition (Kg ha^{-1} a^{-1})		
Total-N	16.78 ± 2.12 (8.30-21.85)	5.80 ± 0.83 (2.65-8.30)
Total-P	0.80 ± 0.76 (0.48-1.65)	0.92 ± 0.16 (0.48-1.86)
Wet deposition (Kg ha^{-1} a^{-1})		
Total-N	20.05 ± 2.85 (11.75-29.80)	9.04 ± 0.98 (5.48-14.71)
Total-P	2.65 ± 0.28 (1.10-3.80)	2.90 ± 0.36 (1.60-4.10)

Table 3: Chlorophyll ***a*** biomass, gross primary productivity (GPP), concentrations of dissolved organic carbon (DOC) and nutrients in Udaisagar and Baghdara lakes of Udaipur. (Values are mean ±1SD)

Variable	Udaisagar	Baghdara
Chlorophyll ***a*** (mg m^{3})	37.70 ± 2.80	26.11 ± 1.76
GPP (g C m^{-2} d^{-1})	3.68 ±0.31	2.45 ± 0.18
DOC (mg L^{-1})	2.91 ±0.18	2.36 ±0.19
NO_{3-}(mg L^{-1})	0.82 ± 0.01	0.511 ±0.04
$PO_4{}^{3-}$(µg L^{-1})	87.50 ±6.11	65.40 ±4.26
NH_4^+ (mg L^{-1})	0.052 ±0.003	0.041 ±0.002

CONCLUSION

The data presented in this study suggest that agricultural intensification is an important forcing factor for nutrient pollution of inland lakes. The study further indicates that the region receives large input of N and P as atmospheric deposition which not only contributes raising trophic status by direct deposition but also indirectly through runoff-driven lateral transport of nutrients and dissolved organic carbon. More importantly as witnessed through Baghdara lake, AD-input could lead even remote lakes towards eutrophication. Additionally, although more studies required our data show if the present trend of AD-input continued, it will steer the system from P to N limitation and consequently a shift in trophic cascades. This has long-term ecological implications and need attention from a lake conservation perspective.

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