Nitrogen pool, flows, impact and sustainability issues of human waste management in the city of Bangalore

H. N. Chanakya[1,]* and H. C. Sharatchandra[2]

[1]Centre for Sustainable Technologies, Indian Institute of Science, Bangalore 560 012, India
[2]Karnataka State Pollution Control Board, Parisara Bhavan, Bangalore 560 001, India

Cities in the developing countries have multiple modes of human and animal waste treatment and disposal that finally decide the overall impact on the urban ecosystem, and these have been studied for the city of Bangalore. Four modes are found, namely underground sewage systems, decentralized soak pits and septic tanks, open defecation and a miniscule effort at composting. The extent of N released per unit area is high, ranging between 0.44 and 1.4 t ha^{-1} of the urban landscape. In this study the N release and outflow have been estimated. The N entering or flowing in the lithosphere, hydrosphere and in wastewater streams forms the major component. The pool size has first been determined. The size and movement through these pools were estimated with a view to determine the state of the N cycle and if there is a cause for alarm in similar cities in other developing countries. N contribution from human waste (excreta and urine) forms the single largest influx and sewage flowing out of the city forms the single largest efflux of N pool. Owing to a seemingly large use of soak pits and open conveyance of sewage in some parts of the city, coliforms and NO_3–N have seeped into shallow and deep-ground aquifers and show up in ground- and sub-soil waters in the city. The level of N in these waters at a few places is slightly higher than the permissible limits. This suggests that there is a need to find alternatives to modes like the ubiquitous soak pit, such that pollution of shallow and deep aquifers is avoided in the future. Currently, there is little effort in stripping the waste water off N. Also, there is no significant effort in recovery and reuse of nutrients, and this is required to increase the sustainability levels.

Keywords: Developing countries, human waste management, nitrogen pool, urban ecosystem.

ANTHROPOGENIC deposition of reactive N is reported to exceed the net N found in the natural cycles and processes. Compared to the anthropogenic interference in the C-cycle of <10%, man-made perturbations of the global N cycle exceed 95% of the overall reactive N in nature[1–3]. It is therefore feared that in the case of such perturbations with reactive N, the resulting disasters will manifest in shorter time-frame and to a greater extent than those found for global C. Among the more sensitive areas of nitrogen perturbations is likely to be the urban ecosystems in developing as well as the developed world, where man-made nitrogen deposition or release can exceed 1500 kg yr^{-1} ha^{-1} of the urban landscape[4]. The N-cycle in urban ecosystems is therefore highly stressed in the presence of disproportionate deposition of N in relation to the net C deposited[5]. It is therefore a cause of serious concern.

The N balance in urban ecosystems could be visualized as a series of transfers or flows between the various pools of N such as the biosphere, lithosphere, hydrosphere and atmosphere[6]. This approach attempts to account for the changing sizes of these pools in the process of man-made perturbations. Nitrogen in man-made waste (sewage and urban solid wastes)[4], followed by N released during fossil-fuel combustion in IC engines of automobiles[7], which form the bulk of the reactive N released or deposited by human interventions. A significant quantity of the NO_x generated in automobiles and engines travels quickly and only a fraction comes back into the city. This article deals with quantifying and determining the various flows of N originating in human waste in a typical urban conglomerate.

As cities grow in size and develop, they set up sewage-treatment plants that generally remove the C content of the sewage. As most often sewage is first treated anaerobically, it leaves an appreciable quantity of N intact in the treated sewage. More modern treatment plants include a combination of nitrification–denitrification steps during the secondary sewage treatment to remove a large portion of N in the treated sewage. When these nitrogen-removal mechanisms are absent or function partially, the residual N almost inevitably enters the nearest freshwater body downstream and causes eutrophication in all parts of the world[8–11].

To ensure that environmental balances are maintained, it is important to account for all sources of N entry, exit and leakages. A few studies have been taken up by cities in the developed countries, that monitor and balance the quantities of N flowing through the wastewater sys-

---

*For correspondence. (e-mail: chanakya@ astra.iisc.ernet.in)

tems[11,12]. Similar studies, experimental and modelling, have been carried out for cities of the developing countries, that point to status of N management as well as the N loads in the receiving bodies[8–10,13,14]. Most of these studies are concerned about the status of pollution in the receiving water bodies and an avoidance of their eutrophication. The rising levels of imbalance in the relative ratios of C and N in the receiving bodies, be it water or soil, are also of concern today. It is therefore suggested that the C and N budgets are studied together rather than singly[15]. This is likely to provide a clearer picture whether it will result in stimulating growth of autotrophs in receiving water bodies[16] or lead to unusable or wasted N fluxes. When biosolids from the sewage-treatment system are applied to agricultural soils, such an approach enables prediction of the levels of N fluxes, N immobilization and potential for its capture in plant biomass or crops[17].

