

Soft Paths in Wastewater Management – The Pros and Cons of Urine Source Separation

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Separate disposal of human urine promises to improve water pollution control and nutrient recycling as compared to conventional wastewater treatment. Collection and reuse of urine is a technological innovation that also involves risks such as contamination by pharmaceuticals when urine is used as fertilizer.

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Abstract

Although our water-borne urban wastewater system is successful, it has drawbacks in industrialized and developing countries alike, particularly in arid regions. It is inflexible and often inefficient. Of late, source control measures are being postulated as a paradigm change. In the Swiss transdisciplinary project *Novaquatis*, urine source separation, or *NoMix* technology, was studied. We compare *NoMix* technology with central wastewater treatment. Separate collection of urine has the potential to eliminate 70 to 80 percent of nitrogen from wastewater, 15 to 50 percent of phosphorus, and at least 50 percent of human pharmaceuticals. Hence, *NoMix* technology can contribute substantially in the reduction of eutrophication of marine ecosystems near fast-growing cities. We discuss the shortcomings of using sewage sludge or urine as fertilizers in agriculture – concerning pharmaceuticals, we also consider the societal perspective. Furthermore, *NoMix* technology introduces flexibility to wastewater management, important especially in light of growing uncertainties with respect to population development and climate change.

Keywords

comparison of wastewater systems, micropollutants, *NoMix* toilets, nutrient recycling, pharmaceuticals, risk perception, source control, sustainability, technological innovation, transdisciplinary research, urine source separation, wastewater management, water pollution control

Today's urban water management system provides clean drinking water and disposes of wastewater with relatively small environmental impact – at least in many industrialized countries. Despite its worldwide dominance, it may not be the best solution to deal with pressing problems, e. g. lack of proper sanitation in developing countries, or with challenges such as climate change and population growth. The most serious problem is that 2.6 billion people, i. e., 42 percent of the world's population, lack satisfactory access to sanitation (data from 2002; WHO 2004). Moreover, we are polluting marine ecosystems with nutrients at a dramatic rate, which is leading to “dead zones” in oceans and to widespread collapse of fish stocks (Pelley 2004). Because grave water issues remain unresolved, Gleick (2003), for instance, postulates a transition in wastewater treatment from the current “hard path” – massive water infrastructure and complex central treatment plants – to a comprehensive “soft path”. The “soft path” should complement carefully planned centralized infrastructure with small-scale decentralized facilities in order to improve productivity of water use rather than seeking endless new water sources (Gleick 2003).

Experience shows that non-technical measures like the ban of phosphates in detergents efficiently combine with a centralized system (Siegrist and Boller 1999). Therefore, it has recently been proposed that *source control* measures – handling wastewater at the place of occurrence – and *waste design*¹ may in the long run be superior alternatives; a hypothetical example is a washing machine with internal recycling of water and washing powder to produce a minimum of waste (Larsen and Gujer 2001). Various technologies for decentralized wastewater treatment are avail-

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¹ Waste design is a concept related to source control. It corresponds to an agreement between wastewater authorities and consumers to influence temporal discharge and composition of wastewater. Today, in urban water management, waste design is put into action with prohibitions and instructions such as not to dispose of sanitary articles or chemicals in the toilet. In future, optimized purification technology could be chosen for each wastewater source in individual households (Larsen and Gujer 2001).

able (table 1). While most of them are appropriate for rural areas, they are not broadly applicable to modern urban settings. Technological development of small-scale wastewater systems for cities is urgently needed.

Urine constitutes less than one percent of domestic wastewater but accounts for most nutrients – typically 80 percent of the nitrogen (N) and 50 percent of the phosphorus (P) contained in wastewater (Larsen and Gujer 1996; see also figure 1). Consequently, urine source separation is a good example of a small-scale technology that could improve central facilities as proposed by Gleick (2003). The idea is intriguingly simple: By separating urine from wastewater, water pollution control could be improved with respect to nutrients, but also to pharmaceuticals and hormones. Wastewater handling at treatment plants would become simpler and cheaper because nutrient elimination is rendered unnecessary (Larsen and Gujer 1996)², provided that for nutrient sources other than households (e.g., industrial wastewater), additional source control measures are implemented. Further advantages of urine source separation are the potential use of



FIGURE 1: Distribution of nutrients contained in wastewater that stem from the human metabolism. Of the two important nutrients, nitrogen and phosphorus, the larger part is derived from urine. Separate collection and treatment of urine could reduce costs and simplify wastewater treatment.

nutrients from urine as fertilizer for agriculture, as well as water savings because some of the relevant toilets require little water. Overall, urine source separation would strongly increase flexibility of urban wastewater management, which is discussed below.

