62e, April 2007
Eawag: Swiss Federal Institute of Aquatic Science and Technology

Eawag News

Tracking Material Flows in Foreign Lands

Editorial

Roland Schertenleib, member of the Eawag Directorate and former head of the Department of Water and Sanitation in Developing Countries (Sandec)

Developing Solutions Using Material Flow Analysis

In developing and emerging countries, more than 1.2 billion people have no access to safe drinking water and more than 2.6 billion lack appropriate sanitary facilities. A large proportion of municipal solid waste is not even collected, let alone disposed of in an environmentally safe manner. Accordingly, the infectious and parasitic diseases directly associated with these conditions remain one of the key problems facing these countries. Also coming increasingly to the fore are acute and chronic environmental problems that have been familiar in industrialized countries for decades.

With its wide-ranging expertise, Eawag has already been active in elaborating solutions for problems in developing and emerging countries for many years. Frequently, this involves applying and adapting methods that have been successfully employed in the industrialized world. At the same time, Eawag always cooperates closely with local partners. The research projects thus also promote knowledge transfer and the building of research capacity in the countries of the South.

In the early 1980s, the method of material flow analysis was developed at Eawag for substances and goods of environmental relevance. Since then it has proved to be a valuable instrument in environmental management, and it can also usefully be applied to urgent environmental problems in developing and emerging countries. The advantage of this approach is that it makes it possible to describe entire regions, providing a good overview of systemic relationships and causes of problems even in cases where only limited data is available.

This issue of Eawag News reports on a series of international projects in which material flow analysis is used to tackle environmental problems. For example, excessive nutrient levels in waterbodies are a major problem in numerous countries, including Vietnam and Thailand, and also in Lake Kivu (DR Congo/Rwanda). By preparing phosphorus, nitrogen and silica balances, Eawag researchers are helping to identify sources of nutrients and possible control measures. In Bangladesh, where paddy fields are contaminated with toxic arsenic from irrigation water, Eawag is working with local partners to find out whether it accumulates in the soil, posing a risk to human health. As populations grow and living standards rise, increasing amounts of waste are also arising in developing and emerging countries. Material flow analyses in Eritrea and Cuba show how the volumes of waste to be disposed of could be reduced, e.g. by composting and recycling. The associated costs are calculated with the aid of a combination of material flow and process cost analysis. In addition, to assess whether possible measures could be effectively implemented, the analysis of waste streams in Cuba was combined with sociological studies. In this way, the attitudes of the public or policymakers can be explored.

Today, material flow analyses are generally used in the simulation of different scenarios and to quantify the ecological effects of potential measures. However, this method alone is not sufficient to assess health risks and alternative measures designed to improve public health – questions of crucial importance given the prevalence of infectious and parasitic diseases in the countries of the South. For this purpose, pathogen flows need to be analysed and combined with a so-called Quantitative Microbiological Risk Analysis (QMRA). Eawag is currently addressing this new challenge in cooperation with the Swiss Tropical Institute in Basel.

Roland Schertenleib

Cover photo: A boy from Srinagar village in Bangladesh helping to collect samples on a flooded paddy field during the monsoon season. This device is used to withdraw water samples from various sediment depths. For more information, see the article entitled "Arsenic in paddy fields – a hazard?" on p. 9. © Linda Roberts, Eawag

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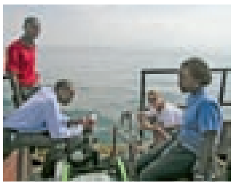
Lead Article

Research Reports

Photos: Eawag



Miscellaneous

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Publisher, Distribution: Eawag, P.O. Box 611, 8600 Dübendorf, Switzerland, Phone +41 (0)44 823 55 11, Fax +41 (0)44 823 53 75, **www.eawag.ch**

Editor: Martina Bauchrowitz, Eawag

Translations: Jeff Acheson, Bottmingen

Linguistic Revisions: Helen Brügger-Clarke, Zurich

Publication: 2–3 times per year in English, German and French. Chinese edition in cooperation with INFOTERRA China National Focal Point.

Figures: Peter Nadler, Küsnacht

Design: TBS Identity, Zürich

Layout: Peter Nadler, Küsnacht

Printed: On original recycled paper

Subscriptions and changes of address: New subscribers are welcome! **eawag.news@eawag.ch**

ISSN 1440-5289

Lead Article


Material Flows: from Analysis to Management

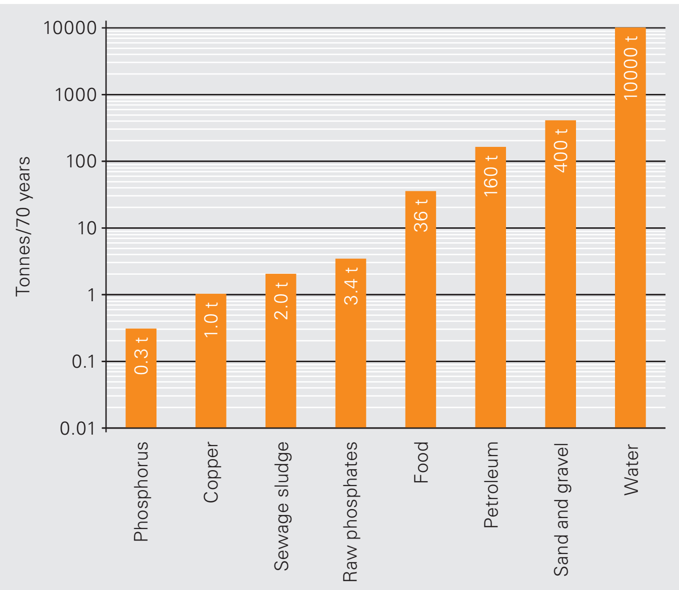
Hans-Peter Bader, theoretical physicist and head of the "Material Flows in the Anthroposphere" group, Hans-Joachim Mosler, social and environmental psychologist and head of the "Social Systems Modelling" group
Co-author: Martina Bauchrowitz

The analysis of material flows is essentially a kind of environmental accounting: rather than financial and other assets, the "balance sheet" records substances and goods of environmental relevance. Eawag is now increasingly also using this method to address acute environmental problems in developing and emerging countries.

In the course of a lifetime, each person is responsible for considerable flows of goods, materials and energy (Fig. 1) [1]. Over the past few centuries, these flows have increased dramatically. This is attributable to two factors – the rapid growth of the global population and the up to 100-fold rise in per capita consumption. These developments have major impacts on the environment – water, soil, air – and hence also on human health.

Effective Environmental and Health Protection Facilitated by Material Flow Analysis. It generally takes a long time for the effects of exposure to pollutants to be revealed. A case in point is the endemic disease that afflicted people working in paddy fields on the lower reaches of the Jinzu River in Japan in the late 1940s. The symptoms of the disease, which claimed many lives, included massive bone deformations and severe pain. For this reason, it was called "itai-itai" in Japanese, which translates as "ouch-ouch". It was not until about 20 years later that the victims were found to have been suffering from the effects of cadmium poisoning. At upstream facilities, both zinc and cadmium were mined, and the mining wastewater was used to irrigate the rice fields. Cadmium was at that time – and in some cases is still today – used in dyes and nickel-cadmium batteries and as a plastic stabilizer and anticorrosive agent. It is widely distributed within the man-made environment or "anthroposphere" (Fig. 2) [2].