Nitrogen moving through urban ecosystems, its sewage and into water bodies has been viewed as a source of potential pollution of the receiving water body. This therefore presents a need to evolve and follow location-specific methods that arrest the flow of N into water bodies. More recently, concepts of sustainability of the underlying methods and the approach to remove N in the water are being reviewed. Even a simplistic approach to sustainability suggests that N flowing through the wastewater system needs to be brought back into productive use – capturing it in crops for direct and indirect human use. Such efforts are expected to achieve sustainability[18]. A higher level of sustainability is measured when the mass balance is combined with energy estimates. This can determine the appropriate route for N handling in urban ecosystems. The concepts of sustainability are often qualitatively expressed, which in the present case must lend itself to quantification, such that it makes a choice of the N-management route or method (including losses) amenable for comparison. Many criteria have been listed[17–20].

1. Efficiency of use of physical resources.
2. Limiting the use of non-renewable inputs.
3. Minimizing the current and future ecological and environmental risks.
4. Retaining ability to reuse N even in the future.

Estimates of mass balance, movement of N between various pools within the urban ecosystem, loss and accumulation, and finally the exergy of N management in specific urban settlements are therefore expected to enable switching to more sustainable practices. The city of Bangalore provides a unique study opportunity. The city is situated on a plateau, with land sloping in all directions. In this situation wastewater and its N do not enter the city from any direction. There are few opportunities for N from other sources to interfere in the estimations. All N generated is from within the city itself. The city has been studied only in a sporadic manner for its N management. The objective of this article is to estimate the flow of N in and out of the various N pools, to evolve a picture of the level of underlying sustainability and areas of concern.

The N-dynamics of urban soils especially with regard to the pool sizes and their relationships with transfers and losses from and to these pools has been inadequately studied, especially for cities in developing countries, where there is a significant proportion of on-land deposition of N compounds by humans. There is a significant level of scatter in the way land is used in urban areas. However, a mass-balance approach is possible to provide a better picture[12,21]. In semi-arid and sub-tropical crop lands, typical land use and agronomic practices lead to soils and crops being N-deficit, making such soils N-sinks[22]. However, urban soils receive large N-influxes. In a developing country situation with large N-influxes brought about by open urination and/or defecation, overflowing septic tanks, soak-pits, open sewerages, etc., there is a large N-influx with poor sinks. This phenomenon of N-accumulation in the absence of tilling and soil disturbance could mean gradual accumulation of N in the soil, with potential for high N-leaching losses[23,24]. Such high N-leaching potential often leads to groundwater pollution[25] and a need to adopt interventions to reverse soil damage, groundwater pollution, meet environmental obligations and address sustainability threats. There is a need for interdisciplinary knowledge-driven decisions making trade-offs between perceived damage, actual damage and anticipated cost of efforts[26]. At an estimated[17] daily per capita deposition of 6–20 g N and a population density of 200 person ha^{-1}, this translates into an N-flux of 0.44 to 1.46 $\text{t ha}^{-1}\text{ yr}^{-1}$, far too large for any soil–plant system to assimilate. Typically N-pool sizes may be determined as input–output mass balances[21], where the overall N pool arises from

$$N_{\text{dep}} + N_{\text{fix}} = N_{\text{i}} + N_{\text{u}} + N_{\text{ad}} + N_{\text{fire}} + N_{\text{eros}} + N_{\text{vol}} + N_{\text{le}},$$

where dep is deposition, fix is microbial fixation, i is immobilization, u is uptake, ad is adsorption, eros is erosion, vol is volatilization and le is leaching.

