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MASS BALANCE FOR WASTEWATER NITROGEN IN THE CENTRAL ARIZONA–PHOENIX ECOSYSTEM

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Abstract—A complete nitrogen mass balance for all wastewater generated in the Central Arizona–Phoenix ecosystem was developed using data from the 18 largest wastewater treatment plants (99% of flow). Components included total N in raw wastewater, denitrification in wastewater treatment plants, biosolids production, and effluent (reuse, recharge, and discharge). Denitrification and biosolids production remove 81% of wastewater N. Nearly all biosolids are recycled to cotton fields within the ecosystem. Most effluent is recycled within the ecosystem. As the result of wastewater management practices developed to reuse wastewater, wastewater N is either deliberately volatilized or accumulates within the system; only 4% of the original wastewater N is exported via the Gila River. © 2000 Elsevier Science Ltd. All rights reserved

Key words—nitrogen, denitrification, wastewater, nitrogen mass balance

INTRODUCTION

Nitrogen pollution is ubiquitous and has serious consequences. Groundwater in many parts of the country, and even some surface waters, often has nitrate concentrations in excess of US drinking water standards (10 mg NO_3–N/l) (Baker, 1992). Elevated concentrations of ammonia (>0.1 mg NH_3–N/l) are toxic to fish. Nitrogen is frequently a limiting nutrient in aquatic ecosystems, particularly in estuaries, but excessive inputs of N can result in an overabundance of algae with deleterious impacts (anoxia of bottom waters; red tides, etc.).

We require nitrogen (in the form of protein) for survival, but the process of obtaining N is not very efficient. Nitrogen fertilizer applied to agricultural fields or urban lawns in excess of crop requirements becomes a pollutant; additional losses of N occur when crops are fed to animals, which excrete N. In modern cities, N enters sewers as human excretion (mostly urine), ground food from garbage disposals and N-containing chemicals (detergents, etc.). Nitrogen removal by conventional wastewater treatment is typically ~50%. Modern nitrification and denitrification (NDN) processes remove more nitrogen, but treatment efficiencies in well-run NDN facilities are still only ~85%. Finally, N_2 fixation by internal combustion engines and other combustion processes may contribute substantially to the nitrogen loading of aquatic ecosystems (Puckett 1994). Because nitrogen pollution arises from various sources and is difficult to control, it is necessary to develop a comprehensive view of N cycling in the entire ecosystem in order to develop effective management strategies to control it (Vitousek *et al.*, 1997).

This paper develops a nitrogen budget for wastewater in the Central Arizona–Phoenix (CAP) ecosystem that includes Phoenix, Arizona and the surrounding landscape. It is part of an effort to develop a comprehensive nitrogen balance for the entire ecosystem (Baker *et al.*, 1999, submitted). The study is part of one of the first of two long-term urban ecosystem studies in NSF's long-term ecological research (LTER) program. The wastewater nitrogen balance will be put into perspective of a whole-system N balance to determine how wastewater management practices affect whole-system nitrogen export and accumulation. The wastewater N balance also points to ways to improve utilization of wastewater N and reduce groundwater N accumulation.

STUDY AREA

The CAP ecosystem is the 12,000 km^2 watershed that encompasses the Phoenix, Arizona metropolitan area. Rivers entering the watershed include the Salt, Verde, Gila, Agua Fria, and Hassayampa (Fig. 1). These converge into the Gila River, which is the sole surface water export route from the