Fig.1: Average material turnover for a human in the course of 70 years of life (N. B. logarithmic scale).



This example illustrates how important it is to detect harmful or undesirable material flows as early as possible – e. g. with the aid of material flow analysis [1]. This method makes it possible to track the fate of substances or goods from the point of origination or production, through residence in the anthroposphere, to final storage, disposal or degradation. However, the method is also attractive in the case of acute environmental problems, as it enables researchers – using literature data, without the need for large-scale measurement campaigns of their own – to gain an initial overview of a system, possible causal factors and remedial measures.

Before this method began to be applied in environmental research, from the mid-1980s onwards [3], it had already been successfully used for more than 20 years in the field of chemical engineering, as a tool for optimizing the consumption of materials and energy in chemical production processes [4]. In economics, the approach can even be traced back to the 1930s [5].

Material Flows Analysed by Eawag Worldwide. As material flow analysis was developed in Europe, initial applications of the method focused on this region. Numerous studies of a wide variety of systems were carried out in Switzerland, Sweden,

M. Schaffner, Eawag

Data collection: fish farm operators in Thailand are surveyed on feeding practices.

the Netherlands and other European countries. The topics of investigation were, firstly, mass goods such as water, timber, construction materials and energy. Also studied was the fate of individual elements, such as the nutrients nitrogen and phosphorus; the heavy metals copper, iron, zinc, cadmium, mercury and lead; and carbon, sulphur and chlorine as important components of biogeochemical cycles.

Studies currently being carried out in Switzerland by Eawag together with partners include analyses of flame retardants, micropollutants, biocides and heavy metals in cement. Increasingly, however, Eawag is also studying material flows in developing and emerging countries. In these cases, the aim is generally to determine the causes of acute environmental problems or identify options for improving existing wastewater or waste management systems.

Procedure for Material Flow Analysis. Depending on the specific research topic, material flow analysis may range in scope from the measurement and representation of material flows in simple systems to the description of complex systemic relationships with the aid of computer-based mathematical models. Today, computer-aided material flow analysis normally involves a series of steps:

► Selection of the system to be studied: it is necessary to define not only the geographical and temporal boundaries of the system but also the materials to be analysed and the degree of detail.

► Development of the model: on the basis of current knowledge of the system, the compartments (e.g. water, soil) or processes (e.g. private households, agriculture, wastewater management) relevant to material flows are first defined (Fig. 2). The relationships (links) within the system are then expressed in terms of mathematical formulae.

► Calibration of the model: in this process, data for the model parameters are collected from various sources – measurements, literature data, estimates and expert knowledge. The model parameters are the characteristic values of the model, whose variation corresponds to different system states. The parameters may be based on direct measurements, e.g. substance concentrations and residence times. Frequently, however, the model parameters are indirect values, e.g. substance transfer coefficients, which first have to be calculated on the basis of the data collected. Subsequent estimation of the model parameters is designed to

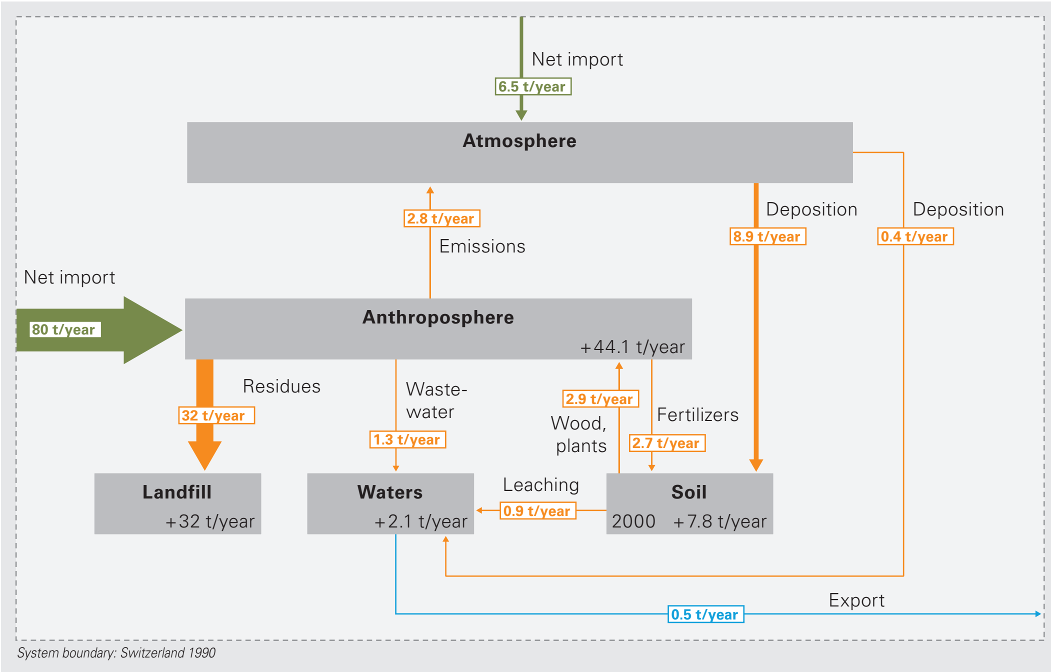


Fig. 2: Cadmium flows (tonnes) in Switzerland in 1990 (data from [2]). The bottom right-hand figures in the boxes indicate the increase in stocks. The bottom left-hand figure in the "Soil" box indicates the amount of cadmium that has accumulated in the past. Corresponding figures are not available for the other compartments.

determine how accurately the model describes the system under investigation.

► Identification of key parameters and remedial measures: the calibrated model is used to represent the current state but also, via a sensitivity analysis, to identify the key parameters (i. e. those parameters whose variation causes material flows to react most sensitively) and to simulate possible options for achieving desired changes.

► Interpretation of results: the results are evaluated and discussed with the involvement of stakeholders.

To facilitate the analysis of material flows, the modelling program SIMBOX was developed at Eawag (see Box). The first relatively simple material flow analyses were carried out without the aid of modelling [3]. Researchers quantified material flows on the basis of data sources, visualized the results in a graphical form and discussed potential control options using this schematic model.

SIMBOX

SIMBOX is a computer program developed by Eawag for the simulation of mass, substance, energy and monetary flows in anthropogenic systems [6]. It is now used internationally by engineers, companies, authorities and research institutes. The system is defined in a graphic-interactive environment. The modelling approach is then defined with a set of mathematical equations. Based on the input data and equations, SIMBOX calculates the flows (and stocks) for a current state (stationary system) or as a function of time (dynamic system). SIMBOX offers a variety of options for presentation of the results: flow charts, variables in function of time, animations and special visualizations. The program can also evaluate the credibility of the output by means of uncertainty analysis and use sensitivity analysis to determine which model parameters decisively influence material flows.

Data Collection by Direct Field Measurements. The essential basis for a material flow analysis is provided by the input data. Ideally, of course, substances should be measured directly in the field. This is possible in cases where the system boundaries are relatively narrowly defined, as in the study described in the article by Linda Roberts and Stephan Hug (p. 9). This is concerned with arsenic concentrations and flows in a paddy. Since groundwater pumps were introduced throughout Bangladesh, arsenic has been continually released onto rice fields in irrigation water. The Eawag researchers wish to assess how arsenic behaves in the environment and whether it poses a risk to human health.