Urban conglomerates have been studied in the recent past for their contribution to environmental problems at a system/sub-system level, mainly driven by a larger political need to efficiently provide urban services and facilities, as well as effective governance. In a resource-constrained country like India, where practices of reuse and recycle have long been in use, we need to examine underlying issues and processes at a higher hierarchic level of sustainability assessment. The case of nitrogen is taken as an example for discussion in this article. Human waste, the single largest component of urban N flow, is deposited on land as well as discharged as sewage. The N-in sewage is an important N-resource that is now appreciable in size and can be considered as inadequately and improperly utilized. Urban wastelands have tight N-cycles that tend to deteriorate with abuse. When human waste is deposited on land, it significantly influences the N-cycles making it favourable for a few plant species to colonize typical 'waste/barren lands'. In the following discussion we first estimate and validate the size of the N-pool. We draw upon examples of constrained N-cycles from nearby wastelands to show that urban wastelands/unvegetated lands continuously discharge unusable N. We also examine how sewage abuse in peri-urban agriculture can threaten water quality in terms of nitrate toxicity in drinking water. We target resource recycling and to some extent environment objectives (greenhouse gas (GHG) emissions) in a larger perspective of sustainability goals.

While anaerobic fermentation of the organic fraction of human waste tends to produce methane, it must be pointed out at the outset that, along with recovery of nitrogen, the current method of sewage management has the potential to generate 0.11 million m^3 methane daily from human waste through typical anaerobic digestion processes (biogas). In this study we focus on quantifying the N-pool size and determining the various pools between which it is moving. Denitrification steps involved in transformations of N tend to release N_2O in small quantities, as the main GHG emitted. N_2O generated is thus quantified. Human and animal excreta and waste contribute maximum to the N-pool size in urban areas and therefore treatment of sewage and solid waste determines the movement of various forms of N between segments. An assessment of current practices and future options for managing household urban waste will also be attempted, to determine whether it is possible to achieve N-recycling with small environmental footprint.

Sources of N in waste

Human and animal waste (excreta and urine) forms the largest source of N waste generated in the city of Bangalore (24,000 t/year). Beside residents, a significant fraction of the population is floating – those who visit Bangalore on a daily basis for work-related activities. We estimate that the floating population contributes N largely in the form of urine and partially in excreta. In addition to human beings, Bangalore is populated by a large number of domestic animals and birds, all of which generate N-rich waste (Tables 1 and 2).

Mode of disposal and its influence on the N-pool

In the city of Bangalore there exist three types of sanitary facilities and practices along with one in which no facility is available to handle human excreta. These are:

(a) Underground drainage (UGD, sewer)-connected water-closet systems.
(b) Soak-pit/septic tank-connected decentralized individual house water-closet systems.
(c) Defecation in open spaces (open defecation and urination).
(d) Public toilets connected to UGDs.

The relative proportion of N from human waste in the above four modes of disposal is presented in Tables 1 and 2. It is important to note that while a certain fraction of human and animal excreta is consigned through conventional sewage/soak-pit routes, a higher proportion of urine-N is sent through direct deposition on land. It is difficult to estimate this fraction, and thus the same distribution used for human excreta is used for urine-N. A detailed study on how these fractions have been estimated has been made earlier[6].

Ecological and environmental impact of open deposition and decomposition

Human excreta when left in the open creates many civic, aesthetic and hygiene problems. Such a practice carries pathogens and cysts (if present) into surface water bodies during periods of heavy run-off. This is common knowledge and is not discussed here. Bangalore is characterized by a generally semi-arid climate conducive to rapid drying of waste. It is estimated that such waste is subject to anaerobic (24 h) and aerobic (48–72 h) decomposition after which it becomes too dry for normal microbiological decomposition with attendant GHG emissions[6]. At this stage the waste is consumed by micro and macro fauna, enabling its N content to re-enter the biosphere.

Nitrogen influx and efflux resulting through human waste management

When we consider the city of Bangalore as an ecosystem into which nitrogen forms enter and leave, the data in Tables 1 and 2 may be summarized as a flowchart as in Figure 1. Nitrogen enters the system largely in the form of human and animal excreta as well as through many forms of waste and emission USW 6570 t N/yr, fertilizers, manure, deposition 1370 t N/yr, 24,000 t NO_x/yr automobile emissions[7] (not discussed). To reduce the complexity, USW is not considered and only human waste is considered here. With regard to the origin of nitrogen, the different sources may be grouped into four broad classes:

- Originating from residential houses in the city.
- Originating from population using Bangalore on a daily basis (floating population).
- Commercially reared animals (major animals – cattle, buffalo, sheep and goat).
- Non or semi-commercially reared animals ('minor animals', see Table 3 for details).

