Biogeochemistry (2010) 101:357–368
DOI 10.1007/s10533-010-9509-3

Identification of nitrogen sources to four small lakes in the agricultural region of Khorezm, Uzbekistan

Margaret Shanafield · Michael Rosen · Laurel Saito · Sudeep Chandra · John Lamers · Bakhriddin Nishonov

Received: 26 October 2009 / Accepted: 7 July 2010 / Published online: 16 July 2010

Abstract Pollution of inland waters by agricultural land use is a concern in many areas of the world, and especially in arid regions, where water resources are inherently scarce. This study used physical and chemical water quality and stable nitrogen isotope (δ^{15}N) measurements from zooplankton to examine nitrogen (N) sources and concentrations in four small lakes of Khorezm, Uzbekistan, an arid, highly agricultural region, which is part of the environmentally-impacted Aral Sea Basin. During the 2-year study period, ammonium concentrations were the highest dissolved inorganic N species in all lakes, with a maximum of 3.00 mg N l^{-1} and an average concentration of 0.62 mg N l^{-1}. Nitrate levels were low, with a maximum concentration of 0.46 mg N l^{-1} and an average of 0.05 mg N l^{-1} for all four lakes. The limited zooplankton δ^{15}N values did not correlate with the high loads of synthetic fertilizer applied to local croplands during summer months. These results suggest that the N cycles in these lakes may be more influenced by regional dynamics than agricultural activity in the immediate surroundings. The Amu-Darya River, which provides the main source of irrigation water to the region, was identified as a possible source of the primary N input to the lakes.

Keywords Nitrogen cycling · Water quality · Stable nitrogen isotopes · Agricultural runoff · Anthropogenic impacts · Lakes

Abbreviations

δ^{15}N	Stable nitrogen isotope
DIN	Dissolved inorganic nitrogen
DO	Dissolved oxygen
N	Nitrogen
NIGMI	Hydrometeorological Research Institute, Uzbekistan
UZ	Uzbekistan

M. Shanafield (✉)
Division of Hydrologic Sciences, Desert Research Institute, 2215 Raggio Parkway, Reno, NV 89512, USA
e-mail: Margaret.shanafield@dri.edu

M. Rosen
Nevada Water Science Center, U. S. Geological Survey, 2730 N. Deer Run Road, Carson City, NV 89701, USA

L. Saito
Department of Natural Resources and Environmental Science, University of Nevada Reno, Mail Stop 186, 1664 N. Virginia Street, Reno, NV 89557, USA

S. Chandra
Department of Natural Resources and Environmental Science, University of Nevada Reno, Mail Stop 186, 1664 N. Virginia Street, Reno, NV 89557, USA

J. Lamers
UNESCO-ZEF German-Uzbek Khorezm Project, 14, Khamid Almjan Street, Khorezm 220100, Uzbekistan

B. Nishonov
Laboratory of Surface Water Quality Investigation, Hydrometeorological Research Institute, 72 K. Makhsumov Str, Tashkent 700052, Uzbekistan

Introduction

The area of land used globally for irrigated agriculture roughly doubled during the second half of the twentieth century, and continues to expand to feed our growing population (Cosgrove and Rijsberman 2000). As more land comes under cultivation, the demand for freshwater is greater, putting increasing stress on water resources. At the same time, the use of industrial fertilizers has increased substantially, especially in developing countries, and it is estimated that the rate of nitrogen (N) input into the terrestrial N cycle globally has more than doubled over background levels since the middle of the 20th century (Vitousek et al. 1997). Ill-managed N-fertilizer application contributes to local groundwater pollution (Biswas 1993; Nolan et al. 1997; Oenema et al. 2005) and eutrophication of lakes (Nixon 1995; Carpenter et al. 1998). In arid regions, water supplies are often scarce, and the pollution of surface and groundwater from nonpoint sources such as agriculture leads to a diminished supply of quality water available for domestic and recreational uses.

Several studies link increased agricultural N use in watersheds or riparian zones to N inputs to lakes (Shannon and Brezonik 1972; Howarth et al. 1996; Oenema and Roest 1998; Vander Zanden et al. 2005). However, variability in agricultural practices, soil type, and hydrologic condition within a particular watershed or riparian area makes it difficult to generalize the impact of land use on surface waters. Decreasing localized N application does not necessarily result in significant changes in surface water quality (Oenema et al. 2005). Physical and chemical water quality data and stable isotopes can be used to investigate these human influences on inland waters. Stable N isotope values (δ^{15}N) provide a good indication of nutrient inputs because dissolved inorganic N sources such as wastewater and fertilizers tend to have distinct isotopic signatures (Cabana and Rasmussen 1996; McClelland et al. 1997; McClelland and Valiela 1998; Lake et al. 2001; Vander Zanden et al. 2005). Because synthetic industrial fertilizer is derived from atmospheric sources, it commonly has a low δ^{15}N value relative to other N sources (Macko and Ostrom 1994), resulting in relatively low δ^{15}N values in the lower portions of foodwebs of areas heavily influenced by industrial fertilizers.

In the Aral Sea Basin of Central Asia, the issue of water scarcity has drawn much attention to current irrigation and cultivation practices because of their impacts on the quantity of water reaching the sea (Micklin 2007) and concurrent problems of degraded water quality and water availability within upstream agricultural areas of the watershed (Spoor 1998; Nihoul et al. 2004). The Khorezm province, located about 200 km upstream of the present Aral Sea in Uzbekistan, is an example of such an area. Beginning in the 1950s, under control of the Soviet Union, this area was developed into a cotton monoculture to supply the Soviet textile factories. Excessive application of industrial fertilizers was common (Wegren 1989; Herrfahrdt 2004). As in other post-Soviet countries, fertilizer use declined in the mid-1990s after independence, although this decrease has not necessarily corresponded to a downward trend in surface water N concentrations (Stalnacke et al. 2003). Recent land restructuring projects have been transitioning the agricultural sector towards a system dominated by family-run farms resulting in increased interest in understanding N pathways to minimize fertilizer waste, and therefore, input costs.