In the following, we discuss one possible technology for small-scale wastewater treatment: urine source separation, or *NoMix* technology. In *NoMix* flushing toilets (figure 2, p. 282), for instance, urine is collected in the front and drained into a separate storage tank. Feces are flushed away in the usual manner. Sweden, where the modern *NoMix* toilet was invented, was among the first countries who widely installed such toilets in pilot projects from the 1990s on.

² N and P removal obtained with simple biological treatment plants (sludge age two days; table 3) is due to their incorporation in the biomass. This incorporation is additive to the effect of urine separation, because urine contains very little organic matter. In countries that do not ban phosphates in detergents, however, some P elimination would still be necessary.

TABLE 1: Typical systems for wastewater treatment, depending on the available sewer system. This list is not comprehensive, but gives an overview of the principal technological options. Decentralized treatment is mainly applied in rural areas; appropriate technologies for urban settings still need to be developed.

sewer system	wastewater treatment system	remarks (e.g., treatment efficiency, suitability)
main technologies for wastewater treatment in Europe		
large sewer system	conventional central wastewater treatment in wastewater treatment plants	for treatment efficiency, see table 3
small sewer system	conventional decentralized wastewater treatment (e.g., constructed wetlands or trickling filters)	many variations with different treatment efficiencies; problems often associated with phosphorus; restricted to rural areas despite decades of experience
no sewer system	septic tanks	good, simple technology for removing organic matter in rural areas; very little nitrogen and phosphorus removal
simple sanitation (only toilet wastewater)		
no sewer system	pit latrines	toilet wastewater not treated
no sewer system	dehydration and compost toilets (dry toilets)	dehydration and composting are both disturbed by urine
no sewer system	dehydration and compost toilets with urine separation	increasingly used in rural areas (e.g., China, South Africa); excellent nutrient removal and recycling if urine and feces are properly disposed of
“new” concepts		
with or without sewer system	decentralized membrane bioreactors (treatment of mixed wastewater)	high costs and high energy demand; for single households very space demanding; nutrient elimination may cause instabilities
with or without sewer system	vacuum toilets (anaerobic treatment of feces and urine, preferably together with organic kitchen waste to dampen the high ammonia concentrations from urine that is toxic for the anaerobic biocenosis)	suitable for new dwellings because entire vacuum systems have to be constructed; very efficient nutrient recycling (nitrogen and phosphorus); if combined with urine separation, ammonia toxicity is avoided
with or without sewer system	urine source separation (possible in dry toilets, in vacuum systems, and with flush toilets)	very efficient since urine contains most of the nutrients from human metabolism; combines well with most other technologies (e.g., septic tanks); however, only in few situations will this technology alone solve all problems (see text)

Recently, various pilot projects were launched outside Scandinavia, e.g. in Germany, Austria, and Switzerland. Most of them show that while the existing *NoMix* technology may be suitable for rural areas, it has only limited applicability in urban areas, and that further technological development is necessary. A prominent problem is urine scaling, which leads to blockages in *NoMix* toilets and urine pipes (e.g., Udert et al. 2003). Here, technological ingenuity from the sanitary industry is required. Also the user comfort of *NoMix* toilets needs improvement: For instance, the necessity to sit when urinating can annoy men, but also women for hygienic reasons. Furthermore, separation efficiency of urine and feces needs to be enhanced. Despite such practical drawbacks, user acceptance of *NoMix* toilets among 1750 users in several Swiss pilot projects in institutions has been shown to be very high (Lienert and Larsen 2006). In households, where users are responsible for maintenance, acceptance of *NoMix* toilets depends on personal goodwill. Finally, transporting the urine to a processing unit forms a major obstacle: It can be conveyed by truck, but this is hardly appealing. In our opinion, the most attractive option is to circumvent urine transport by developing a decentralized urine treatment unit that can be installed near the *NoMix* toilet – in the cellar or bathroom.