Field measurements are also appropriate whenever the focus is on a unique system, such as that described in the article by Martin Schmid (p. 24) – Lake Kivu in Central Africa. The deep waters of this lake contain large amounts of carbon dioxide and methane. If these gases reached the surface, the local population would be asphyxiated as a result of the lack of oxygen that would then prevail. Recent measurements indicate that methane concentrations – and the associated risk of a gas eruption – have risen further over the past three decades. Eawag is investigating the causes of this development.

Using Estimates to Fill Data Gaps. What can be done if the system to be analysed is too extensive and complex to permit comprehensive direct measurements? In this case, researchers have recourse to available literature data (including data from comparable systems) and attempt to fill gaps in the data with estimates. One possible approach is to carry out direct surveys of the parties or people involved in the system. For example, in order to evaluate how much feed the fish receive in the aquaculture facilities on the Tha Chin River in Thailand, the Eawag researchers Monika Schaffner and Irene Wittmer visited the operators and asked them to provide details of their feeding practices. The aim of this project is to identify the sources of excessive nutrient inputs to the Tha Chin River and to define possible control measures (see the article on p. 18).

Data gaps can also be filled with the aid of expert judgements. For her project in Hanoi Province, Vietnam, the Eawag researcher Agnes Montangero elicited the views of experts (see the article on p. 21). She was thus able to estimate that relatively little phosphorus is retained in the septic tanks, which are the standard type of sanitary system. This project is also designed to show how the nutrient load in waterbodies can be reduced. The calculations indicate that the introduction of a urine-diverting latrine system would significantly improve water quality.

Assessment of Results. Another key step in the material flow analysis process is assessment of the results. The aim is to evaluate the actual impacts of the material flows in question on the environment and human health. However, this is not possible with material flow analysis alone: additional knowledge is required from other fields, such as ecotoxicology, biology and limnology. For example, the data from the material flow analysis need to be viewed in relation to ecotoxicological "quality targets". These specify substance concentrations that are not to be exceeded (limit values), so as to prevent adverse effects on the environment and human health. Material flows occurring naturally in the region also need to be taken into account in the assessment.

Combining Material Flow Analysis with Participatory Processes. The results of a material flow analysis are ultimately intended to facilitate environmental management, providing decision support for future measures. Accordingly, material flow analysis is now increasingly coupled with participatory processes, and efforts are made to involve stakeholders and decision-makers at the earliest possible stage [7]. For this purpose, it is helpful to present the data in a readily comprehensible form (Fig. 2), permitting direct comparison of the current state of the system with potential mitigation scenarios.

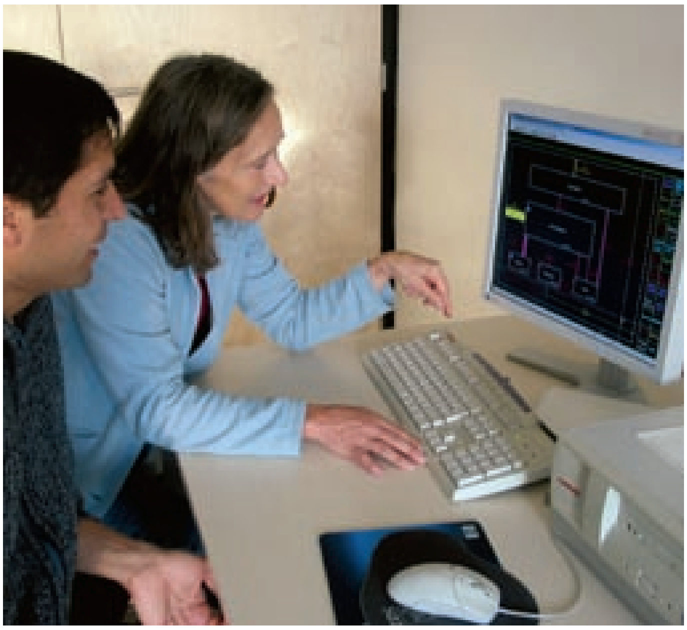
Management: Seeking Opinions and Developing Solutions Together. One possible approach is to seek the views of representatives of specific groups or the public by conducting a survey or organizing a workshop. In order to discover which scenario is most appealing and thus most likely to be successful, the participants are asked to assess the various options, e.g. with regard to environmental consequences, costs and feasibility. If the difficulty of putting the mitigation scenarios into practice is also to be evaluated, the participants can be asked to what extent they would support implementation efforts. This approach was adopted by Hans-Joachim Mosler (see the article on p. 15), whose study considered the question of what the population of Santiago de Cuba

Data collection: in Bangladesh, arsenic concentrations are measured in the groundwater used to irrigate paddy fields.

S. Hug, Eawag

Modelling: on the basis of the data collected, material flows can be modelled and change scenarios simulated.

S. Rothenberger, Eawag



C. Wongsupap, Asian Institute of Technology, Bangkok

Decision support: the results of a material flow analysis and possible remedial measures are discussed at a workshop.

could do to reduce the volumes of wastes arising in households. Here, public attitudes to waste management were explored in a survey. One of the items was specifically concerned with the willingness of households to participate in waste separation, composting or recycling schemes.

In projects involving small or medium-sized groups, material flow analysis can also be used to try out newly developed options – group discussions on problem-solving can frequently generate new ideas, which can be tested immediately in further scenarios. This may possibly give rise to a consensus-seeking process, in which the group members' different positions are gradually reconciled.

Convincing the Authorities with Sound Arguments. Material flow analysis is a particularly suitable method for achieving an unbiased picture of the material flows within a system. Although the various parties concerned will have their own views, for example, on the sources and main types of pollutants, they find themselves confronted with a well-founded account of the problems. However, to ensure that the actors are committed to the process and do not call the foundations into question, they should be involved in the development of the material flow analysis. For example, the analysis prepared in the project carried out by Silke Rothenberger (see the article on p. 12) was designed to demonstrate the benefits of decentralized composting of organic wastes to the authorities responsible for waste management in Asmara, Eritrea. In this analysis, not only were the waste streams recorded but the disposal costs were also quantified. This led the local authorities to see the issues in a completely different light, and the findings were very well received. Nonetheless, it remains an open question whether the use of material flow analysis can promote a shift away from predominantly interest-driven and power-based decision-making towards sustainable solutions.

Increasingly Wide-ranging Material Flow Analyses. Recent years have seen considerable expansion of the scope of material flow analysis, both at Eawag and elsewhere. For example, material flow analysis has been combined with new modelling methods and extended to dynamic systems [1]. Economic considerations can be incorporated by representing monetary flows [8]. In the assessment of results, expert judgements are evaluated with probability functions as so-called subjective knowledge of the system [9]. The development and implementation of solutions is supported by participatory processes [7]. Analysis of substance flows can be combined with modelling of the residence of materials in environmental compartments and assessment of health risks [10]. In short, material flow analysis is a flexible and powerful instrument for environmental management. ○○○

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Arsenic in Paddy Fields – a Hazard?