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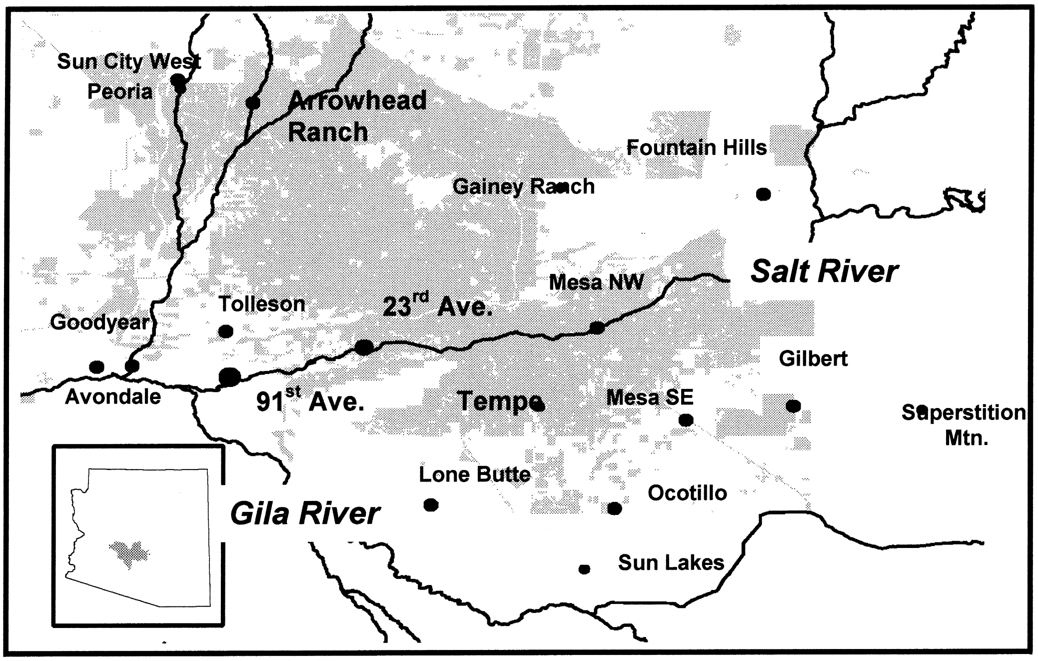

Fig. 1. Map of the CAP ecosystem, showing the location of wastewater treatment plants. Inset shows location of the study area in Arizona.

watershed. Upstream dams on the Salt, Verde, and Agua Fria rivers form storage reservoirs for the metropolitan water supply. This water is transmitted through canals; river channels running through the metro area are dry much of the year. Except during flooding periods, flow exiting the watershed in the Gila River is composed primarily of treated municipal wastewater and irrigation return flow.

About 80% of the municipal wastewater in the metro area is treated by two large facilities (the 91st Avenue and 23rd Avenue plants) located near the Salt River (Fig. 1). These, together with 16 other treatment plants, produce 97% of the total municipal wastewater generated in the ecosystem (Table 1; Fig. 2). Five large plants have no on-site sludge treatment facilities but instead route their sludge via sewers to the 91st Avenue treatment plant.

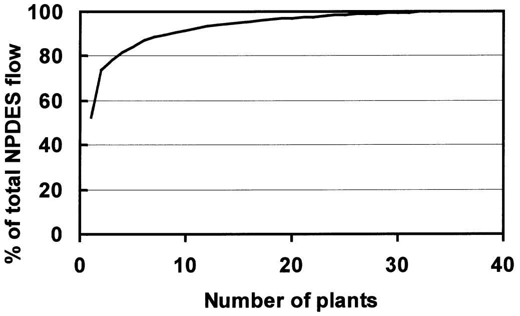

Fig. 2. Cumulative flow of wastewater treatment plants in the CAP ecosystem.

Because water is in short supply, most wastewater produced in the CAP ecosystem is reused or recharged to depleted aquifers for later use. Treated wastewater effluent has been reused for agricultural irrigation in the Phoenix metro area since the first wastewater treatment plant was constructed in the 1920s (Carollo Engineers, 1968). Effluent is also used for many turf areas (parks, golf courses, and greenways). A smaller amount is used to fill man-made lakes. Wastewater is also recharged to depleted aquifers through surface infiltration basins or vadose zone injection systems. The 23rd Avenue plant discharges some of its effluent directly to the Salt River during the non-irrigation season. The 91st Avenue treatment plant sends some of its effluent directly to the Palo Verde nuclear generating station, where it is used for cooling water. The waste cooling water is evaporated in ponds designed to contain salts permanently. The rest of the effluent from the 91st Avenue plant is discharged to the Salt River, where it comprises most of the river flow during the summer. During the irrigation season, most of this effluent is diverted to the Buckeye irrigation district several miles downstream from the discharge point.

Most wastewater treatment plants in the ecosystem use the activated sludge process. In 1997, eleven of the 18 wastewater treatment plants include nitrification-denitrification (NDN) in their treatment processes in order to meet the permit requirements (10 mg N/l) for reuse or recharge.