After six years of research in the large Swiss transdisciplinary project *Novaquatis*³, we are convinced that *NoMix* technology could substantially improve urban wastewater management in developing, emerging, and industrialized countries alike. How-

ever, while many environmental benefits can be expected from such a paradigm change, introducing an innovation is always associated with uncertainties. The technical difficulties mentioned above are discussed elsewhere. In this article, we give a systematic overview of the main benefits, disadvantages, and risks of *NoMix* technology compared to central wastewater management (table 2) and discuss the major points that should be taken into account when further pursuing this innovation.

Wastewater Treatment: End-of-Pipe or At-the-Source?

Urban Sanitation and Water Usage

Modern urban wastewater management is based on the ancient *cloaca maxima* that was reinvented in the 19th century after the occurrence of diseases such as cholera in medieval cities.⁴ The historic development can explain our liberal water consumption. In Switzerland, for example, 162 liters of drinking water are used per person and day (data from 2003; BAFU 2007); of these, 30 percent (48 liters) are used to flush the toilet. Additional 240 li-

3 www.novaquatis.eawag.ch (accessed November 2, 2007); see also Larsen and Lienert (2007).

4 www.sewerhistory.org (accessed November 2, 2007).

FIGURE 2: A modern *NoMix* toilet. Urine is collected separately in the front bowl, while feces and toilet paper are flushed away in the back compartment. The urine drain is connected to a storage tank in the cellar. While the principle is simple, there are still various problems to be solved. For instance, smaller children find it difficult to position themselves correctly.



TABLE 2: Benefits and disadvantages of two approaches to wastewater management. a) Current end-of-pipe system with sewers and central wastewater treatment plants. b) Source control measure where urine is separated from wastewater; urine can then be treated to eliminate nutrients and micropollutants (human pharmaceuticals and hormones), or the nutrients can be reclaimed as fertilizer for agriculture. Details are discussed in the text.

	A) CURRENT END-OF-PIPE SYSTEM		B) URINE SOURCE SEPARATION	
	benefits	disadvantages	benefits	disadvantages
current status	well-established, many years of experience	natural monopoly hinders better solutions	innovation that could potentially be developed into a superior technology	very little experience in modern, urban areas
urban sanitation	successful in industrialized countries	not successful in water-scarce, rapidly developing countries	viable alternative to centralized system in rural areas (e.g., dry separation toilet)	adequate technology for urban areas not yet available; various system components need further development
water usage		system relies on large amounts of water to flush waste	potential for lower water consumption and easier wastewater recycling	not all NoMix toilets save water
water pollution control (removal of nitrogen, phosphorus, micro-pollutants)	relatively high standards possible; centralized monitoring possible	system comes to its limits at high population densities (e.g., sewer leaks and overflows, limited treatment capacity)	potential for even higher water pollution standards; no urine loss if urine is treated locally	monitoring decentral devices is more difficult
nutrient recycling (nitrogen, phosphorus)	all nutrients recyclable via reuse of wastewater for irrigation; most phosphorus recyclable via sewage sludge	irrigation: problems with hygiene, contaminants, and over-fertilization; sewage sludge: problems with plant availability and contaminants	most nutrients in wastewater come from urine and are recyclable via direct spreading of urine; precise application of nitrogen and phosphorus possible through processing	problems with hygiene, contaminants, and loss of nitrogen; urine processing technologies not yet available for full-scale application
infrastructure	usually well-established in industrialized countries	difficult to establish in rapidly growing cities; high investment costs and longevity of wastewater treatment plants make shift to other technologies uneconomical	first step towards decentralized wastewater management; more decentralized technology leads to higher flexibility and innovation	much technology development necessary, especially for cities; shift from central installation and maintenance to households
flexibility		extremely inflexible; fast adaptation to new problems not possible; limited variety of process engineering technologies	highly flexible; quickly adaptable to changing requirements; large technological variability; different aims possible (e.g., removal of nutrients or micropollutants)	
costs	economy of scale with centralized wastewater treatment plants	high costs, usually carried by community; often too expensive for low-income countries	potential for very effective wastewater treatment at low costs; economy of scale possible (mass-produced units from individual firms)	current costs are high since urine source separation technology is still in pilot phase