Table 1. Consolidated data of N-pool size and N_2O production from various sources and treatment methods for human and animal waste (excreta) in Bangalore

						Fraction dried			Sewage fraction			Fraction composted			
Source	Number	KgTS hd^{-1} d^{-1}	DM d^{-1} tons	N% TS	Total N (kg d^{-1})	Percentage	Factor	Kg N_2O	Percentage	Factor	kg N_2O	Percentage	Factor	kg N_2O	Total kg N_2O
Human (residents)	5200000	0.06	312.0	3.00	9360	10	0.005	4.7	89	0.010	83.3	1	0.005	0.5	88
Human (floating)	2000000	0.03	60.0	3.00	1800	20	0.005	1.8	80	0.010	14.4	0	0.005	0.0	16
Total as (DM per d) N kg d^{-1}			372		11160		1296			9770			94		
Cattle	185087	1.66	307.2	1.25	3841	30	0.005	5.8	30	0.010	11.5	40	0.005	7.7	25
Buffalo	27429	2.50	68.6	1.25	857	30	0.005	1.3	30	0.010	2.6	40	0.005	1.7	6
Sheep	108317	0.132	14.3	3.00	429	30	0.005	0.6	15	0.010	0.6	55	0.005	1.2	2
Goat	41392	0.132	5.5	3.00	164	30	0.005	0.2	15	0.010	0.2	55	0.005	0.5	1
Total as (DM per d) N kg d^{-1}			395.6		5291		1587			1498			2205		
Horse	500	1.60	0.8	2.30	18	10	0.005	0.0	10	0.010	0.0	80	0.005	0.1	0
Dog	80000	0.05	4.0	3.00	120	50	0.005	0.3	40	0.010	0.5	10	0.005	0.1	1
Cat	50000	0.05	2.5	3.00	75	70	0.005	0.3	15	0.010	0.1	15	0.005	0.1	0
Pig	100	1.30	0.1	3.80	5	10	0.005	0.0	80	0.010	0.0	10	0.005	0.0	0
Poultry	500000	0.06	30.0	6.00	1800	20	0.005	1.8	10	0.010	1.8	70	0.005	6.3	10
Duck	500	0.06	0.0	6.00	2	10	0.005	0.0	10	0.010	0.0	80	0.005	0.0	0
Other birds		0.06	0.0	6.00	0		0.005	0.0		0.010	0.0		0.005	0.0	0
Total as (DM per d) N kg per d			37.5		2020			475		241			1299		
Fish				6.00	0		0.005	0.0		0.010	0.0		0.005	0.0	0
Aquatics				4.00	0		0.005	0.0		0.010	0.0		0.005	0.0	0
Total			805		18471			16.8			115.1			18.0	150

Data on the population of animals were obtained from individual administrative units (Wards) of the city of Bangalore available for 2003–04. Average quantity of daily excreta, animal-wise, was first obtained from various CST field and recorded data sources measured for biogas potential and suitably corrected for average body weight of animals typical for this location. For details on the methods of estimation for each of the sources, see Chanakya and Sharatchandra[6]. TS, Total solids; DM, Dry matter.

Table 2. Nitrogen pool size arising from urine fraction undergoing different processes of mineralization and N_2O liberation

Source	Number	Litre/d	Urea (%)	Total N tons	Fraction dried			Sewage fraction			Fraction composted			Total t N_2O
					Percentage	Factor	t N_2O	Percentage	Factor	t N_2O	Percentage	Factor	t N_2O^a	
Human (residents)	5200000	1.250	0.7	42.3	10	0.005	0.02	89	0.010	0.4	1	0.005	0.0	0.40
Human (floating)	2000000	0.650	0.7	9.1	20	0.005	0.01	80	0.010	0.1	0	0.005	0.0	0.08
Total as N kg per d or N_2O				51.4			0.03			0.45			0.0	0.48
Cattle	185087	4.000	0.7	5.2	30	0.005	0.01	30	0.010	0.0	40	0.005	0.0	0.03
Buffalo	27429	4.000	0.7	0.8	30	0.005	0.00	30	0.010	0.0	40	0.005	0.0	0.00
Sheep	108317	1.000	0.7	0.8	30	0.005	0.00	15	0.010	0.0	55	0.005	0.0	0.00
Goat	41392	1.000	0.7	0.3	30	0.005	0.00	15	0.010	0.0	55	0.005	0.0	0.00
Total as N kg per d				7.0			0.01			0.02			0.01	0.04
Horse	500	1.600	0.0	0.0	10	0.005	0.00	10	0.010	0.0	80	0.005	0.0	0.00
Dog	80000	0.050	0.0	0.0	50	0.005	0.00	40	0.010	0.0	10	0.005	0.0	0.00
Cat*	50000	0.050	0.0	0.0	70	0.005	0.00	15	0.010	0.0	15	0.005	0.0	0.00
Pig*	100	1.300	0.0	0.0	10	0.005	0.00	80	0.010	0.0	10	0.005	0.0	0.00
Poultry*	500000	0.060	0.0	0.0	20	0.005	0.00	10	0.010	0.0	70	0.005	0.0	0.00
Duck	500	0.060	0.0	0.0	10	0.005	0.00	10	0.010	0.0	80	0.005	0.0	0.00
Other birds		0.060	0.0	0.0		0.005	0.00		0.010	0.0		0.005	0.0	0.00
Fish				0.0		0.005	0.00		0.010	0.0		0.005	0.0	0.00
Aquatics				0.0		0.005	0.00		0.010	0.0		0.005	0.0	0.00
Total				58.4			0.04			0.47			0.02	0.53