Table 1. Wastewater treatment facilities included in the study. Data reflects conditions in 1997

Facility	Average flow (mgd)	Treatment	Denitrify	Effluent disposal	Solids disposal
91st Avenue	143.4	Activated sludge	Yes	64% to Salt River, 36% to Palo Verde	Land application
23rd Avenue	56.4	Activated sludge	Yes	65% to irrigation, 35% to Salt River	Land application
Tolleson	11.6	Trickling filter	No	84% to Palo Verde, 16% to Salt River	Land application
Lone Butte	8.0	Aerated Lagoons	No	100% to irrigation	None
Ocotillo	7.5	Activated sludge	Yes	100% to irrigation and recharge	Landfill
Gilbert	4.6	Activated sludge	Yes	100% to irrigation and recharge	To 91st Avenue
Mesa NW	3.6	Activated sludge	Yes	78% recharged, 22% to Salt River	To 91st Avenue
Arrowhead Ranch	2.8	Activated sludge	No	100% to irrigation	To 91st Avenue
Sun City West	2.1	Trickling filter + aerated lagoons	No	100% recharged	Land application
Mesa SE	1.8	Trickling filter	No	100% to irrigation	To 91st Avenue
Avondale	1.6	Activated sludge	Yes	100% to Agua Fria River	Land application
Goodyear	1.4	Activated sludge	Yes	100% to recharge and irrigation	Land application
Fountain Hills	1.3	Activated sludge	No	100% to irrigation	Landfill
Sun Lakes	0.8	Activated sludge	Yes	100% to irrigation	Landfill
Gainey Ranch	0.8	Activated sludge	No	100% to irrigation	To 91st Avenue
Tempe	0.7	Activated sludge	Yes	44% to irrigation, 56% to Salt River	To 91st Avenue
Superstition Mountain	0.5	Activated sludge	Yes	100% to Weekes Wash	None
Peoria	0.2	Activated sludge	Yes	100% recharged	To Tolleson

METHODS

Inflow

An extensive study of the municipal sewage treatment systems that discharge effluent or sludge to the 91st Avenue treatment plant showed that the average N content of raw wastewater was 46 mg/l (Greeley and Hansen Engineers, 1998). We used this concentration to represent all raw wastewater throughout the metropolitan area.

Effluent N

Initially, data on flows and chemical concentrations were obtained from state permit records for the year 1997. The method of effluent disposal dictates the type of permit required. Any discharge that enters a river requires a national pollutant discharge elimination system (NPDES) permit. An aquifer protection permit (APP) is required for water that is deliberately recharged to an aquifer. Reuse permits are issued to facilities that reuse treated effluent for irrigation. Data on wastewater flows were compiled for all three types of permits. The APP and reuse permit reports generally contain nitrogen levels, reported monthly or quarterly, broken down into total Kjeldahl nitrogen (TKN) and nitrate (NO_3–N). Total N was computed as the sum of TKN + NO_3–N. Since nitrogen is not subject to permit requirements for the few plants that had only NPDES permits, we obtained nitrogen data for these plants directly from plant operators.

For most plants, records for deliveries of effluent for various uses were obtained from federal or state permit records. At two sites, Lone Butte and Peoria, no reports were available; nitrogen and flow data were based on estimates given by the plant supervisors. The Ocotillo and Goodyear facilities upgraded their treatment processes mid-year. Flows and effluent nitrogen values were flow-weighted for 1997 to reflect treatment upgrades made during the year.

Denitrification

Denitrification was computed as the difference between influent TN and effluent TN, after subtracting biosolids N production.

Biosolids

The supervisor at each facility was interviewed concerning treatment methods and disposal of effluent and biosolids. Facilities that process biosolids provided the figures for amount produced in 1997. The amount of N in biosolids was calculated using an N content of 3.3% (Doerge *et al.*, 1991).

N in wastewater used for irrigation

Facilities that provide effluent for irrigation water were asked whether information on nitrogen levels was given to the end users for consideration in fertilizer application rates. Many end users (golf course superintendents, farmers, and agricultural irrigation district managers) were also contacted and interviewed to determine how they utilized this information.