The Khorezm landscape is characterized by numerous small lakes that are fed by irrigation water runoff (Fig. 1), some of which are used for aquaculture and recreational purposes. At present it is unclear how the new farm structures and agricultural practices impact water quality in these lakes. This study examined the effects of localized agricultural land use on water quality in four representative lakes in Khorezm between June 2006 and November 2008. The objectives of the study were to determine the fate and transport of N at a local scale and sources of N contributions to the lakes. Lake physical and chemical water quality parameters were evaluated in relation to land use patterns to evaluate local versus regional influences of N concentrations on the lakes. Additionally, zooplankton δ^{15}N values were used to evaluate whether the aquatic foodweb was influenced by direct inputs of N fertilizer runoff from surrounding fields.

Study area

The Khorezm province is a 6,400 km^2 region located in the northwest corner of Uzbekistan approximately

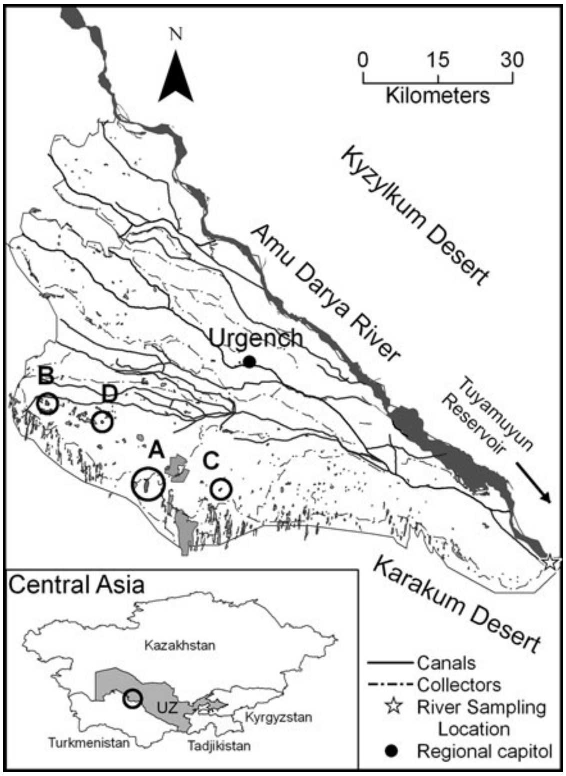

Fig. 1 Map of the study area in Khorezm, Uzbekistan and its location within Central Asia (shown *circled* on *inset* map). Study lakes (*circled*) **a** Eshan Rabat, **b** Shur, **c** Tuyrek, and **d** Khodjababa

200 km upstream of the present shore of the Aral Sea. The province is bordered on the south and west sides by Turkmenistan and on the north and east by the Amu-Darya River (Fig. 1). As part of the Amu-Darya's floodplain, roughly half of the province is suitable for irrigable agriculture. Historically, this area was largely covered by Central Asian floodplain forest (locally known as Tugai); however, beginning in the 1950s, an extended irrigation network was constructed to develop the region for cotton production. By 1991, when Uzbekistan gained independence from the former Soviet Union, Uzbekistan ranked second in the world as a cotton exporter (USDA-Foreign Agriculture Service 2009).

Cotton continues to be the principal crop grown in the region, with 46% of total agricultural land used for cotton cropping, followed by winter wheat and rice at 23 and 21%, respectively (Conrad 2006). The region has a continental climate and receives an average annual precipitation of 100 mm (Glavigdromet 2003); the Amu-Darya River provides the primary source of irrigation water. Over 9,000 km of irrigation canals supply water to crops, but only about 11% of these canals are concrete-lined (Vodproject 1999), resulting in over 40% water loss due to seepage (Martius et al. 2004). Flood irrigation is the predominant technique used to supply water to crops, and excess irrigation water is channeled into drainage canals, which provide the main inflow to the region's small lakes. None of the drainage water is currently returned to the Amu-Darya River.

Soils in Khorezm are typically alluvial, and are comprised of loam and silty loam (Rizayev 2004). A history of irrigated agriculture has led to increased soil salinity, resulting in the necessity of leaching fields up to three times each spring to flush salts from topsoils. Only low levels of nutrients are naturally found in the top 30 cm of the soil, and overall, the soils are generally considered to be of low fertility (Martius et al. 2004). Soil organic matter ranges from 10.5 to 80.5 t ha^{-1} and total N is between 1.1 and 4.9 t ha^{-1} (WARMAP and EC-IFAS 1998; ZEF 2006). Because of this soil composition, large amounts of fertilizers are used; officially 160–250 kg N ha^{-1} is applied on average to cotton, wheat, and rice each season, although actual application rates are likely higher (Djanibekov 2008). N fertilizer is applied to fields in Khorezm, predominantly in the form of urea, ammonium nitrate, ammonium sulfate and some ammonium phosphate (FAO 2003; Ibrakhimov, N. personal communication 12/28/08). Once nitrogen is applied, it may be utilized by plants, converted to nitrate by bacteria and then volatilized to the atmosphere, leached into the groundwater (or surface runoff) during irrigation, or immobilized in the topsoil. Studies in cotton fields of Uzbekistan found only 40% of the applied N was utilized by crops, while 20% was immobilized in the soil and 40% was lost to the groundwater and atmosphere (Khadjiyev and Bairov 1992; Ibrakhimov et al. 2007). In the Khorezm region, N efficiency studies have produced varied results. A recent study on cotton and wheat in Khorezm indicated that plant uptake may account for only 35% of applied synthetic N, estimated 20% N loss to groundwater, and reported a high amount of fertilizer N immobilized in the topsoil (Kienzler 2010). Another study in Khorezm found that up to 72% of applied N fertilizer is lost to the atmosphere as nitrous oxide, nitric oxide, and N gas (Scheer et al. 2008).

There are over 400 lakes scattered about the Khorezm region. Lake levels are directly influenced by agricultural activities through input from irrigation runoff and inflows from drainage collector canals, as well as from groundwater. The groundwater table in this region fluctuates between approximately 1–3 m below ground during the year, with levels generally deeper during the winter and increasing sharply with spring leaching and during the growing period of March–September (Ibrakhimov et al. 2007). Very few of the lakes in the region have outflows; lake level is largely regulated by evaporative losses and inflows from drainage canals, as well as limited input from groundwater (Scott 2009).

Four lakes, Eshan Rabat, Khodjababa, Shur, and Tuyrek, were chosen for this study to cover a range of salinity, size, and land use in the riparian zone (Table 1). Additional criteria included accessibility and the cooperation of local landowners. The selected lakes are very shallow, with average depths of only 1–2 m (Table 1), and large seasonal fluctuations in lake depth and surface area.