Linda Roberts, an environmental scientist who is writing her doctoral thesis on this topic, and Stephan Hug, chemist, head of the "Chemistry of Water Resources" group

In many parts of Bangladesh, paddy fields are irrigated with arsenic containing groundwater. The resulting input of arsenic to agricultural soils amounts to more than 1000 tonnes per year. Together with partners at ETH Zurich and in Bangladesh, researchers at Eawag are studying its fate: does arsenic accumulate in the soil or is it remobilized during the rainy season?

In many respects, Bangladesh is a country of extremes. It is situated on the world's largest river delta, formed by the confluence of the Ganges, Brahmaputra and Meghna rivers. With an area of 144,000 km^2 – only three and a half times the size of Switzerland – it has a population of over 147 million. While during the monsoon season (from July to October) almost the whole country is flooded, the rest of the year is marked by drought. With an annual per capita income of USD 440 [1], Bangladesh faces major social, economic and environmental challenges. Politically, the country is relatively stable and democratic, and the government has made successful efforts to improve the general situation. Providing the population with safe water both for drinking and irrigation purposes is one of the greatest challenges for Bangladesh.

Arsenic in Drinking Water. With the aid of international assistance, the source of drinking water supply was shifted from surface water to groundwater from 1970 onwards. Today, more than 10 million hand-pumped tube wells supply almost the entire rural population – a development that has significantly reduced the incidence of water-borne infectious diseases and can be regarded as a considerable success in this respect. Unfortunately, however, the groundwater was not tested for problematic chemical substances at the time. Between 1992 and 1998, it became known that about a quarter of the wells deliver water containing more than 50 µg arsenic per litre [2]. Arsenic (As) is a so-called geogenic contaminant of groundwater: it occurs naturally in underground sediments and, under anoxic conditions, gradually dissolves into the groundwater. Consumption of the contaminated water can lead to chronic arsenic poisoning. With 30–50 million people exposed in Bangladesh, this has been described by the WHO as "the largest mass poisoning in the history of mankind" [3]. The guideline value specified by the WHO, US and EU for arsenic in drinking water is 10 µg/l.

Arsenic Input to Rice Fields. Closely associated with the drinking water problem is the use of groundwater in agriculture. The cultivation of irrigation-dependent high-yielding boro rice during the dry season has made it possible for rice production to keep pace with population growth. Alongside the traditional aman variety, boro rice now accounts for 50% of the total rice harvest, maintaining Bangladesh self-sufficient in food production [4]. Like the wells for drinking water, most irrigation pumps draw water from a depth of 30–60 m, where the highest arsenic concentrations are found. Between January and May, the fields are irrigated with a total of about 1 m of groundwater. An estimated 1000 tonnes of arsenic [5] are thus pumped directly onto the rice fields. The fate of this arsenic is a matter of vital importance both for local agriculture and the population. If the arsenic accumulates over the years, it will cause increasing soil contamination and enter the food chain.

Diesel-powered irrigation pumps deliver arsenic-contaminated groundwater to the paddy fields.

S. Hug, Eawag

In the long term, yields could decline and the land could become unusable for agriculture.

Hazard for Crops and Human Health? According to a number of studies, topsoil arsenic concentrations increase strongly during the irrigation period but decrease again after the monsoon floods [5, 6]. However, these analyses lack sufficient accuracy and spatial resolution to allow the establishment of mass balances or long-term predictions. If it is correct that the arsenic concentrations in the soil decrease after the monsoon flooding, the question is where the arsenic is transported to: is it washed towards the ocean with the floodwater or does it migrate to deeper soil layers?

Measurements of arsenic in rice plants showed increased concentrations in the roots, moderately increased concentrations in the stems and leaves, and practically normal concentrations in rice grains [7]. In the short term, these findings are reassuring and provide reason to hope that exposure to arsenic via food will not add significantly to the existing exposure via drinking water over the next years. Whether this will remain the case in the long term is unclear, however.

Joint SNF Project Involving Eawag and the ETH. In an effort to answer these fundamental questions, Eawag has been collaborating with the Soil Chemistry group of the Institute of Biogeochemistry and Pollutant Dynamics (IBP) of ETH Zurich and with the Bangladesh University of Engineering and Technology (BUET) since the beginning of 2005. The research strategy is to focus on a small number of paddy fields in a typical rice-growing area and to analyse the processes taking place in detail. Based on the results of this study, material flow models shall be developed which can also be applied to other regions. In parallel, hydrological and geochemical aspects are being investigated by research groups from the US, Bangladesh and Eawag.

The study site (Fig. 1) is situated near Srinagar village in Munshiganj District, 30 km south of Dhaka. In this area, only boro rice is produced. At the study site, a single groundwater pump supplies water to a number of fields via channels, which are opened and closed off with clay as required. Between periods of irrigation

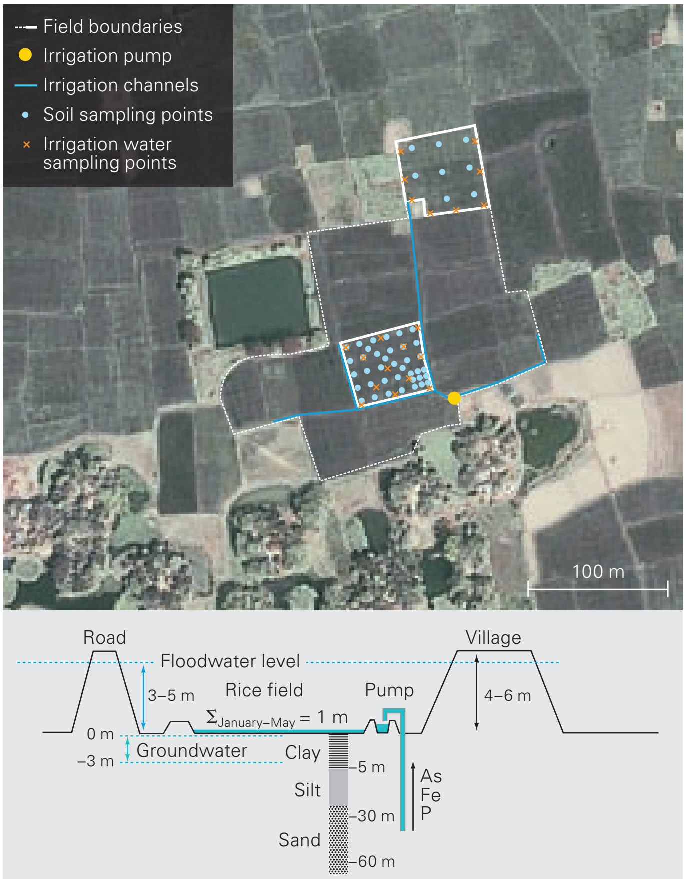
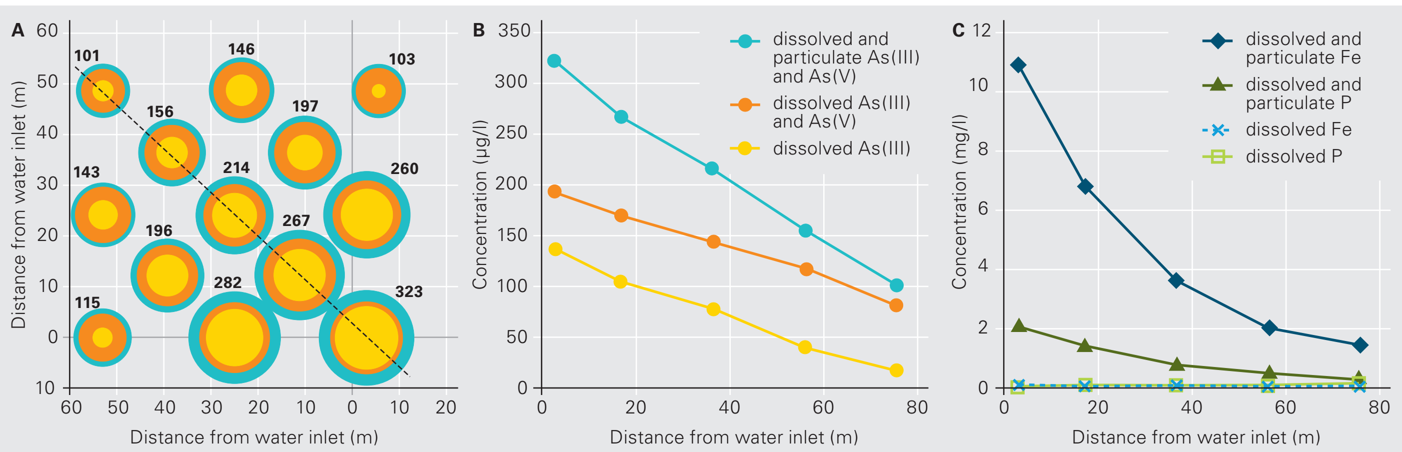