Septic tanks

Approximately 182,000 individuals in Maricopa County live outside incorporated areas (MAG, 1996). To this we added an estimate of the population living within incorporated areas that lacked municipal sewage systems (23,000; from MAG, 1993). We also assumed that individuals using septic tanks produced the same amount of wastewater as municipal users in Maricopa County (118 gal/capita-day; MAG, 1993) and that the sewage going to septic tanks had the same N concentration (46 mg/l; Greeley and Hansen Engineers, 1998) as municipal sewage. We assumed that N removal in septic tanks occurs only by sedimentation. Data from 11 small community systems tabulated by (Reed *et al.*, 1995) show that septic tanks typically remove 80% of suspended solids (SS). Wastewater typically has an SS concentration of 200 mg/l; a typical N content for primary sedimentation tank sludge is 2.5% (Metcalf and Eddy, 1991). Starting with 46 mg/l total N in raw sewage, this yields an N removal efficiency of 9% for septic tanks. We assumed that the rest of the N reached the leach field and would eventually reach underlying aquifers.

RESULTS

The wastewater nitrogen mass balance is summarized in Fig. 3. The fate of effluent N is summarized in Table 2 and the fate of biosolids is summarized in Table 3.

Municipal wastewater N

The average per capita production of wastewater was 118 gal/day (446 l/day). Approximately 15.8 × 10^6 kg N/yr entered municipal wastewater treatment systems in the ecosystem.

Denitrification

Eighty-nine percent of the wastewater was treated by nitrification-denitrification (NDN). NDN plants removed 86% of influent nitrogen, yielding a flow-weighted average effluent TN of 6.4 mg/l. For NDN plants where a breakdown of N species were available (all but two plants), 66% of TN was in the form of nitrate (4.1 mg NO_3-N/l) and 30% (2.1 mg N/l) was ammonium + organic N. Non-NDN plants removed 45% of influent TN, yielding a flow-weighted average effluent TN of 25 mg/l. For non-NDN plants where a breakdown of N species was available (all but one plant), 70% TN was in the form of organic N + ammonium (16.4 mg/l) and 30% (6.9 mg/l) was nitrate. Overall, municipal treatment plants removed 81% of the influent wastewater N (12.87 × 10^6 kg/yr). After accounting for biosolids production (1.45 × 10^6 kg N/yr; below), the denitrification loss was 11.42 × 10^6 kg N/yr.

Fate of effluent (flow and N)

The fate of effluent (reuse, recharge, discharge) for each treatment facility is shown in Table 1. We assumed riverbed infiltration was unimportant and that effluent discharged to the Salt River was exported from the system, except when it was withdrawn for irrigation. Twenty-five percent of the effluent was reused for cooling at the Palo Verde nuclear power plant. This water contained 27% of the effluent N (0.80 × 10^6 kg N/yr). The cooling water is evaporated to dryness in a lined pond. This represents a permanent sink for nitrogen in cooling water. Forty-three percent of the effluent containing 47% of the effluent N (1.37 × 10^6 kg N/yr) was reused for irrigation. Only 4% of wastewater effluent was deliberately recharged to aquifers, accounting for 0.12 × 10^6 kg N/yr. Most of the N in recharged water is in the form of NO_3^-, which moves easily through soils. We therefore assumed that all N in recharged effluent eventually reaches an aquifer.

Biosolids

Nintey-four percent of the 44 × 10^6 kg of biosolids (sludge) produced from wastewater treatments was applied to agricultural fields; the remaining 6% was disposed in landfills (Table 2). Only the Sun