For details on the method of estimation for each of the sources, see Chanakya and Sharatchandra[6] and footnote of Table 1.

*Urine fraction for dog, pig and poultry (uric acid) could not be ascertained accurately and is therefore taken as a relative value from similar sized and similarly fed animals. [a]0.0 only indicates quantity estimated is less than 0.01 t.

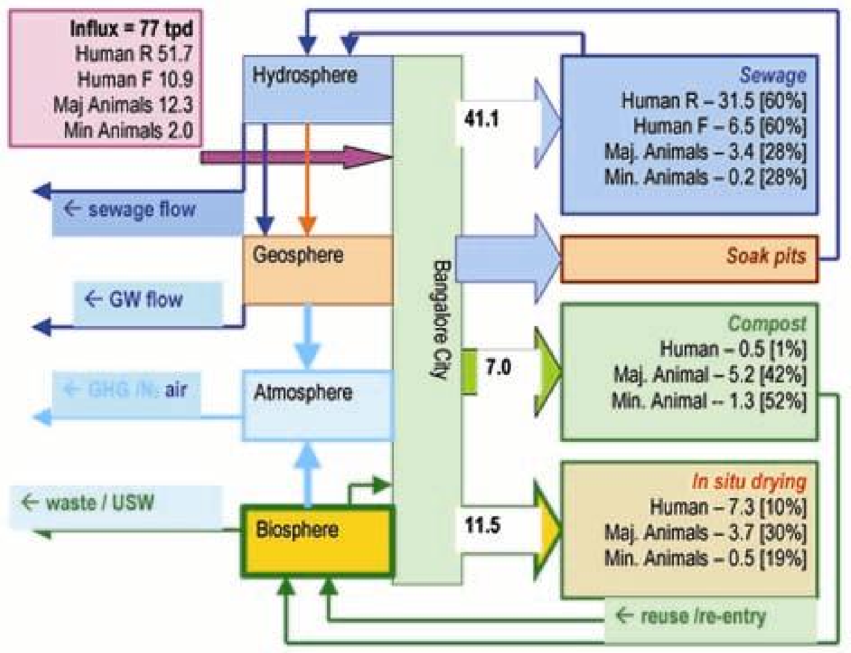

Figure 1. Estimates of nitrogen flows through various spheres calculated for Bangalore city. The total influx and efflux into various streams is shown. The total sewage is partitioned into that flowing through underground pipes and that leading to soak pits. This number is not accurately available and placed as one.

Table 3. Nitrate, ammonia and coliform counts in various water samples from Bangalore[a]

Source, location or area name	Data source	Water type	Nitrate (mg/l)	Ammonia (mg/l)	Coliform count
Near sewage-treating water bodies (K&C valley)	1	BW	42–54	ND	<1.8
Near sewage-treating water bodies (K&C valley)	1	OW	28.7	12.5	220
Random sampling range in K&C valley course	1	BW	1.9–54	ND-22	<1.8–>1600
Random sampling Bangalore district[b]	2	BW	NA–316[b]	NA	NA
Bellandur township	3	BW	52-60	NA-6	NA
Bellandur lake	3	TW	7.33–12[c]	NA-32[3]	220[b]

[a]From KSPCB, Bangalore; [b]Department of Mines and Geology, Bangalore; [c]Chanakya *et al.*[4].

Nitrogen originating from these sources may move through three modes:

- Into sewage (or soak pits) and suffer anaerobic digestion soon after discharge.
- Transported out of the city for the purpose of compost preparation and land application.
- Deposited in open spaces and subject to rapid drying, partial decomposition and ingested by micro-fauna/flora subsequently.