Methods

Water quality and stable isotope data were collected at all four lakes (Fig. 1) from June 2006 to December 2008. Water quality samples were also collected from June 2006 to May 2007 from the Amu-Darya River at an upstream location where water is first diverted from the river into Khorezm via large irrigation canals (Fig. 1). This site served as a benchmark for comparison of lake samples. Each lake was sampled monthly. During field visits, grab samples were collected at a depth of 0.3 m at the center of each lake. Physical water quality parameters, including dissolved oxygen (DO) concentration, temperature, and salinity were measured in a vertical profile at increments of 0.5 m between 9:00 and 19:00 h using a hand-held sonde (YSI, Yellow Springs, USA). The grab sample was tested for pH using a hand-held meter (Consort, Turnhout, Belgium). The hand-held sondes were calibrated before use each month according to the manufacturers' instructions. Additional samples were collected from the inflow

Table 1 Water quality parameters, area, volume, depth, and percent land use within 500 m of each lake

Parameters	Eshan Rabat	Khodjababa	Shur	Tuyrek
Area (ha)[a]	158.5	23.6	48.7	19.3
Volume (m^3)	866935	265298	770952	~192725
Avg. depth (m)	0.8	1.1	1.4	~1
Physical water quality: average (standard deviation, number of samples)				
DO (mg l^{-1})	8.6 (3.0, 22)	8.8 (1.6, 23)	8.4 (2.8, 24)	8.8 (2.8, 27)
pH	7.8 (0.6, 12)	7.7 (0.3, 10)	7.8 (0.4, 14)	7.7 (0.5, 18)
Salinity (g l^{-1})	13.7 (9.1, 22)	3.9 (1.9, 23)	3.1 (1.0, 24)	3.7 (0.9, 27)
Area (ha)[a]	158.5	23.6	48.7	19.3
Volume (m^3)	866935	265298	770952	~192725
Avg. depth (m)	0.8	1.1	1.4	~1
Percent agricultural land use within 500 m of lake				
Cotton	6.6	36.1	16.7	14.3
Wheat	0.0	11.1	24.1	17.1
Other	1.9	13.9	0.0	11.4
Total agricultural use[b]	8.5	61.1	40.7	42.9

Average depth was calculated from volumes surveyed by ZEF in November 2004 at Eshan Rabat, Khodjababa and Shur Lakes divided by lake area. Volume was not surveyed at Tuyrek Lake; lake area was multiplied by averaged depths measured during sample collection trips in the present study to approximate volume. Water quality parameters were measured once per month during the study period 2006–2008

[a] Area calculated using ESRI Arcmap software (Redlands, CA)

[b] Other crops grown in the region include rice, sorghum, and vegetables

drainage canal approximately 500 m upstream from Eshan Rabat Lake between April and August 2008 to monitor N contributions from surface inflows.

Water samples were immediately filtered in the laboratory in Urgench upon return from the field and kept frozen until analysis for nutrient concentrations. All samples were analyzed for ammonium (NH_4^+), nitrate (NO_3^-), and nitrite (NO_2^-) concentrations at the Hydrometeorological Research Institute (NIGMI) in Tashkent, Uzbekistan using photometric methods (indophenol for ammonium, Griss reagent for nitrite, and reduction in cadmium column followed by Griss reagent for nitrate) with a Spectrophotometer Specord 50 (Analytik, Jena, Germany) (Semenov 1977).

Detection limits were 0.005, 0.0005, and 0.001 mg N l^{-1} for ammonium, nitrate, and nitrite, respectively. Preliminary sample analysis of selected samples showed that organic N levels were very low; therefore, only the dissolved inorganic N compounds were measured as part of this study. Replicates (two separate samples collected simultaneously and analyzed individually) were analyzed for 11% of all lake samples, and 67% of the replicates were within 15% of one another. Duplicates (one sample homogenized, separated, and analyzed twice) were analyzed for 4% of lake samples, 75% of which showed a difference of less than 15%. While error levels may appear high, absolute errors were low due to low N concentrations; 72% of replicates had concentrations of less than 0.1 mg N l^{-1}. Mann–Whitney tests showed that replicate and duplicate concentrations were significantly similar (0.85 and 1.00 correlation, respectively) at a 95% confidence level ($p < 0.05$). Four laboratory matrix spikes were performed on all three N compounds with recovery at over 98%. Blanks were analyzed for 10% of samples and were always below detection limits.

Zooplankton samples were collected 6–8 times during the study period by pulling a Jeddy net (mesh size 76 μm, 18 cm mouth diameter) through the water column a minimum of five times. The zooplankton samples were immediately preserved in 70% ethanol. Zooplankton samples were dried for 24 h at 60°C in preparation for stable isotope analysis. If enough biomass was available, approximately two milligrams of each sample was placed in 5 × 9 mm tin cups. Otherwise, all available biomass was placed a tin cup for analysis. The samples were analyzed at the University of Nevada Reno Stable Isotope Laboratory using a Eurovector (Milan, Italy) elemental analyzer interfaced to a Micromass (Manchester, UK) IsoPrime continuous-flow stable-isotope ratio mass spectrometer.

The $\delta^{15}N$ value for each sample is expressed in parts per thousand (‰) computed as $\delta^{15}N = [(Rsample/Rstandard) - 1] * 1000$, where the standard is atmospheric nitrogen and $R = {}^{15}N/{}^{14}N$. For comparison with lake zooplankton samples, a sample of industrial N fertilizer applied to local fields during August 2006 was also analyzed. Some zooplankton $\delta^{15}N$ values were removed from the data set because the N_2 peak heights were less than 1 nA, indicating that not enough biomass was present during isotope analysis.