Fig. 1: Satellite image (top) of the 3-hectare study site and vertical cross-section (bottom). To prevent flooding during the monsoon season, roads and villages are built on earthen embankments.

Fig. 2A: Arsenic concentrations (µg/l) in field water 1–2 hours after the end of irrigation. 2B and 2C: Arsenic, iron and phosphorus concentrations along the transect marked in 2A. The decrease in arsenic concentrations is due to co-precipitation of arsenic with iron hydroxides.



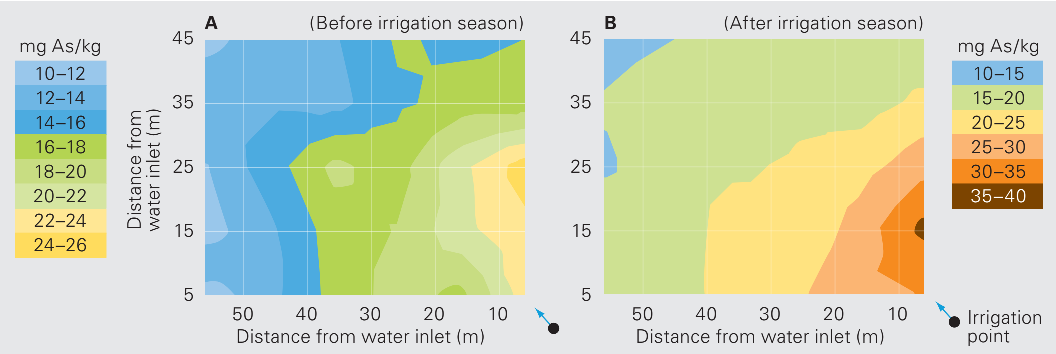


Fig. 3: Arsenic concentrations in topsoil (0–10 cm) before (A) and after (B) the irrigation season from January to May 2005 (Jessica Dittmar, Andreas Voegelin and Ruben Kretzschmar, IBP, ETH Zurich).

– each lasting 3–5 hours and submerging the fields to a depth of 3–10 cm – the fields remain unirrigated for several days, often until the soil dries up again.

Arsenic Binds to Fine Iron Hydroxide Particles which Settle on the Soil. An initial sampling campaign was conducted in order to find out what happens to the arsenic during and after irrigation. Since arsenic interacts with iron and phosphate in particular, it was important to also determine the concentrations of these substances. In addition, one has to consider that arsenic occurs in two oxidation states: As(III) is the form of arsenic that is stable under reducing conditions. It binds relatively weakly to mineral surfaces and is thus mobile in water. As(V), in contrast, predominates under oxidizing conditions and adsorbs strongly to minerals, especially to iron oxides.

Upon contact with air, the Fe(II) dissolved in anoxic groundwater is oxidized to Fe(III) within 30–60 minutes. Brown iron(III) hydroxide particles are formed, which bind As(V), phosphate and other previously dissolved substances partly or completely. Our studies indicated that these very fine particles already begin forming in the channels, but cannot settle in the fast flowing water and are washed onto the fields. Thus, the arsenic input does not depend on the distance between the irrigation pump and the field. However, once the groundwater has passed from the channel through an inlet onto a field, the flow rate decreases and the water takes 2–3 hours to reach the distant parts of the field. During this time, the iron hydroxides are deposited on the soil surface, so that part of the arsenic is removed from the water (Fig. 2). This gives rise to a heterogeneous distribution of arsenic in the soil and in the water. Two days after irrigation, iron, arsenic and phosphate have almost completely disappeared from the water. The heterogeneous distribution of arsenic in the fields was also clearly apparent from the soil samples taken at the end of the irrigation season (Fig. 3).

Arsenic that Accumulated in the Soil is Remobilized During the Monsoon Season. What happens to the arsenic during the wet monsoon season, when the fields are inundated by river- and rainwater for 4–5 months? We showed that arsenic concentrations in soils decline again substantially during this period. This is probably attributable to reductive dissolution of iron hydroxides, a process during which adsorbed arsenic is also dissolved. First measurements in the water column of a flooded paddy field indicated that part of the mobilized arsenic is released into the floodwater. The soil arsenic concentrations measured at the end of the rainy season in 2004 and in 2005 lie in the same order of magnitude. Nevertheless, the heterogeneous distribution of arsenic in the soil suggests that irrigation with arsenic-rich groundwater – which started about 15 years ago in our study area – has already led to some arsenic accumulation.

Which proportion of the arsenic is leached to deeper soil layers or transported superficially with the floodwater into the ocean has yet to be studied in detail. In any event, transport of arsenic to deeper soil layers can be considered as much more problematic than horizontal transport with floodwater into the ocean. In the latter case, the arsenic would be sufficiently diluted and thus no longer pose a hazard.

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Silke Rothenberger, an industrial and environmental engineer, is the Solid Waste Management Project Officer in the Department of Water and Sanitation in Developing Countries (Sandec). Co-authors: Chris Zurbrügg and Christian Müller

Does Decentralized Composting Make Economic Sense?

In developing countries, the benefits of decentralized composting have been demonstrated by a number of small-scale pilot projects. But how would the establishment of a city-wide network of composting plants affect a municipal waste management system? Taking as an example the Eritrean city of Asmara, Eawag researchers used a newly developed model to calculate waste flows and waste management costs, and to simulate various alternative scenarios.