ters per person per day are used for other purposes (e. g., industry) or lost from leaky pipes (twelve percent). In water-rich countries, high water consumption is rarely a problem. However, in water-scarce regions such as Australia or Mediterranean countries, this is a pitiable waste. In many developing countries, it has proven impossible to transfer our system successfully – with disastrous results. An estimated 1.8 million people per year, 90 percent of which are children under five years, die from diarrheal diseases, including cholera (WHO 2004). 88 percent of diarrheal diseases are attributed to inadequate water supply, sanitation, and hygiene – a situation similar to medieval Europe. Many of these countries are arid, and a water-based sewer system is hardly feasible – even if it were affordable.

How can urine source separation contribute to solve these problems? Theoretically, a water-saving *NoMix* flushing toilet reduces water consumption by over 50 percent compared to a conventional modern 3/6 liter dual flush toilet. However, since many people use the six liter flush to get rid of the toilet paper after urinating, in practice the potential savings are lower (Lienert and Larsen 2006), a problem that remains to be solved. In public buildings, urine from men can be collected with waterless urinals. These also save large amounts of water, which is the reason for their growing distribution.⁵ In arid regions, reuse of wastewater is gaining importance. Urine source separation can contribute to safe and efficient wastewater reuse, because treatment is easier if salt contents are low (urine has a high salt content). Combined with separate treatment of feces, the hygiene of wastewater recycling is also improved.

Water Pollution Control

Urban wastewater management in industrialized countries has a history of lagging behind environmental problems. Early treatment plants were built in the 1960s to deal with organic matter. Additional treatment steps followed to tackle eutrophication, phosphate loading of lakes, and N over-fertilization, e. g. of the North Sea (Siegrist et al. 2003). Today, many countries are discussing measures to deal with organic micropollutants (e. g., pharmaceuticals and hormones). Moreover – although in Switzerland,

for instance, 97 percent of the houses are connected to sewers – treatment efficiency is usually less than 80 percent, even with the best available technology. This is mainly due to sewer leaks and discharge of untreated wastewater during strong rain events (Larsen and Gujer 2001). Source control measures can therefore augment the system's efficiency, especially if the concentrated wastewater streams are treated locally.⁶ Because urine contains a large fraction of nutrients and micropollutants, all mentioned aspects can be influenced by *NoMix* technology, as we discuss below.

Removal of Nutrients

Worldwide, improved nutrient elimination is required to protect estuaries, for instance in the Baltic Sea (Conley et al. 2002), but increasingly also in developing and fast-industrializing countries. Many large cities cannot cope with their wastewater; it reaches the environment untreated, with severe impacts on marine ecosystems. The *United Nations Environment Programme* warned in 2004 that while over-fishing was the biggest marine issue in the 20th century, in the 21st century it could well be oxygen depletion in marine “dead zones” caused by massive input of nutrients, particularly N (Pelley 2004). Population densities in coastal areas are already high; population growth and urbanization will enhance this problem. It can only be circumvented by strict nutrient management (Mee 2006). *NoMix* technology could be a comparatively simple but highly effective measure (table 3).

In view of the global N fluxes, *NoMix* technology could have a dramatic impact. The estimated total flux of reactive N from

5 Vacuum toilets (necessitating installation of vacuum sewers) also save water, albeit usually without separate collection of urine (table 1). Of course, dry toilets are even more water-saving.

6 Local processing of urine would imply a shift from centralized wastewater management to households, and concepts on how this could best be organized still need to be developed. In wastewater management, this approach is new and possibly intimidating. However, central organization of decentralized household units is well known from other areas such as heating, where controlling and maintenance are carried out by professionals on a contract basis.