Approximately 89% of the nitrogen fraction in human waste is subject to short-term anaerobic digestion of sewage. Nitrogen ending up in the sewage is handled in two ways.

- Sewage collected through a reticulated network of underground pipes and passing through one of the three large sewage-treatment plants.
- Sewage moving through household-level soak-pit-type treatment systems. This is a decentralized treatment method. Obviously, here nitrogen travels to deeper horizons of sub-soil and reaches the groundwater. There is only sporadic information on its impact on groundwater sources, which will be discussed later in the article. Nitrate entering groundwater from the soak pits, where groundwater forms an important drinking water source, is potentially dangerous. However, under normal circumstances, in the presence of a small concentration of organic matter in this nitrate-bearing water, the nitrate is used up quickly by ubiquitous denitrifiers and the water is rendered reasonably safe in a short while.

A total of about 245 million litres per day (MLD, current estimates 1100 MLD) of sewage from Bangalore flows out through three treatment systems located along

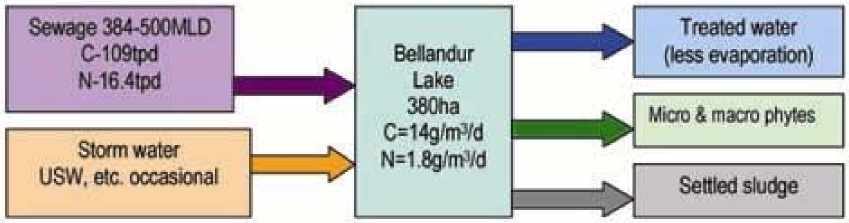

Figure 2. N flow through the last water purification system at the K&C valley, namely the Bellandur tank. It is seen that the wastewater treatment plant upstream and the Bellandur tank together remove significant C content while producing treated water, phyto biomass and settled sludge. Bangalore sewage N = 58.4 tpd (× 0.4 Bellandur fraction = 23.5 tpd) × 0.7 UGD fraction = 16.35 tpd into lake.

the course of three major streams (AUS-AID, 2001; figures in italics are from other sources[4] for May 2006).

- Vrishabhavati valley (installed capacity 180 MLD; *500 MLD*)
- Koramangala and Challaghatta (K&C) valley (installed capacity 180 MLD; *500 MLD*)
- Nagavara–Hebbal system (60 MLD; *100 MLD*).

Soil sub-system in urban conglomerates

As urban conglomerates expand a significant area of land around the city is taken off agriculture and the land is kept barren for nearly a 10-yr period and then becomes real estate. During this shift from arable to urban land, a lot of N held in the soil is lost with gradually reducing annual N inputs in the form of plant-derived organic matter entering the soil. As soil N goes through the annual cycle of mineralization, ammonification, nitrification and partial reabsorption by soil microbiota, a part of it remains as unused NO_3–N and is quickly leached downwards when there is no vegetative cover to function as a sink. In wastelands this forms a significant mechanism for N loss[24]. Similar situations exist in urban soils. In the absence of vegetative cover as a sink, nitrate is irrecoverably lost to lower horizons and possibly groundwater. While this mechanism was measured for farm lands its magnitude and behaviour in urban soils where the N pool is artificially kept high by human deposition of urine and foeces is not studied well. While wasteland soils function with a small size of N-pool and often suffer a high degree of competition between various N-sinks and N-reabsorption mechanisms, urban soils on the other hand, are expected to be characterized by a high levels of N-pool and organic-material deposition. This arises from a combination of open defecation and urination, a large proportion of soak pits that release N at levels below the root zone and due to the small size of vegetative sinks in the system. Further, NO_3 release in the soils and water availability (favourable soil moisture levels) are asynchronous and increase the incidence of N loss[6].

These N-abused soils function in N-excess conditions unlike typical agro-ecosystems that are chronically N-deficit[27]. Such high levels of the N-pool without a natural sink can be deleterious and tend to keep these soils in a perpetual state of eutrophication[21,28,29]. In cities with distributed locations receiving constant influx of urine, high levels of ammonification and its subsequent volatilization hinder plant growth and subsequent reabsorption. The N-pool size from urine is presented in Table 2 along with the N_2O generated. It is expected that a significant quantity of NO_3–N travels downwards in the soil, with potential threat for mixing with groundwater.