Biodegradable wastes make up a large proportion of municipal solid waste in developing countries, ranging from 50 to 70%, according to the specific development status and nutritional patterns. Generally, these materials also end up in landfills, with valuable nutrients being lost as a result. In such cases, decentralized composting could offer substantial benefits. Schemes of this kind involve small facilities with the capacity to collect, sort and compost up to 3 tonnes of waste per day from nearby sources. They are attractive not only from the perspective of nutrient recycling but also because they improve local hygienic conditions and reduce the total volume of waste that has to be collected by trucks and disposed of in landfills.

However, decentralized composting facilities are seldom integrated into municipal waste disposal operations. Usually, they are merely tolerated by the authorities. But decentralized composting could make a significant contribution as a strategic element within the city-wide waste management system. If local authorities are to be convinced of the advantages of these schemes, waste flows and the associated costs need to be quantified. Such analyses have rarely been performed at the municipal level in developing countries, and this was the starting point for the Eawag study.

A road sweeper gathering biodegradable wastes near the market.

Photos: S. Rothenberger, Eawag

Analysis of Material Flows and Process Costs. The method adopted combines material flow analysis and cost accounting in order to determine the consequences of composting for municipal waste management. The aim is to model waste flows and municipal waste disposal processes, as well as to show the influence of the waste flows on the costs of these processes. One of the strengths of our model is the ability to simulate, within a short time, a variety of scenarios involving different processes – e.g. disposal systems with or without composting plants. Finally, the model indicates how the new processes and the associated changes in waste streams affect the overall costs of waste management. Our model, developed on the basis of existing experience with municipal waste management in developing countries, was first tested in the Eritrean capital Asmara.

Reduction of Waste Volumes and Transport Costs. The study in Eritrea was carried out in cooperation with the University of Asmara and the municipal authorities [1–3]. Although Asmara does not at present have any composting plants, a considerable demand for compost has been identified in peri-urban agriculture [4]. The waste management model developed for Asmara in 2004 is shown in Fig. 1A. The total amount of waste collected and landfilled by the municipal authorities was 44,364 tonnes. This included 17,745 tonnes – mainly dust, leaves and litter – collected by street sweepers. Household waste is either directly collected by refuse trucks or disposed of in communal containers, which

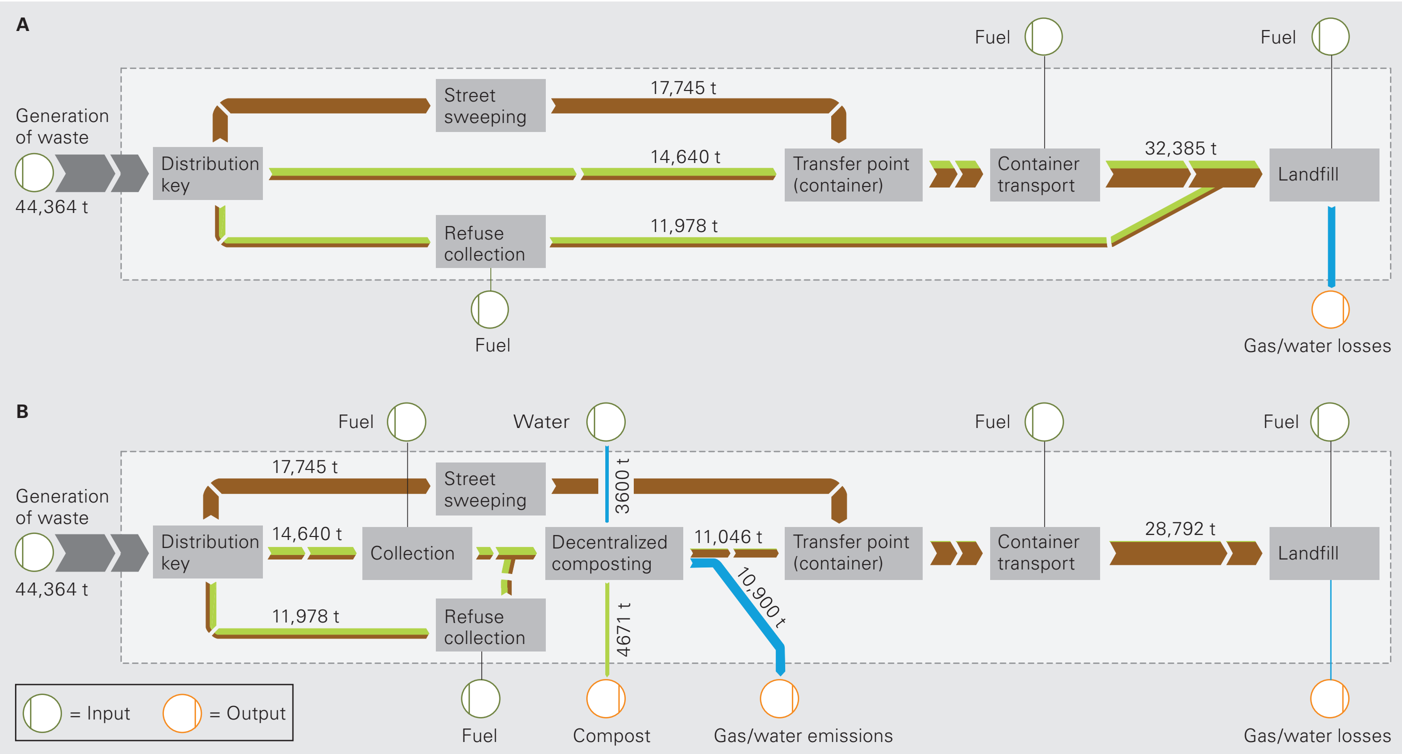


Fig. 1: Processes and material flows in the current solid waste management system of Asmara without a composting scheme (A) and under a scenario with decentralized composting plants (B). Arrow thickness is proportional to the waste flows. Grey: mixed wastes; green: biodegradable wastes, brown: residual wastes.

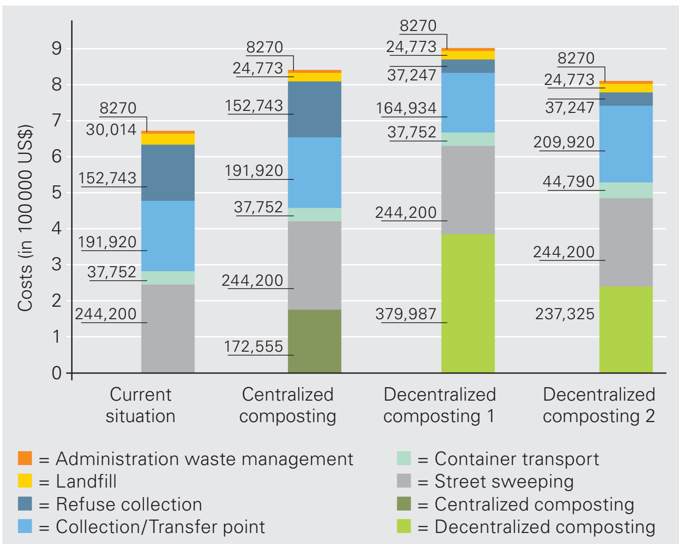
are regularly exchanged. These skips, like the refuse trucks, are emptied at the landfill site, 6 km from the city. About 52% of all the solid waste arising in Asmara is biodegradable and suitable for composting. In the calculation of costs, the fuel required to transport waste is also taken into account in the model, as are the administrative costs of waste management.