TABLE 3: Estimated efficiency of nutrient elimination in different wastewater treatment plants (WWTPs) compared with urine source separation (modified from Larsen et al. 2007). The estimates are based on European technical standards and consider domestic wastewater only; we assumed that all households are connected to WWTPs and that five percent of raw wastewater is lost in sewer overflows.

	typical removal efficiencies (%)			NH ₄ ⁺ effluent concentration ^b
	COD ^a	nitrogen	phosphorus	
WWTP, primary treatment (only sedimentation)	30	5	5–15	high
WWTP, chemical precipitation (like above, but with addition of chemicals)	60–75	15–30	85–95	high
WWTP, sludge age 2 days	75	25	15–85 ^c	high
WWTP, sludge age 8–10 days	90	25	15–85 ^c	low
WWTP, sludge age > 12 days	90	50–75	15–85 ^c	low
WWTP, sludge age > 12 days, with addition of organic carbon source	90	85	15–85 ^c	low
WWTP, like row 1–6, but with phosphorus elimination and phosphorus filter	see row 1–6	see row 1–6	> 85	see row 1–6
urine source separation (90% separation efficiency)	15	70–80	15–50	low

a Chemical oxygen demand, a measure for the amount of organic substrate. | b Ammonium that is released from WWTP to receiving water. | c Depending on the amount of phosphorus from detergents and whether phosphorus elimination (biological or chemical, but without phosphorus filter) is included at the WWTP.

continents to the sea amounts to 48 million tons per year (Galloway et al. 2004). About 20 million tons are excreted by the world's population (Larsen et al. 2007). Today, only few countries have denitrifying wastewater treatment plants (WWTPs) with 50 to 75 percent N removal (sludge age > 12 days, without organic carbon source; table 3), and many have no WWTPs at all. Urine source separation as *only measure* could equal or surpass the standards of conventional denitrifying WWTPs by removing about 70 to 80 percent of the N in wastewater (table 3). Hence, in areas without WWTPs, *NoMix* technology combined with discharge of the remaining wastewater to the sea can potentially improve marine water quality rapidly. Combined with fecal sludge management and a phosphate ban for detergents, urban hygiene could also be improved, and P emissions could be drastically reduced. In industrialized countries, *NoMix* technology would simplify existing WWTPs and reduce costs. Its large N elimination potential would allow for high standards of water pollution control – a positive outcome also because ammonia (NH₃) is toxic for fish.

Generally, P elimination is acknowledged as an efficient measure to prevent eutrophication of lakes; 15 to 50 percent of P can be removed from wastewater if 90 percent of the urine are separated (table 3). There are examples showing that conventional technology is reaching its limits. The Swiss Lake Greifen, for instance, located in a densely populated area with intensive agriculture, is strongly eutrophicated; 52 percent of the biologically available P stems from wastewater, and conventional measures are probably insufficient to achieve the desired water quality (Meier 2003). Similarly, even the best available conventional technology would not sufficiently reduce the massive phosphate loading of Dianchi Lake near Kunming in China (Huang et al. 2007). Presumably, only a combination with source control measures – in agriculture and urban water management – will bring success. Stakeholders in Kunming are open towards source control measures, including *NoMix* technology (Medilanski et al. 2006).

Removal of Micropollutants

Some organic micropollutants are known to pass wastewater treatment plants and have been detected in receiving waters, ground water, and even drinking water (e. g., Kolpin et al. 2002). Whether they pose a risk to aquatic ecosystems is unknown. We do know that certain substances affect organisms – a well-known example are hormones; e. g., vitellogenin synthesis in male fish was observed after exposure to estrogens (Routledge et al. 1998). Other unexpected effects are possible. For instance, frequently prescribed heart medicals, beta blockers, were found to inhibit photosynthesis of algae (Escher et al. 2006). However, the consequences for real populations or ecosystem functioning are unclear, and the precautionary principle seems therefore justified.