When components of solid wastes are added, the cycle depiction is expected to be complete. We believe under N-excess conditions, significant N losses occur and alternative strategies to tap the N efflux and convert it to plant biomass need to be evolved and monitored. The concentrations of NO_3 and NH_4–N from various studies are summarized in Table 3. It may be seen that while there is the presence of NO_3 at levels marginally higher than the standards along sewage courses, it is also clear that many random samples across the Bangalore district have shown higher NO_3. The NO_3 levels are much higher than those found in the flowing sewage nearby. The N levels in groundwater of areas having only soak pit-type treatment is higher. Yet adequate data are not available to explain how the NO_3–N concentrations increase significantly compared to the levels found in the sewage itself. This requires a more intense study. More so, in the easterly flow reaching K&C valley and Bellandur tank. Earlier studies have also found similar results that wastewater treatment plant and Bellandur tank together remove about 109 and 16.4 t of C and N/d (Figure 2). Here we find that the N estimates based on population and estimates based on determining wastewater composition have only 15% difference. This indicates that much of the estimates is realistic.

Conclusion

Nitrogen in human waste forms the single largest source of N flow through various pools in the city of Bangalore. A large proportion of N is lost in the outflow of the Bellandur tank, indicating that there is great potential to tap this N and reconvert it to plant biomass. At present there is only sporadic increase in NO_3–N in the water sources and it is time to wake up to the cause of efficient wastewater treatment and better N recovery methods. The coliform count is widespread among the wastewaters tested and this indicates that sewage, especially from soak pits is entering the soil water (both groundwater and subsoil water resources). This increase shows that the extensive soak pits adopted in Bangalore fail to remove coliforms and potential pathogen hazard from sewage. It also indicates that sometimes sewage infiltrating through soil fails to remove NO_3–N. Alternative treatment systems substituting soak pits need to be developed and deployed soon. Significant increase in the concentration of nitrates in groundwater compared to that of the wastewaters is currently explained inadequately, and requires further research.