Figure 1B shows a scenario in which waste is initially separated at a number of decentralized facilities in the city, with the organic component being composted. Only the residual waste and street sweepings are taken to the landfill. Decentralized composting leads to a 35% reduction in the amount of waste – as is apparent from the CO_2 and water vapour emissions – thus decreasing transport costs. The reduction in volume is equivalent to around 500 truckloads. In addition, the operating life of the landfill is extended by 30% – for a lifetime of 20 years, this represents an increase of up to 6 years. With the aid of process cost accounting, these changes in the system can now also be expressed in monetary terms.

Any Improvement Results in Additional Costs. In Asmara, about USD 670,000 per year is spent on waste management. In consultation with the municipal authorities, the expenditures were broken down by cost headings (e.g. wages and salaries, maintenance, fuel, depreciation, etc.) and also by the processes defined in the material flow analysis. Municipal officers yielded a radically new perspective and an unexpected degree of transparency, which was very favourably received. At present, collection and transport account for 57% of the waste management budget (Fig. 2, left-hand column).

In addition to the current situation, the costs of three alternative scenarios were calculated for Asmara (Fig. 2). The "central-

Fig. 2: Process cost analysis for the existing waste management system in Asmara, Eritrea, and for three scenarios involving composting schemes.



Refuse collection in Asmara: women and children bring out the household waste when they hear the refuse truck's signal.

ized composting" scenario, with 180 tonnes of waste per day treated in one large composting plant at the landfill site, shows annual costs increasing by approx. USD 167,000. The "decentralized composting 1" scenario envisages 60 small composting plants operating throughout the city. In this case, additional costs of USD 213,000 are to be expected; these are mainly attributable to the labour-intensive nature of the operations. Under the "decentralized composting 2" scenario (cf. Fig. 1B), by contrast, only waste from households is treated in the decentralized composting plants. Waste from street sweeping is separately collected and disposed of directly at the landfill. Accordingly, only 36 plants (rather than 60) are required to process the remaining waste. In this case, the total costs only rise by USD 140,000 and are lower than for the "centralized composting" scenario. For the management system as a whole, decentralized composting would thus appear to be advantageous when it is restricted to selected waste streams with a high proportion of compostable materials. The lower costs are primarily due to savings in collection and transport: they are reduced by almost 30% compared to the current situation.

Transparency Enhanced by Cost Accounting. The cost analysis indicates that any improvement to the waste management system, whether it involves centralized or decentralized composting, entails additional costs. However, a detailed breakdown of the costs involved makes it possible to assess the relative advantages and disadvantages of the two systems. Although a large number of decentralized composting plants may be more expensive to operate than a single centralized facility, the transport costs under the decentralized composting scenarios are lower. In the lowest-cost scenario, "decentralized composting 2" (Fig. 2, right-hand column), up to USD 113,300 can be saved. These savings, together with potential revenues from compost sales (approx. USD 6000 per year), cover half of the costs of the decentralized plants. This offsetting of costs would not be possible under the centralized composting scenario, as in this case transport costs remain unchanged.

A further benefit associated with decentralized composting is the fact that it relieves the pressure on the weakest link in the waste management chain, i.e. transport. For many developing countries, the operation and maintenance of collection vehicles is a major challenge, both technically and financially. In the case of Asmara, the introduction of decentralized composting could free up existing transport capacity, allowing waste management services to be extended to other areas of the city. The problem of transport is exacerbated as soon as the capacity of a landfill has been exhausted and a new site has to be established at a greater distance from the city centre. Resources would be better invested in decentralized composting schemes than in the expansion of transport fleets or landfill sites. A detailed analysis of the system is to be found in the study by Müller [1].

Material Flow Analysis and Cost Accounting: a Planning Tool? The approach described here not only makes it possible to predict the financial outcomes of changes in the waste management system but also provides support for municipal planning activities. Initially, however, many municipal authorities in developing countries require a careful explanation of what are for them unfamiliar concepts – the representation of waste flows and the assignment of costs to individual processes. The question of how the results of the study can be implemented is currently being discussed with the authorities concerned in Asmara and other municipalities. They are particularly interested in the possibility of extending the model to the regional waste management system. ○ ○ ○

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Hans-Joachim Mosler, professor of social and environmental psychology at the University of Zurich and head of the social systems modelling research group at Eawag

Waste Flows in Santiago de Cuba

Waste is a problematic issue in developing countries. Due to the rise of living standards, the amounts of waste increase as well. Very often, rather than being appropriately disposed of, it is simply dumped in landfills. This is also the case in Santiago de Cuba. What can the public do to stem the tide of waste?

Santiago de Cuba is the second-largest Cuban city, with a population of about 500,000. Although it has a relatively efficient municipal waste collection system, there is a lack of appropriate disposal facilities, such as incineration, biogas or composting plants. The only available option is landfilling – with dramatic consequences for the environment and human heath: in addition to soil, water and air pollution, these sites are a source of diseases spread by rodents and birds.

In the absence of any plans to establish waste disposal facilities in Santiago de Cuba in the foreseeable future, the question arose: what measures could be taken by households to reduce the volumes of waste being landfilled as far as possible. To answer this question, a material flow analysis and a household-level survey were conducted in cooperation with our Cuban project partner, the Institute of Sociology of the *Universidad del Oriente* (Santiago de Cuba) [1–4].

Waste Management Stakeholders. As Cuba suffers from acute shortages of resources, the state invests heavily in campaigns to promote recycling. Wastes in the form of glass, plastics, metals of all kinds, paper and cardboard are seen as valuable resources, and efforts are already made to recycle as much as possible. In order to gain a comprehensive picture of material flows, we initially identified the local waste management stakeholders:

- Waste is generated by private households.
- Two to three times a week, household waste is picked up by the *Servicios Comunales* (public refuse collection agency) in open trucks. To a limited extent, materials considered valuable by the refuse collectors are sorted out and sold to recycling centres known as *Casas de Compra*.
- Recyclables can also be sold to the *Casas de Compra* by the public: for example, 20 empty 1.5-litre PET bottles can be traded in for a full one.
- Citizens are sporadically called on by the *Comité de Defensa de la Revolución* – a neighbourhood-level political organization with a wide variety of functions – to donate materials for recycling.
- Both the *Casas de Compra* and the Comité de Defensa de la Revoluci*ó*n deliver recyclables to central waste separation agencies known as *Materias Primas,* which sort the materials and pass them on to industrial plants for processing.

Waste was weighed by students at the households participating in the survey.

Photos: H.-J. Mosler, Eawag

Actual Volumes and Handling of Waste. The data providing the basis for the material flow analysis was gathered from 1180 households – a representative sample in relation to Santiago de Cuba. The study involved, firstly, direct measurement of waste volumes. For this purpose, each of the households received seven plastic bags, which were to be used for collecting plastic, aluminium, other metal, paper and cardboard, organic materials, glass and residual wastes for a week. At the end of the week, students called at the households to weigh the bags, using a spring balance.

In addition, the households were surveyed with the aid of a standardized questionnaire. This covered topics such as waste generation and disposal practices, satisfaction with the existing waste management system and ideas for improvements. The data was subsequently summarized in diagrams, which demonstrate the various paths taken by waste (Figs. 1 + 2).