Many pharmaceuticals are strongly metabolized in the human body, which increases their water solubility and allows excretion with urine. On average, about two thirds of a pharmaceutical are excreted with urine (64 percent; Lienert et al. 2007a). However, the difference between pharmaceuticals is immense. X-ray contrast agents, for instance, are almost exclusively excret-

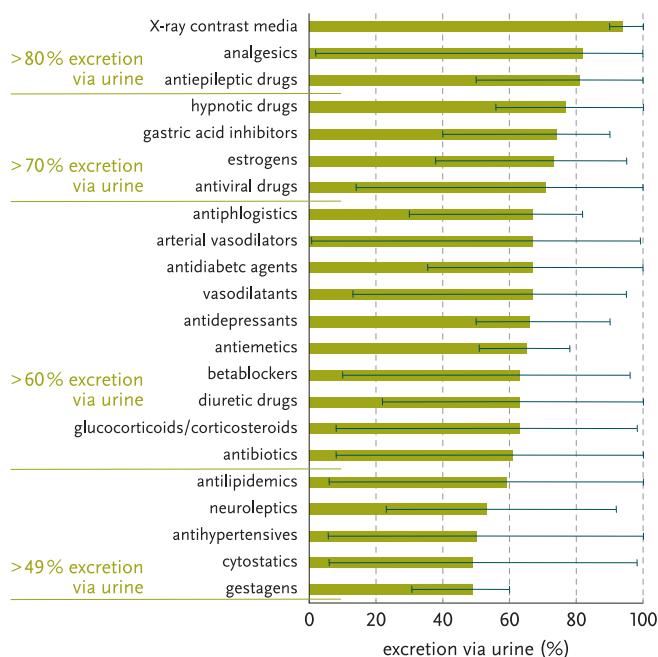


FIGURE 3: Percentage of pharmaceuticals excreted via human urine. The green bars represent the average in percent of the ingested quantity; the error bars show the maximal and minimal values, respectively. By separating urine from wastewater, two thirds of the anthropogenic medicals in wastewater might be eliminated. Diagram after Lienert et al. (2007a).

ed with urine; drugs such as the antibiotic erythromycin are excreted to 90 percent or more via feces. Many other compounds are found in both fractions (figure 3). The ecotoxicological risk of urine and feces is about equal (Lienert et al. 2007b). Hence, from a quantitative point of view, separating urine would eliminate around two thirds of the anthropogenic medicals in wastewater, but would reduce the ecotoxicological risk only by about 50 percent.⁷ However, if the (mostly lipophilic) substances contained in feces adsorb better to sewage sludge, their removal in wastewater treatment plants should be easier than the removal of the (mostly water soluble) substances in urine. This hypothesis merits verification; if it proves true, *NoMix* technology could contribute to eliminating most human medicals from wastewater.

Nutrient Recycling

Known P reserves will last for only about 120 years at the present rate of consumption – a short time in view of the essential nature of P and the increasing need for fertilizers in the developing world. There are P reserves about three times larger in the Atlantic and Pacific Oceans (USGS 2007). P recycling is thus not primarily a question of limited resources, but of economic avail-

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⁷ We did not take into account the disposal of medicals via toilets and sinks because these numbers vary greatly and have not been much investigated. In a survey of 500 visitors of a public Swiss library, only one percent said that they disposed of medicals via the toilet, while numbers from England and Germany seem to be considerably higher (discussed in Lienert et al. 2007b).

ability for the poor. Regarding N, there exists an unlimited N₂ supply to produce N fertilizer; it is, however, a question of energy.

Due to the fear of organic contaminants, P recycling via sewage sludge is increasingly questioned (e.g. in Sweden; Bengtsson and Tillman 2004). In Switzerland, after a polemic public debate, use of sludge in agriculture has been forbidden.⁸ Urine could overcome this restriction since it contains most nutrients in wastewater, but hardly any heavy metals and only few organic pollutants (e.g., Hammer and Clemens 2007). In Switzerland, based on the 2005 use in agriculture (BLW 2006) and typical N and P contents of urine (Larsen and Gujer 1996), urine fertilizers could replace roughly half the N and half the P from mineral fertilizers. Several studies showed that urine, including the processed urine products from *Novaquatis*, is suitable as plant fertilizer (Larsen and Lienert 2007). However, we must ensure that co-recycling, e.g. of micropollutants, does not counteract the positive effects.⁹