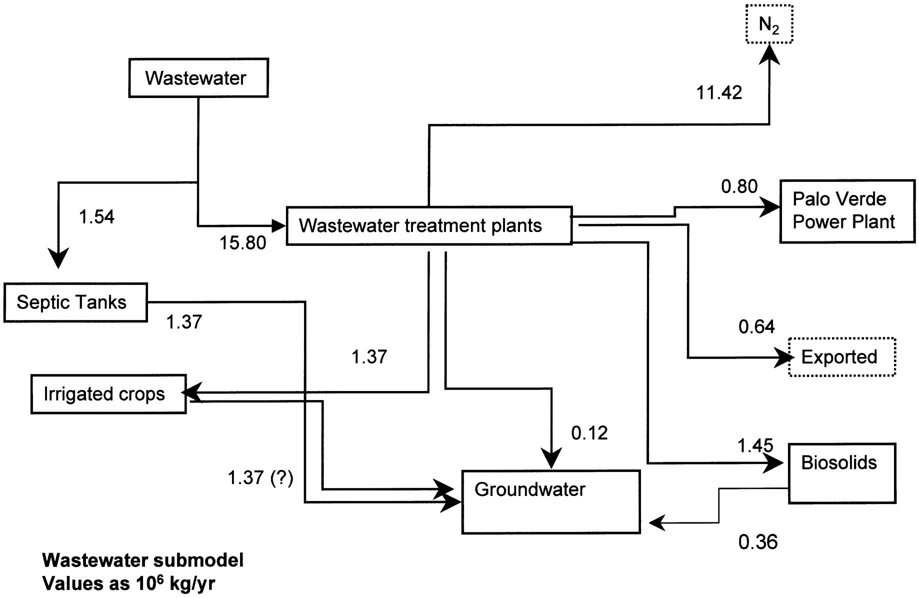

Fig. 3. Nitrogen mass balance for wastewater in the CAP ecosystem.

Table 2. Flows and nitrogen loadings from Phoenix area wastewater treatment plants in 1997

Treatment plant	Total effluent 10^6 gal/yr	Reused effluent 10^6 gal/yr	Recharged effluent 10^6 gal/yr	Exported (Gila River) 10^6 gal/yr	Average total N (ml/l)	No. of samples	Total N in effluent 10^6 kg/yr	N in reused effluent 10^6 kg/yr	N in recharged effluent 10^6 kg/yr	N exported to Gila River 10^6 kg/yr
91st Avenue	52323	17091	0	16420	6.5	12	1.29	0.42	0.00	0.40
23rd Avenue	20578	13523	0	7055	5.5	12	0.43	0.28	0.00	0.15
Tolleson	4242	0	0	693	25.0	46	0.40	0.00	0.00	0.07
Mesa NW	1305	0	1012	293	3.8	7	0.02	0.00	0.01	0.00
Tempe	239	104	0	135	4.7	8	0.00	0.00	0.00	0.00
Gainey Ranch	285	285	0	0	14.5	3	0.02	0.02	0.00	0.00
Fountain Hills	474	474	0	0	29.0	4	0.05	0.05	0.00	0.00
Mesa SE	649	649	0	0	22.9	4	0.06	0.06	0.00	0.00
Gilbert	1665	716	949	0	5.5	12	0.03	0.01	0.02	0.00
Ocotillo	2728	2538	190	0	5.9/23	3/est.	0.12	0.11	0.01	0.00
Lone Butte	2920	2920	0	0	30.5	1	0.34	0.34	0.00	0.00
Sun Lakes	309	309	0	0	3.0	12	0.00	0.00	0.00	0.00
Arrowhead Ranch	1012	1012	0	0	19.6	4	0.07	0.07	0.00	0.00
Peoria	73	0	73	0	6.0	est.	0.00	0.00	0.00	0.00
Goodyear	515	64	390	61	13/25	3/est.	0.03	0.01	0.02	0.01
Avondale	585	0	0	585	2.2	12	0.00	0.00	0.00	0.00
Superstition Mountain	192	0	0	192	12.2	12	0.01	0.00	0.00	0.01
Sun City West	782	0	782	0	18.9	12	0.06	0.00	0.06	0.00
Totals	90876	39685	3396	25434	–	–	2.93	1.37	0.12	0.64
% of Total		43	4	28	–	–		47	4	22

City West plant disposed of biosolids on non-agricultural land. Using an N content of 3.3%, total biosolids N production was 1.45×10^6 kg N/yr.

Septic tank effluent

Total N input to septic tanks in the ecosystem was 1.54×10^6 kg/yr. Nine percent of this N is removed (see Methods section) within the septic tanks, so 1.36×10^6 kg N/yr reaches the underlying vadose zone (the zone between the root zone and the aquifer). Presumably most of this eventually reaches underlying aquifers.

Surface water discharge

Twenty-eight percent of wastewater effluent was exported from the ecosystem via the Gila River. Most of this discharge occurs during the winter months, when less effluent is used for irrigation. If none of this discharged effluent is inadvertently recharged through the river bed, total wastewater N export from the CAP ecosystem was 0.64×10^6 kg N/yr.