Conrad et al. (2007) used remote sensing techniques to develop land use maps for the entire Khorezm province during the 2004 growing season based on NASA MODIS data. Using ESRI ArcMap software (Redlands, USA), a buffer was created to determine lake area, the percent of land used for each individual agricultural crop and total agricultural use within 500 m of each lake (Table 1). In Khorezm, industrial N fertilizer is applied to cotton, wheat, and rice crops at least three times during their growing periods (Kienzler 2010). Due to state control of cotton and wheat production and fertilizer subsidies, the area devoted to these primary crops has been relatively constant between years, and fertilizer application has been fairly standard across the province for each crop during recent years (Kienzler 2010). Monthly application of fertilizer to each crop was therefore determined by multiplying the area devoted to each crop within 500 m of each lake by the N fertilizer mass generally applied to that specific crop during its expected growth stage in a particular month. Ammonium, nitrate, and nitrite concentrations were summed to dissolved inorganic nitrogen (DIN). The total mass of DIN in each lake was calculated by multiplying the water DIN concentration by lake volume (Table 1). For comparison with field fertilizer loads, monthly DIN from 2006 to 2008 was averaged for each month of the growing season (March–September).

Results

During the 30-month study period in 2006–2008, DIN concentrations in all four lakes were dominated

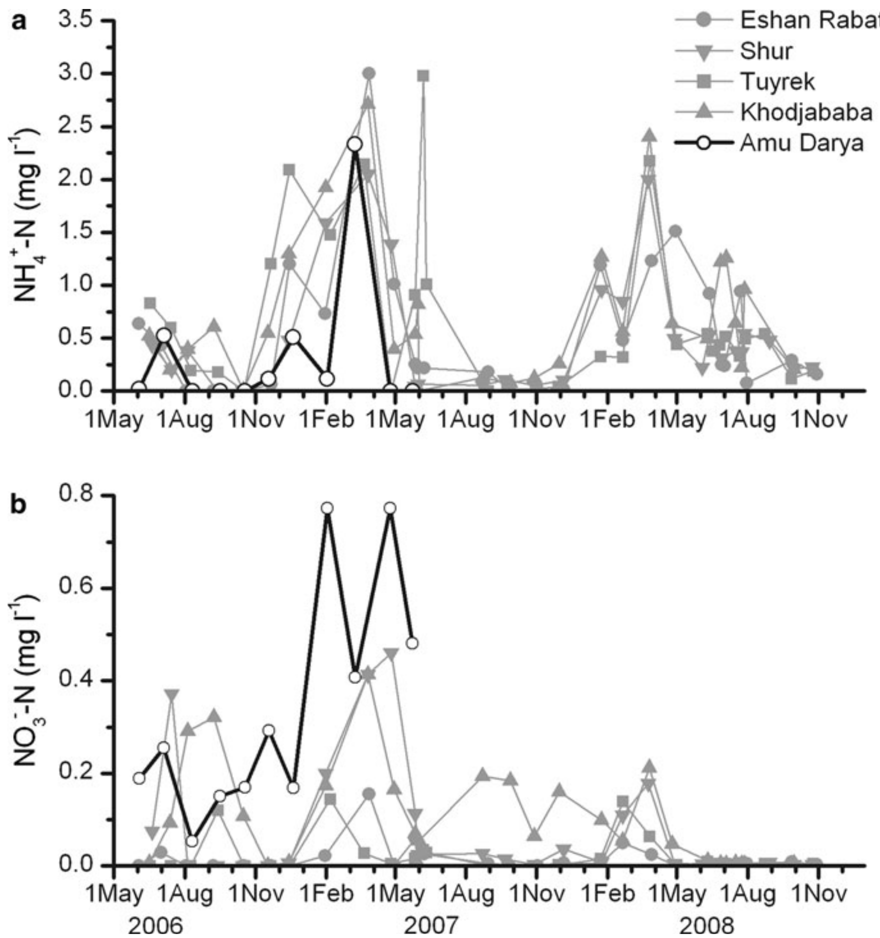

Fig. 2 **a** Ammonium and **b** nitrate concentrations in four study lakes in Khorezm, Uzbekistan, between June 2006 and November 2008. Measurements could not be collected in all lakes in January 2007 due to ice covering some of the lakes, and in July 2007. Amu-Darya River concentrations were collected from June 2006 to May 2007. Connecting *lines* are presented for increased visualisation only

by ammonium. Ammonium concentrations were highest during the winter and spring, with lower concentrations in the summer and fall (Fig. 2a). Despite differences in land use surrounding the lakes (Table 1), ammonium patterns were similar between the lakes (Fig. 2a). Ammonium concentrations in the Amu-Darya River showed a pattern similar to that seen in the lakes, although the concentrations in several lakes were slightly higher than that of the river water.

Nitrate concentrations were relatively low. Peak concentrations were observed in winter–spring for some of the lakes, although a seasonal influence was not apparent (Fig. 2b). Nitrate in the Amu-Darya River was higher than in any of the lakes from November 2006 to June 2007 (Fig. 2b). During the period June 2006 to December 2008, the maximum and average ammonium concentrations over all lakes were 3.00 and 0.62 mg N l^{-1}, respectively. For the same period, nitrate concentrations were approximately an order of magnitude lower, with a maximum concentration of 0.46 mg N l^{-1} and an average of 0.05 mg N l^{-1}. Nitrite concentrations were low, with a maximum value of 0.057 mg l^{-1} observed in any of the study lakes. See Appendix for concentrations by lake.

Monthly estimates of N fertilizer use for 2006–2008 for fields within 500 m of each lake were highest in July and August across all lakes, with an average of 4880 and 3780 kg N applied during those 2 months, respectively (Fig. 3). Water column DIN concentrations calculated from estimated lake volumes were much lower compared to the amount of N applied to nearby fields, although they fell within the expected range of 20–40% of applied N lost to groundwater for some months.