In Sweden it is recommended to store urine for six months to hygienize it (Hoglund et al. 2002). Despite of this, direct spreading of urine on fields may lead to unintended effects, even if prolonged storage eliminates the risk of contamination with pathogens. The fixed ratio of N and P in urine – determined by the nutrition of the population and the transformations occurring during storage (Udert et al. 2006) – may not correspond to the requirements of the crops, leading to over-fertilization with N or P. In dry climates, accumulation of salts from urine may harm soils and crops. Whereas high demand for nutrients may justify direct spreading (e.g., in Africa), we deem processing of urine appropriate in most other situations. For P, precipitation of struvite (magnesium ammonium phosphate) efficiently concentrates P as a dry, white powder without any heavy metals and practically free of pharmaceuticals (Ronteltap et al. 2007). For N, technologies exist that increase the N concentration in urine five- to tenfold with an energy demand of around 30 megajoules per kilogram N compared with the average 45 megajoules needed to produce conventional N fertilizer (Maurer et al. 2003). However, uptake efficiency of N fertilizer may be more important than the energy required for its production: An N fertilizer from urine may lead to less or more N emissions – including the strong greenhouse gas N₂O (Galloway et al. 2003) – from fields than the commercial fertilizer it replaces.

Do Pharmaceuticals in Urine Pose a Risk to Agriculture?

It has been postulated that micropollutants from urine are no risk for agriculture because they are degraded in the soil. Butzen et al. (2005) and Schneider (2005) found that the concentration of some medicals decreased in the soil, with large variability between different substances. The mechanisms were unclear; sorption to the soil matrix seems probable (Schneider 2005). Additionally, 15 to 30 percent of some polar pharmaceuticals were taken up by plants; of some substances, a part infiltrated and leached from the soil (Schneider 2005). For analytical reasons, unrealistically high concentrations were used, but the results still give rise to concern.

In *Novaquatis* we wished to avoid a new pathway of introducing pharmaceuticals to the environment – the sewage sludge debate in Switzerland having shown that food safety ranks high on the public agenda. This was confirmed by our own surveys concerning urine fertilizers among Swiss consumers (Pahl-Wostl et al. 2003) and farmers (Lienert et al. 2003). The precautionary principle is also adopted by the Swiss agricultural authorities, who will only give definite approval to use the processed urine from a pilot project in the Cantonal Library of Basle-Land if stringent quality targets are met.

While high quality standards are demanded for recycled urine, many pollutants are released via common agricultural practice. For instance, the potential input of heavy metals by human urine is at least ten times lower than from animal slurry (assuming optimal fertilizer doses), and the fluxes of copper, nickel, and lead are even 100 times lower (Hammer and Clemens 2007). Also the potential flux of the antibiotic oxytetracycline from human urine is 25 times lower compared to cattle slurry and more than 300 times lower compared to pig slurry. A decrease from pig slurry over cattle slurry to human urine was also found for estrogens (Hammer and Clemens 2007). On the other hand, some widely-used human medicals (e.g., diclofenac) are hardly applied in veterinary medicine.

Can Micropollutants be Removed from Urine?

Our research indicates that in Switzerland urine fertilizer containing micropollutants will not be accepted by society. Therefore, we investigated how human medicals can be removed from urine. A variety of technologies for processing urine were developed in *Novaquatis* in order to profit from the benefits of nutrient recycling while excluding potential environmental damage. By separating P and N, unintentional over-fertilizing with one of the nutrients could be avoided, and separating microorganisms, micropollutants, and even salts from nutrients would allow fertilizing without risking harm. Maurer et al. (2006) give a comprehensive overview of these technical options.

Future Challenges and Flexibility

Most importantly, maybe, *NoMix* technology introduces flexibility in wastewater treatment. The current centralized sewer system is built to last for 50 to 100 years. In future, we expect growing uncertainty concerning the longer-term prospects of urban water management systems, which makes planning increasingly difficult (Lienert et al. 2006). The world's population is growing by nearly 80 million people per year,¹⁰ with increasing urbanization and water scarcity, also due to climate change. Today's

8 www.bafu.admin.ch/abfall/01472/01481 (accessed November 6, 2007).