DISCUSSION

Accumulation and recycling of N

Some N accumulation is benign: evaporated salts (including N-containing salts) from the Palo Verde power plant (0.80×10^6 kg N/yr) plus a very small amount of biosolids from the wastewater treatment plants (0.07×10^6 kg N/yr) is sent to landfills, where it probably resides indefinitely. Farmers account for the N in biosolids applied to their fields (1.38×10^6 kg/yr). Assuming that fertilization efficiency is 50% and that denitrification removes half of the excess N (Rice *et al.*, 1989), N leached from sewage biosolids is probably $\sim 0.36 \times 10^6$ kg/yr.

Wastewater effluent that is deliberately recharged (0.12×10^6 kg N/yr) or recharged via septic tanks (1.4×10^6 kg N/yr) probably moves to the underlying groundwater because there is little opportunity for denitrification or other N removal processes to occur in the vadose zone.

Treated wastewater that is reused for irrigation also may contribute a substantial amount of N to the aquifer because the fertilization potential of treated wastewater is probably ignored by most irrigators. In numerous interviews with wastewater treatment operators and irrigators, we found only one plant (the Kyrene plant in Tempe) that reported the N content of effluent to the irrigator that received its effluent (a city park). The 91st Avenue and 23rd Avenue treatment plants provide water quality data to the agricultural irrigation districts, but this information is not routinely passed on to individual farmers. Some golf course operators were vaguely aware that the effluent contained N but tended to fertilize for “greenness”,

Table 3. Sludge disposal practices for wastewater treatment plants in the CAP ecosystem

	Sludge production, tons/yr	Destination
91st Avenue	35569	Land application (cotton fields)
23rd Avenue	5993	Land application (cotton fields)
Tolleson	3000	Land application (cotton fields)
Ocotillo (Chandler)	1825	Hauled to Butterfield landfill
Fountain Hills	648	Hauled to Salt River landfill
Goodyear (est.)	450	Land application to agricultural fields
Avondale	439	Land application to agricultural fields
Sun Lakes	250	Hauled to Sierra Estrella landfill
Sun City West	200	On site storage
Superstition Mountain	–	On site storage
Total	48374	

not by recommended application rate. Many golf courses receive varying mixtures of effluent and non-effluent water, making it difficult to account for the fertilization potential of the effluent.

The failure to fully account for the fertilization potential of wastewater effluent probably leads to overfertilization and may contribute to groundwater contamination. For perspective, an effluent with 7 mg N/l (the flow-weighted average TN for all NDN plants) applied to cotton (the most important agricultural crop in the region) at a rate of 6 ft/yr would result in an N application rate of 140 kg/ha-yr. This represents 50–82% of cotton's fertilizer requirement (170–280 kg/ha-yr; Doerge *et al.*, 1991). Nitrogen added at rates greater than crop requirements would likely leach into the aquifer. Even if half of the N in effluent used for irrigation is lost by denitrification the remainder (0.7×10^6 kg N/yr) likely reaches the aquifer. For comparison, all deliberate agricultural fertilization in the ecosystem contributes about 9×10^6 kg N/yr, of which about 54% is removed by crops (Baker *et al.*, 1999, submitted). Assuming that 50% of the N not assimilated by crops is lost by denitrification and 50% is leached to groundwater (Rice *et al.*, 1989), total leaching from agricultural fertilization is 2.4×10^6 kg N/year. Thus, the N in wastewater effluent used for irrigation may contribute about a third as much N to the underlying aquifers as agricultural fertilization. In reality, even though farmers do not explicitly recognize the N provided by irrigation wastewater, some account for this additional N implicitly if they fertilize on the basis of soil N content or petiole N content (for cotton). Thus, the actual loading of N to the groundwater that results from using effluent for irrigation may be somewhat less than we have calculated but is probably still a major component of the overall N input to the underlying aquifer in this watershed. Further research on the fate of N in effluent used for irrigation is needed given the potential importance of overfertilization.