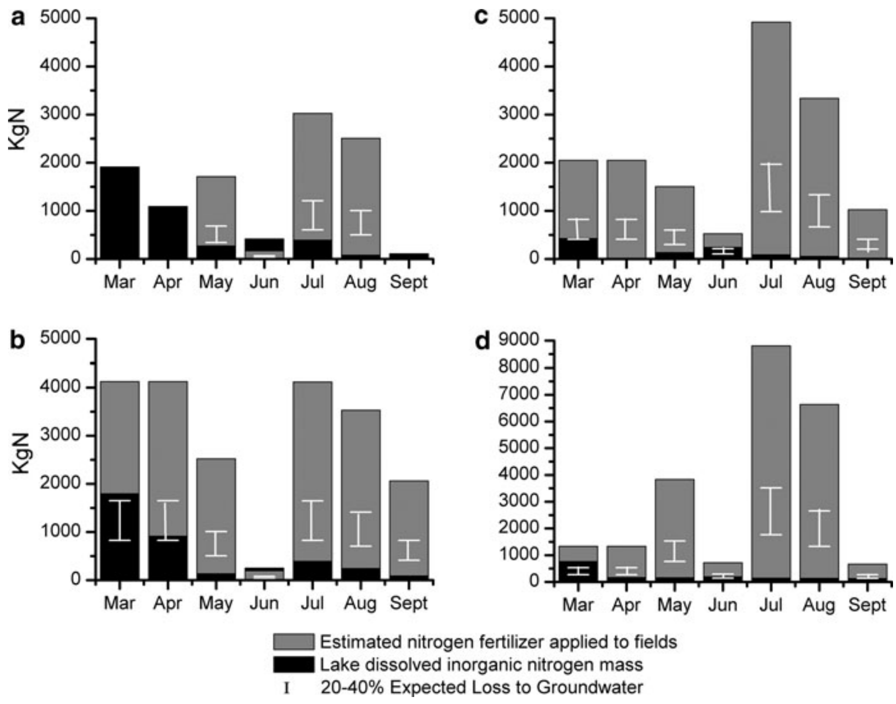

Fig. 3 Average estimated synthetic nitrogen fertilizer loads applied to the fields surrounding **a** Eshan Rabat, **b** Shur, **c** Tuyrek, and **d** Khodjababa lakes in Khorezm, Uzbekistan, and corresponding average dissolved inorganic nitrogen mass measured within the lakes for 7 months in 2006–2008. Literature values of 20–40% applied nitrogen to fields and subsequently lost to groundwater (Khadjiyev and Bairov 1992; Ibrakhimov et al. 2007; Kienzler 2010) are indicated by white bars for comparison

Estimated lake water N masses were between 0 and 294 kg N in the four lakes for August 2006 and August 2007. A comparison of Figs 2 and 3 indicates that lake N concentrations were generally low during the summer months when the highest loads of fertilizer are applied.

Physical water quality field measurements generally showed well-mixed conditions throughout the water column. During most months, water column DO measurements indicated oxygenated waters throughout the water column (Fig. 4). On occasions when the sonde touched the lake sediment, DO readings were generally below 2.0 mg l^{-1}. In addition, a strong sulfuric smell was always observed when lake sediments were disturbed, indicating anoxic sediments. No general seasonal trends in DO were observed at all lakes; however, lowest water column DO concentrations occurred during the hot summer months and in winter when the lakes were ice covered (Fig. 4). Although water temperatures in all four study lakes were similar at all times of the year, low DO was observed in Tuyrek Lake in summer 2007 and in Shur and Eshan Rabat Lakes in summer 2008. During the winter of 2007–2008, all lakes were ice covered between mid-December and February, and anoxic conditions were observed in Shur and Eshan Rabat Lakes during that time.

The predominant source of water to most lakes in Khorezm is from ungaged irrigation drainage canal inputs, making it difficult to quantify the contribution of N from inflows. Unlike most of the Khorezm lakes, there were few agricultural fields around the shore of Eshan Rabat Lake, and the lake received surface inflow only from one canal, which is one of the largest drainage canals in the Khorezm province. Ammonium concentrations sampled 4–6 times in summer 2008 in the large drainage canal that entered Eshan Rabat Lake showed inconclusive patterns compared with lake concentrations (Fig. 5).

Because synthetic fertilizer is derived from atmospheric sources, and atmospheric N is the reference standard for $\delta^{15}N$ with a value of 0‰, zooplankton would be expected to exhibit correspondingly low $\delta^{15}N$ values if they utilized N sources from fertilizers that contained synthetic fertilizer. The fertilizer sample had a $\delta^{15}N$ value of 1.42‰, indicating it was derived from a synthetic N source. Although the limited zooplankton samples and variation in

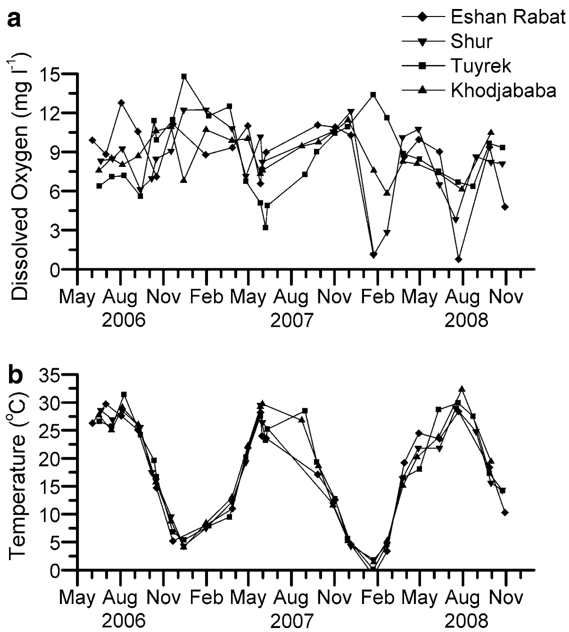

Fig. 4 **a** Dissolved oxygen concentrations and **b** water temperatures at a depth of 0.5 m in the study lakes in 2006–2008. Connecting *lines* are presented for increased visualisation only and are not meant to represent what the actual values would have been

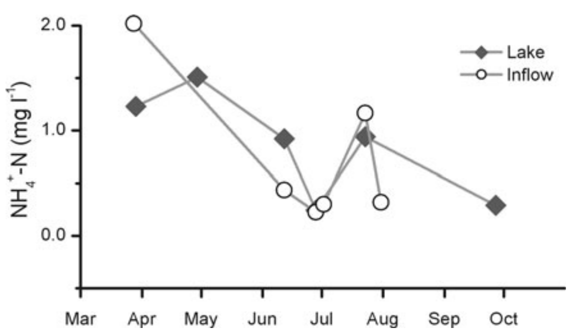

Fig. 5 Ammonium concentrations for Eshan Rabat Lake and the drainage canal that provides inflow to the lake in Khorezm, Uzbekistan during April–October 2008. Connecting lines are presented for increased visualisation only

observed species made it difficult to discern clear trends (Fig. 6), zooplankton $\delta^{15}N$ values were not lower throughout the months (March–August) in which fertilizer was applied to fields (Fig. 3) and then potentially available to the lakes as irrigation runoff. A wide range of zooplankton $\delta^{15}N$ values was observed, with values between 2.3‰ (Tuyrek Lake