---

1. Janzen, H. H., Carbon cycling in earth systems – A soil science perspective. *Agric. Ecosyst. Environ.*, 2004, **104**, 399–417.
2. NAAS, Policy options for efficient nitrogen use – Policy Paper No. 33, National Academy of Agricultural Sciences, New Delhi, 2005, pp. 1–17.
3. World Resources Program, Nutrient overload: Unbalancing the global nitrogen cycle. In *World Resources 1998–99*, 1998.
4. Chanakya, H. N., Karthick, P. and Ramachandra, T. V., Nitrogen and carbon flows through Bellandur Lake – Role of Bellandur lake as a natural wetland treating Bangalore wastewater. In *Environmental Education for Ecosystem Conservation* (ed. Ramachandra, T. V.), Capital Publishing Co, 2008, pp. 25–32.
5. Steinberg, D. A., Pouyat, R. V., Parmelee, R. W. and Gropfman, P. M., Earthworm abundance and nitrogen mineralization rates along an urban-rural land use gradient. *Soil Biol. Biochem.*, 1997, **29**, 427–430.
6. Chanakya, H. N. and Sharatchandra, H. C., N-pool size, its reuse and sustainability issues of a developing country city – Bangalore. In *Agricultural Nitrogen Use and its Environmental Implications* (eds Abrol, Y. P., Raghuram, N. and Sachdev, M. S.), IK Publishing House, New Delhi, 2007, pp. 477–497.
7. Balachandra, P. and Reddy, B. S. S., Energy and climate change implications of road transport in million plus cities of India. Technical Report, Department of Management Studies, IISc, Bangalore, 2007.
8. Scheren, P. A. M. G., Kroeze, C., Janssen, F. J. J. G., Hordijk, L. and Piansinki, K. J., Integrated water pollution assessment of the Ebrie Lagoon, Ivory Coast, West Africa. *J. Mar. Syst.*, 2004, **44**, 1–17.
9. Burnett, W. C., Wattayakorn, G., Taniguchi, M., Dulaiova, H., Sujisuporn, P., Rungsupa, S. and Ishitobi, T., Groundwater derived nutrient inputs to the upper gulf of Thailand. *Continental Shelf Res.*, 2007, **27**, 176–190.
10. Duc, T. A., Vachaud, G., Bonnet, M. P., Prieur, N., Loi, V. D. and Anh, L. L., Experimental investigation and modeling approach of the impact of urban wastewater on a tropical river: A case study of the Nhue River, Hanoi, Vietnam. *J. Hydrol.*, 2006, **334**, 347–358.
11. Cebron, A. and Garnier, J., Nitrobacter and Nitrospira genera as representatives of nitrite-oxidizing bacteria: Detection, quantification and growth along the lower Seine River (France). *Water Res.*, 2005, **39**, 4979–4992.
12. Lauver, L. and Baker, L. A., Mass balance for wastewater nitrogen in the Central Arizone–Phoenix ecosystem. *Water Res.*, 2000, **34**, 2754–2760.
13. Zhang, Q. L. *et al.*, Surface water quality of factory based and vegetable based peri urban areas in Yangtze River delta region, China. *Catena*, 2007, **69**, 57–64.
14. Harashina, K., Takeuchi, K., Tsunekawa, A. and Arifin, H. S., Nitrogen flows due to human activities in the Cianjur–Cisokan water shed area in the middle of Citarum drainage basin, West Java, Indonesia: A case study at hamlet scale. *Agric. Ecosyst. Environ.*, 2003, **100**, 75–90.
15. Vezina, A. F. and Pahlow, M., Reconstruction of ecosystem flows using inverse methods: How well do they work? *J. Mar. Syst.*, 2003, **40–41**, 55–77.
16. Dokulil, M., Chen, W. and Cai, Q., Anthropogenic impacts to large lakes in China: the Tai Hu example. *Aquat. Ecosyst. Health Manage.*, 2000, **3**, 81–94.
17. Ojeda, G., Tarrason, D., Ortiz, O. and Alcaniz, J. M., Nitrogen losses in runoff waters from a loamy soil treated with sewage sludge. *Agric. Ecosyst. Environ.*, 2006, **117**, 49–56.
18. Hellstrom, D. and Karrman, E., Exergy analysis and nutrient flows of various sewerage systems. *Water Sci. Technol.*, 1997, **35**, 135–144.
19. Glandon, R. P., Payne, F. C., McNabb, D. C. and Batterson, T. R., A comparison of rain related phosphorus and nitrogen loading from urban wetland and agricultural sources. *Water Res.***,** 1981, **15**, 881–887.
20. Harremois, P., The challenge of managing water and material balances in relation to eutrophication. *Water Sci. Technol.*, 1998, **37**, 9–17.
21. Rodriguez, L. and Macias, F., Eutrophication trends in forest soils in Galicia (NW Spain) caused by the atmospheric deposition of nitrogen compounds. *Chemosphere*, 2005, **63**, 1598–1609.
22. Muller, F, Schrautzer, J., Reiche, E.-W. and Rinker, A., Ecosystem based indicators in retrogressive successions of an agricultural landscape. *Ecol. Indicators*, 2006, **6**, 63–82.
23. Brye, K. R., Norman, J. M., Gower, S. T. And Bundy, L. G., Methodological limitations and N-budget differences among a restored tall grass prairie and maize agro-ecosystems. *Agric. Ecosyst. Environ.*, 2003, **97**, 181–198.
24. Chanakya, H. N. and Nagaraja, N. S., Reclamation and sustainability of wastelands, ASTRA technical Report, IISc, Bangalore, 1993.
25. Gupta, A. B. and Gupta, S. K., Simultaneous carbon and nitrogen removal from high strength domestic wastewater in an aerobic RBC biofilm. *Water Res.*, 2001, **35**, 1714–1722.
26. Meyer-Aurich, A., Economic and environmental analysis of sustainable farming practices – A Bavarian case study. *Agric. Syst.*, 2005, **86**, 190–206.
27. Laclau, J.-P., Ranger, J., Deleporte, P., Nouvellon, Y., Saint-André, L., Marlet, S. and Bouillet, J.-P. Nutrient cycling in a clonal stand of Eucalyptus and an adjacent savanna ecosystem in Congo 3. Input–output budgets and consequences for the sustainability of the plantations. *For. Ecol. Manage.*, 2005, **210**, 375–391.
28. Liu, J., Price, D. T. and Chen, J. M., Nitrogen controls on ecosystem carbon sequestration: A model implementation and application to Saskatchewan, Canada. *Ecol. Model.*, 2005, **186**, 178–195.
29. Wegehenkel, M. and Mirschel, W., Crop growth, soil water and nitrogen balance simulation on three experimental field plots using the Opus model – A case study. *Ecol. Model.*, 2006, **190**, 116–132.

ACKNOWLEDGEMENTS. This study has been greatly benefited by the data provided by the Karnataka State Pollution Control Board, Bangalore. Data on water quality of Belandur tank was measured for an earlier study, where the inputs of Mr Karthick and Dr T. V. Ramachandra are acknowledged. The recent estimates of wastewater flow were provided by Mr Umesh, LDA, Bangalore.