Export of N

Because most of the wastewater generated in the CAP ecosystem is recharged or reused, very little wastewater N is exported: only 22% of the N in wastewater effluent (0.64×10^6 kg N/yr; about 4% of the N in raw wastewater) is exported to the Gila River. This is about one-quarter of the total N export from the watershed (2.7×10^6 kg/yr for 1988–1996; Baker *et al.*, 1999, submitted). For comparison, if all wastewater were treated by NDN (effluent TN = 7 mg) and discharged, wastewater N export would be about four times higher (2.4×10^6 kg/yr) and the total N export via the Gila River would increase by 65%.

Management implications

Water resource decisions intended to conserve and reuse wastewater tend to promote volatilization and ecosystem accumulation rather than export of N. Because most municipal wastewater produced in the CAP ecosystem is reused or recharged, it undergoes NDN processing, which removes about 81% of the influent N. Nitrogen in evaporated salts produced at the Palo Verde facility and nitrogen in sludge sent to landfills accumulates harmlessly.

Of greater concern is nitrogen that accumulates in the vadose zone and aquifers. This includes septic tank leachate (1.37×10^6 kg N/yr), recharged municipal water (0.12×10^6 kg N/yr), some of the N in treated wastewater used for irrigation (0.68×10^6 kg N/yr) and a small amount of N leached from application of biosolids to agricultural fields (0.36×10^6 kg/yr), a total of 2.53×10^6 kg N/yr. This is comparable with the amount of N leached from agricultural land and very roughly about one-third of the total N leached to groundwater from all sources in the ecosystem (about 8×10^6 kg/yr; Baker, 1999, submitted). Other groundwater inputs include leaching from dairy operations and residential fertilization, plus recycling of NO_3^- from nitrate-contaminated groundwater used for irrigation.

Interviews with various irrigators indicated that the N in wastewater effluent used for irrigation is ignored in computing fertilization requirements. Although these irrigators may implicitly account for some of this N through soil or petiole analyses, we hypothesize that much of the N in effluent used for irrigation becomes a groundwater contaminant. This overfertilization would be easy to control because irrigators could easily be motivated to reduce fertilizer applications if they had accurate knowledge regarding the N content of irrigation water. Providing this information would not be difficult. Most of the N in effluent is nitrate, which could easily be measured continuously with in-situ probes linked to data loggers. Information relayed to satellites would then be downloaded to a web site, where farmers and other irrigators would receive concentration data in real time. More importantly, a simple algorithm could integrate data on concentration and irrigation rate (the latter provided by the farmer) to show how much N is being applied for a given irrigation cycle. The irrigator would then reduce commercial fertilization additions accordingly. Because most of the wastewater used in irrigation is transmitted through a few canals and many canals are already equipped with equipment sheds and data loggers to collect flow data, the proposed monitoring system would be inexpensive. In addition to reducing groundwater contamination, such a program would reduce fertilizer costs. It may also result in higher cotton yields, which can be reduced by overfertilization with N (Doerge *et al.*, 1991).

A second major source of N contamination of aquifers is septic tanks, which we estimate contribute about 1.4×10^6 kg N/year to the subsurface environment. Many areas served by septic tanks in the CAP ecosystem are located on "county islands", vestiges of unincorporated areas within larger, sewered incorporated areas. Elimination of septic tanks in these areas would substantially reduce N leaching to underlying aquifers.

By contrast, deliberate recharge of wastewater adds only 0.12×10^6 kg N to aquifers. This quantity is small because the amount of wastewater currently being deliberately recharged is small (about 4% of all effluent).

CONCLUSIONS

Wastewater management practices intended to conserve and reuse water promote volatilization and accumulation of N rather than export from the ecosystem via surface water. Seventy two percent of the N in raw municipal wastewater is deliberately volatilized by NDN and another 9% is removed by biosolids production. Only 19% of N in raw wastewater remains in the effluent and only 21% of this (4% of the N in raw wastewater) is exported from the ecosystem via the Gila River.

Accumulation of N within the ecosystem occurs by reuse and recharge of municipal sewage effluent, leaching of N from biosolids applied to land, and leaching from private septic tanks. In the aggregate, these processes account for one-third of the N that moves through the vadose zone in this ecosystem. N accumulation could be probably be reduced by careful management of the N in wastewater used for irrigation and by reducing the number of septic tanks within the urban area.

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