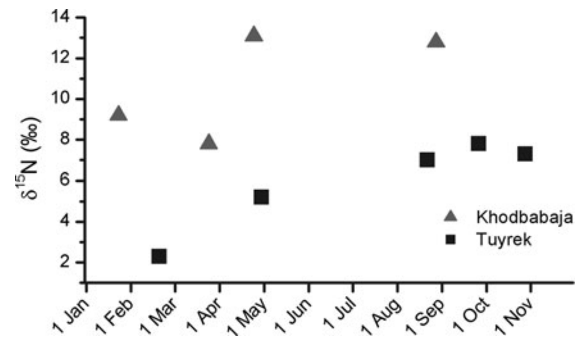

Fig. 6 Zooplankton $\delta^{15}N$ values for two study lakes in Khorezm, Uzbekistan from January to November 2008

February 2008) and 16.7‰ (Eshan Rabat Lake May 2007).

Discussion

The DIN concentrations in all study lakes were dominated by ammonium throughout the year, and highest concentrations were observed in the winter and early spring, despite heavy application of synthetic N fertilizer to surrounding fields throughout the summer. Many studies suggest that high ammonium concentrations typically result from anoxic lake conditions (e.g. Moore et al. 1992; Rysgaard et al. 1994; Beutel 2006). However, aerobic conditions were observed in the water columns of three of the lakes in 2007 and two of the lakes in 2008 during summer months despite high water temperatures, which may suggest an outside source of N. Only Tuyrek Lake showed low DO in June 2007, which did correspond to a spike in ammonium in that lake at that time. It must be noted that field samples were collected monthly, and periods of higher DO or anoxia between visits may have occurred, potentially creating pulses of ammonium pools in the water column that our study did not detect. Further, it is unknown whether algae in the lakes may have caused diel swings in DO, and therefore ammonium release and conversion to nitrate in the lakes.

Several studies outside of the study region have shown clear connections between aquatic biota and watershed land use (Harrington et al. 1998; Vander Zanden et al. 2005; Borderelle et al. 2009). Specifically, agricultural land use in the riparian zone has been shown to correlate with higher N concentrations in lakes and influence stable isotope values of aquatic communities relative to undeveloped areas. However, in the study lakes nutrient concentrations did not show an immediate response to field N applications within the province, despite direct runoff from the fields into the drainage canals that provided inflow to the lakes. Although estimated losses of agricultural N loads to groundwater and the atmosphere were 20–40% (Khadjiyev and Bairov 1992; Ibrakhimov et al. 2007), overall lake water DIN mass was over an order of magnitude lower than the amount applied to nearby fields and roughly two orders of magnitude lower during the summer growing season when the majority of fertilizer was applied. Furthermore, zooplankton δ^{15}N did not appear to respond to N fertilizer input during the growing season. Ammonia volatilization from fields may have resulted in lake input water δ^{15}N values higher than that of the synthetic fertilizer applied to the fields (Kreitler 1979; Kaplan and Magaritz 1986), making it difficult to discern the source of N utilized by zooplankton.

In basins where agriculture is the primary land use, nitrate is commonly the primary N species of concern (Addiscott 1996). For example, in Kesterson National Wildlife Refuge, located in the semi-arid San Joaquin Valley of California, ponds fed exclusively by irrigation runoff water accumulated nitrate concentrations of over 40 mg l^{-1} (Presser and Barnes 1985). Similarly, Domagalski et al. (2008) concluded that irrigation of fields by imported river water resulted in high nitrate loads accumulating in the groundwater and in downstream surface waters. In the Khorezm study area, groundwater levels are relatively shallow throughout the cropping season, with an average October water table level of only 182 cm below ground. With spring leaching, the water table rises rapidly, and April water table levels in Khorezm average 125 cm below ground (Ibrakhimov et al. 2007). Based on the shallow groundwater table and high levels of synthetic fertilizer used, high levels of nitrate would have been expected in the drainage canals flowing into the lakes. However, based on the previous studies in Khorezm, it is possible that a high percentage of the fertilizer not used by crops is either immobilized in the topsoil (Kienzler 2010) or volatilized (Scheer et al. 2008).

Slug tests conducted in summer 2008 at Khodjababa and Tuyrek Lakes (Scott 2009) estimated high hydraulic conductivities of 0.8–15.4 m d^{-1} in the vicinity of these lakes, but concluded that groundwater constituted only a minor portion of the water balance of the lakes. The DIN concentration of groundwater in the immediate vicinity of the lakes was not measured, but previous studies in Khorezm indicated that vertical conductivity is greater than horizontal conductivity, and that the top layer of soil has lower permeability than the sandy soils beneath (Ibrakhimov 2004; Forkutsa 2006). Kienzler (2010) found that up to 50% of applied N fertilizer was found in topsoils during the growing season, and that high nitrate levels were only found in the groundwater directly following irrigation events in the Khorezm region. Therefore, nitrate may not reach the lakes, despite high application rates to the landscape surrounding the lakes.

Upstream of Khorezm, the Amu-Darya River flows along the border between Uzbekistan and Turkmenistan and into Tuyamuyun Reservoir. Along this upstream reach, water quality in the river is significantly degraded in terms of salinity and organic pollutants due to return waters from irrigated areas (Dukhovny and Stulina 2001), especially during the period of low flow from October through March (Crosa et al. 2006). Although the reservoir was not sampled during the study period, the high ammonium observed in river water collected at a short distance downstream of the reservoir outlet during some months may also have resulted from reservoir nutrient cycling and the release of water from the bottom of the reservoir. Stagnant conditions in the reservoir during winter, combined with possible ice cover, could account for the high ammonium concentrations observed in the river when water was released to irrigation canals in early spring. Cold air and water temperatures at this time of year would allow ammonium to stay in solution, instead of converting immediately to nitrate, as would be expected during the summer. Although none of the Amu-Darya River water should have entered the lakes directly, a previous study showed that water applied during flood irrigation for spring leaching can flow into drainage canals without extensive contact with soils (Veldwisch 2008), which would result in inflow to the lakes with ammonium concentrations similar to those observed in the river. This ammonium contribution from the river may account for the high ammonium concentrations during winter–spring of 2007, and could also be an alternative source of N for lake zooplankton.