9 A potential scenario for nutrient reuse from wastewater could look as follows: Urine is separated from wastewater and processed to remove unwanted substances such as pharmaceuticals. Its nutrient composition is optimized to meet specific crop requirements. Sewage sludge still contains many contaminants but only few nutrients and is incinerated.

10 www.unep.org/geo2000/ov-e/index.htm (accessed November 6, 2007).

wastewater infrastructure cannot keep pace with the growth rate of many cities. Higher population density and lower water resources call for more efficient treatment systems: Separation of at least 50 percent of human urine from wastewater allows for smaller, energy-efficient treatment plants with excellent removal of N and P, which might even transform wastewater management from an energy-consuming to an energy-producing process (Wilsenach and van Loosdrecht 2006). Decentralized units can be introduced at a much faster rate than a central system. Moreover, decentralized *NoMix* units can be adapted to suit local requirements; e.g., they can be made cheap and simple or sophisticated and expensive, and they can deal with N only or also handle P or even micropollutants.

Climate change could strongly affect urban water management in Europe in the form of drier summers and water scarcity (Rowell and Jones 2006): Because of reduced water flow in rivers, the wastewater discharged by treatment plants will be less diluted, and ammonia and nitrite toxicity might again be an issue. As discussed above, *NoMix* technology allows more stringent nutrient emission standards, which would help overcome these problems. Heavy rain events could occur more often, resulting in loss of untreated wastewater in combined sewer overflows. Also in this regard, *NoMix* technology could be helpful because urine would no longer be mixed with storm water.

As a new innovation, *NoMix* technology is still more expensive than conventional technology. In Switzerland, reduced investment costs at wastewater treatment plants as a consequence of *NoMix* technology could make available about 1250 to 2100 CHF per household for installing *NoMix* technology (assuming a 15-year lifetime of a *NoMix* unit and no increase in maintenance costs; Maurer et al. 2005). We expect that with mass-produced *NoMix* units, it is possible to reach this benchmark.¹¹

Conclusion

NoMix technology is remarkably flexible; it can improve water pollution control, help to close nutrient cycles, and is adaptable to different situations in industrialized, emerging, and developing countries. It exemplifies a small and relatively simple source separation measure that could have a high impact and might trigger a worldwide paradigm change. It is currently in an early stage of technological innovation. Some components such as *NoMix* toilets are available, albeit not yet quite equaling the standards of modern bathroom technology. Nonetheless, *NoMix* toilets are widely accepted by the public (Lienert and Larsen 2006). This justifies further development of the *NoMix* technology by sanitary firms, which are currently reluctant to invest in a technology without existing markets. Other components, such as urine processing units, are still in the laboratory phase (Maurer et al. 2006).

Hence, as a next step, further technology research and development is needed, both in scientific institutions and in innovative companies, in order to bring important *NoMix* components

on the market. An example is the German firm Huber¹² who recently developed a struvite reactor to recover phosphate from urine. Most importantly, however, concepts are needed to help introducing *NoMix* technology into the existing system. Entry markets have to be identified, as well as technological pathways that bring major advantages compared to the current central system. This is usually a task of (socio-economical) innovation research; in later stages, market analyses are to be carried out by enterprises. However, it will not be easy to overcome the current lock-in situation of urban wastewater management, i.e., high investment costs and longevity of wastewater treatment plants make a shift to other technologies uneconomical. Presumably, the only way is to combine technological and natural science with socio-economic research in transdisciplinary projects such as *Novaquatis* that include cooperation with private firms. We are convinced that *NoMix* technology merits these large efforts.

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- 11 Costs are crucial to any technology. Because many components of the *NoMix* technology have not yet been developed, cost estimates are very difficult – among other factors, they depend on the technology envisaged and the materials used. Urine processing can aim at different goals (e.g., nitrification, micropollutant removal, fertilizer production), and different possible technologies entail different costs. Even with initially high costs, mass production can make prices fall rapidly, as has recently been the case with membrane technology.
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