Summary and Conclusions

This study examined possible connections between agricultural land use and water quality in several lakes of the Khorezm province, in the post-Soviet state of Uzbekistan. Poor soils and state-mandated cotton crops have resulted in heavy fertilizer use (particularly N fertilizers) across the region. High ammonium concentrations were observed during winter and early spring, while low nitrate concentrations were found year-round, possibly due to immobilization of N within the soil column or volatilization directly from the agricultural fields. A possible explanation for the observed N trends is that Amu-Darya River water, which is used to irrigate crops, contributed ammonium pulses to the lakes. More frequent sampling, especially during spring months, and the ability to monitor groundwater and inflow water throughout the year may yield a clearer picture of the inputs driving the nutrient cycles in these lakes. Additionally, an understanding of nutrient dynamics in the upstream reservoir, which determine inflow nutrient concentrations from the Amu-Darya River, would add clarification to N sources at the regional scale.

Acknowledgments This study was funded by North Atlantic Treaty Organization (NATO) Science for Peace Grant 982159 and a student Fulbright Fellowship. We appreciate the help of Marhabo Bekchanova, Diana Shermetova, Nodir Mullaboev, Elena Ginatullina, Dilorom Fayzieva, and Julian Scott in Uzbekistan. We are grateful for the use of lake surveys completed by ZEF intern Bjoern Kaiser. Our thanks also to the ZEF/UNESCO Khorezm Project for making this work possible, especially Liliana Sinn. Reviews by Tim Rowe, Nancy Alvarez, Lari Knochenmus, and Glenda Singleton at the USGS in Carson City, as well as two anonymous reviewers were very helpful. This paper is dedicated to Akmal Nigmatjanov, whose enthusiasm and charisma continue to inspire us.

Appendix

See Table 2.

Table 2 Minimum, maximum, average, and median nitrogen species concentrations in the study lakes between June 2006 and November 2008

	Lake	Shur	Tuyrek	Eshan Rabat	Khodjababa	Amu Darya River
	Number of samples	29	30	28	28	11
Ammonium (mgN l^{-1})	Minimum	<0.01	<0.01	<0.01	<0.01	<0.01
	Maximum	2.05	2.98	3.00	2.71	2.33
	Average	0.50	0.68	0.55	0.73	0.33
	Median	0.37	0.44	0.25	0.54	0.22
Nitrate (mgN l^{-1})	Minimum	<0.01	<0.01	<0.01	<0.01	0.05
	Maximum	0.46	0.14	0.16	0.41	0.77
	Average	0.07	0.02	0.02	0.10	0.34
	Median	0.01	<0.01	0.01	0.06	0.26
Nitrite (mgN l^{-1})	Minimum	<0.01	<0.01	<0.01	<0.01	<0.01
	Maximum	0.02	0.04	0.06	0.02	0.01
	Average	<0.01	<0.01	<0.01	<0.01	<0.01
	Median	<0.01	<0.01	<0.01	<0.01	<0.01

References

Addiscott T (1996) Fertilizers and nitrate leaching. Issues Environ Sci Technol 5:1–26

Agriculture Food Organization (FAO) (2003) Fertilizer use by crop in Uzbekistan. United Nations, Rome

Beutel M (2006) Inhibition of ammonia release from anoxic profundal sediments in lakes using hypolimnetic oxygenation. Ecol Eng 28:271–279

Biswas A (1993) Water for agricultural development: opportunities and constraints. Int J Water Resour Dev 9(1):3–12

Borderelle A-L, Gerdeaux D, Giraudoux P et al (2009) Influence of watershed's anthropogenic activities on fish nitrogen and carbon stable isotope ratios in nine French lakes. Knowl Managt Aquatic Ecosyst 392:1–13

Cabana G, Rasmussen J (1996) Comparison of aquatic food chains using nitrogen isotopes. Proc Natl Acad Sci USA 93:10844–10847

Carpenter S, Caraco N, Correll D et al (1998) Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecol Appl 8:559–568

Conrad C (2006) Remote sensing based modeling and hydrological measurements to assess the agricultural water use in the Khorezm region (Uzbekistan). Dissertation, University of Wuerzburg

Conrad C, Dech S, Hafeez M et al (2007) Mapping and assessing water use in a Central Asian irrigation system by utilizing MODIS remote sensing products. Irrig Drain Sys. doi:10.1007/s10795-007-9029-z

Cosgrove W, Rijsberman F (2000) World water vision: making water everybody's business. Earthscan, London

Crosa G, Froebrichb J, Nikolayenkoc V et al (2006) Spatial and seasonal variations in the water quality of the Amu Darya River (Central Asia). Water Res 40:2237–2245

Djanibekov N (2008) A micro-economic analysis of farm restructuring in the Khorezm region, Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Domagalski J, Ator S, Coupe R et al (2008) Comparative study of transport processes of nitrogen, phosphorus, and herbicides to streams in five agricultural basins, USA. J Environ Qual 37:116–1158

Dukhovny V, Stulina G (2001) Strategy of transboundary return flow use in the Aral Sea basin. Desalination 139:299–304

Forkutsa I (2006) Modeling water and salt dynamics under irrigated cotton with shallow groundwater in the Khorezm region of Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Glavigdromet (2003) Meteo data of the Republic of Uzbekistan. Main Administration on Hydrometeorology (Glavgidromet) at the Cabinet of Ministers of the Republic of Uzbekistan, Tashkent

Harrington R, Kennedy B, Chamberlain C et al (1998) 15 N enrichment in agricultural catchments: field patterns and applications to tracking Atlantic salmon (Salmo salar). Chem Geol 147:281–294

Herrfahrdt E (2004) Landwirtschaftliche Transformation, Desertifikation und nachhaltige Ressourcennutzung: Fallbeispiel Usbekistan. DIE Studies No. 2. Deutsches Institut für Entwicklungspolitik (DIE), Bonn

Howarth R, Billen G, Swaney D et al (1996) Regional nitrogen budgets and riverine N and P fluxes for the drainage to the North Atlantic Ocean: natural and human influences. Biogeochemistry 35:75–139

Ibrakhimov M (2004) Spatial and temporal dynamics of groundwater table and salinity in Khorezm (Aral Sea Basin), Uzbekistan. Dissertation, ZEF/Rheinische Friedrich-Wilhelms-Universität Bonn

Ibrakhimov M, Khamzina A, Forkutsa I et al (2007) Groundwater table and salinity: spatial and temporal distribution and influence on soil salinization in Khorezm region (Uzbekistan, Aral Sea Basin). Irrig Drainage Syst 21(3–4): 219–236. doi:10.1007/s10795-007-9033-3

Kaplan N, Magaritz M (1986) A nitrogen-isotope study of the sources of nitrate contamination in groundwater of the pleistocen coasal plain aquifer, Israel. Water Res 20(2): 131–135

Khadjiyev T, Bairov A (1992) Fertilizer-nitrogen and nitrification inhibitors in cotton production. FAN Publishing House, Tashkent

Kienzler KM (2010) Improving the nitrogen use efficiency and crop quality in the Khorezm region, Uzbekistan. Ecol Dev Ser Bd 72:265

Kreitler C (1979) Nitrogen-isotope ratio studies of soils and groundwater nitrate from alluvial fan aquifers in Texas. J Hydrol 42:147–170

Lake J, McKinney R, Osterman F et al (2001) Stable nitrogen isotopes as indicators of anthropogenic activities in small freshwater systems. Can J Fish Aquat Sci 58:870–878

Macko S, Ostrom N (1994) Pollution studies using stable isotopes. In: Lajtha K, Michener R (eds) Stable isotopes in ecology. Blackwell Scientific Pub, Oxford

Martius C, Lamers JPA, Wehrheim P et al (2004) Developing sustainable land and water management for the Aral Sea Basin through an interdisciplinary research. In: Seng V, Craswell E, Fukai S (eds) Water in agriculture, ACIAR Proceedings No. 116 Canberra, Australia

McClelland J, Valiela I (1998) Linking nitrogen in estuarine producers to land-derived sources. Limnol Oceanogr 43:577–585

McClelland J, Valiela I, Michener R (1997) Nitrogen-stable isotope signatures in estuarine food webs: a record of increasing urbanization in coastal watersheds. Limnol Oceanogr 42(5):930–937

Micklin P (2007) The Aral sea disaster. Annu Rev Earth Planet Sci 35:47–72

Moore P, Reddy K, Graetz D (1992) Nutrient transformations in sediments as influenced by oxygen supply. J Environ Qual 21:387–393

Nihoul J, Zavialov P, Micklin P (eds) (2004) Dying and dead seas, climatic versus anthropic causes. Kluwer Academic Publisher, Dordrecht

Nixon S (1995) Coastal marine eutrophication: a definition, social causes, and future consequences. Ophelia 4(1): 199–219

Nolan B, Ruddy B, Hitt K et al (1997) Risk of nitrate in groundwaters of the United States—a national perspective. Environ Sci Technol 31:2229–2236

Oenema O, Roest C (1998) Nitrogen and phosphorous losses from agriculture into surface waters; the effects of policies

and measures in the Netherlands. Water Sci Tech 37(2):19–30
Oenema O, van Liereb L, Schoumans O (2005) Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in the Netherlands. J Hydrol 304:289–301
Presser T, Barnes I (1985) Dissolved constituents including selenium in waters in the vicinity of Kesterson National Wildlife Refuge and the west Grassland, Fresno and Merced Counties, California. USGS Water Resources Investigations Report 85-4220. USGS, Denver, CO
Rizayev F (2004) Soil texture of irrigated soils of Khorezm oasis (in Russian). Proceedings of soil science and agrochemistry in the XXI century, Tashkent, 9–10 October 2003
Rysgaard S, Risgaard-Petersen N, Sloth N et al (1994) Oxygen regulation of nitrification and denitrification in sediments. Limnol Oceanogr 39(7):1643–1652
Scheer C, Wassmann R, Kienzler K et al (2008) Nitrous oxide emissions from fertilized, irrigated cotton (Gossypium hirsutum L) in the Aral Sea Basin, Uzbekistan: influence of nitrogen applications and irrigation practices. Soil Biol Biochem 40:290–301
Scott J (2009) Understanding the hydrology of two small arid-climate lakes in Khorezm, Uzbekistan. Master's thesis, University of Nevada, Reno
Semenov A (ed) (1977) Manual on chemical analysis of terrestrial surface water. Gidrometeoizdat, Leningrad (in Russian)
Shannon E, Brezonik P (1972) Relationships between lake trophic state and nitrogen and phosphorous loading rates. Environ Sci Technol 6(8):719–725
Spoor M (1998) The Aral Sea Basin crisis: transition and environment in former Soviet Central Asia. Dev Chang 29(3):409–435
Stalnacke P, Grimvall A, Libiseller C et al (2003) Trends in nutrient concentrations in Latvian rivers and the response to the dramatic change in agriculture. J Hydrol 283: 184–205
USDA-Foreign Agriculture Service (2009) Cotton Production Ranking, 1991. National Cotton Council of America. http://www.cotton.org/econ/cropinfo/cropdata/rankings.cfm. Cited 23 Oct 2009
Vander Zanden MJ, Vadeboncoeur Y, Diebel M et al (2005) Primary consumer stable nitrogen isotones as indicators of nutrient source. Environ Sci Technol 39:7509–7515
Veldwisch GJ (2008) Cotton, rice and water: the transformation of agrarian relations, irrigation technology and water distribution in Khorezm, Uzbekistan. Dissertation, University of Bonn, Centre for Development Research (ZEF)
Vitousek PM, Aber JD, Howarth RW et al (1997) Human alteration of the global nitrogen cycle: sources and consequences. Ecol Appl 7:737–750
Vodproject (1999) Production association, the Ministry of Agriculture and Water Resource Management. Annual report, Tashkent, Uzbekistan
WARMAP and EC-IFAS (1998) Water use and farm management survey (WUFMAS)—Agricultural year 1998—annual report. Water Resources Management and Agricultural Production in the Central Asian Republics (WARMAP-2), Executive Committee Interstate Fund for the Aral Sea (EC-IFAS), TACIS Project
Wegren S (1989) The half reform: Soviet agricultural policy and private agriculture, 1976–1989. Dissertation, Columbia University
ZEF (2006) Literature review of soils in Khorezm. Internal Report, Urgench, Uzbekistan