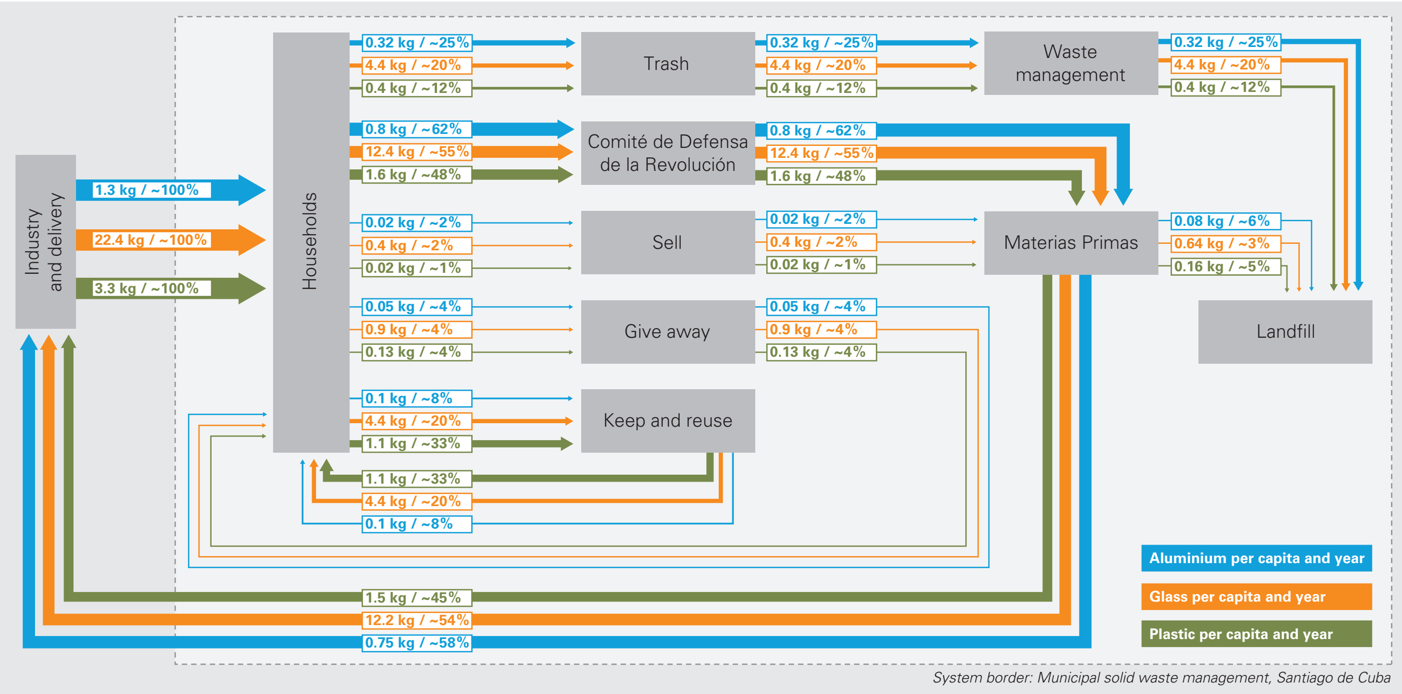
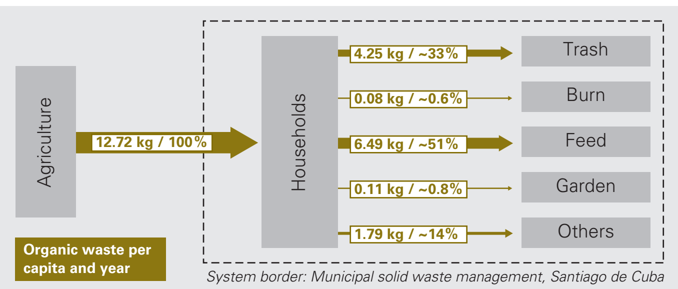


Fig. 1: Disposal paths for glass, plastic and aluminium from 1180 households in Santiago de Cuba. Arrow thickness is proportional to the percentages.

High Rates of Recycling. A large proportion of recyclable waste is donated to the *Comité de Defensa de la Revolución* – 55% of glass, 48% of plastic, and 62% of aluminium (Fig. 1). Even though incomes in Cuba are relatively low, the amounts of materials sold to the *Casas de Compra* are extremely small. Another 24% of waste glass, 37% of plastic and 12% of aluminium is reused within the home or given away to other households. For example, PET and glass bottles are often used for storing liquids. The remaining 20% of glass, 12% of plastic and 25% of aluminium is thrown away (Fig. 1).

The recycling rates achieved by Santiago de Cuba households are thus comparable to those of the European leaders, Switzerland and Germany: 79% for glass (versus 95% in Switzerland and 83% in Germany), 88% for plastic (versus 71% and 64%) and 74% for aluminium (versus 75% and 78%). These rates are doubtless attributable to a combination of factors – a history of resource scarcity, promotion of environmental awareness by the state and social pressure. The population's environmental awareness is reflected by the fact that, for example, more than 80% of the respondents rated environmentally sound waste disposal as very important. The extent of social pressure can be gauged from the large proportion of recyclables supplied to the *Comité de Defensa de la Revolución* despite the fact that much of this material could actually be sold for a profit.

Fig. 2: Handling of organic wastes (inedible parts of fruit and vegetables, and food scraps) in 1180 households of Santiago de Cuba.



Organic Waste Largely Fed to Livestock. More than 50% of organic waste is used to feed animals (Fig. 2). In Santiago de Cuba, chickens and pigs are widely kept, even in the centre of the city, and almost 40% of all households are involved in feeding either their own or other people's animals. These are housed in back yards, on balconies, or in lavatories, or simply share their owners' living quarters.

A further large proportion of the organic waste is collected as refuse. Small amounts are burnt, or disposed of in gardens or elsewhere. Composting is virtually unknown in Santiago de Cuba, and probably also throughout the country.

Psychological Aspects to Be Considered in Future Measures. While the material flow analysis provides essential foundations for future waste management, it is important to be aware of public attitudes to possible new recycling practices if appropriate measures are to be developed. Otherwise, there is a danger that "improvements" will not be accepted. For this reason, a series of additional items were included in the questionnaire:

Pigs are kept even in the city centre – housed in the lavatory, if necessary.

► Sentiment: Would it be pleasant or unpleasant to recycle/compost/reuse your waste?
► Cost-value ratio: Would it be more of an effort or a benefit to recycle/compost/reuse your waste?
► Difficulties: Do you think it is difficult to recycle/compost/reuse your waste?
► Reputation: What would your friends think of you if you recycle/compost/reuse your waste?
► Intention: Will you recycle/compost/reuse your waste?
The responses indicated that increased reuse within the household is considered to be relatively easy to implement (Tab 1).

Tab. 1: Mean values (SD) obtained for the various factors investigated in the household survey on waste management practices.
N = number of households surveyed (questionnaires on recycling, composting or reuse were distributed in equal proportions across 1180 households, but none of the three groups showed a 100% return rate).

	Recycling	Compost-ing	Reuse
Factor	N = 299	N = 347	N = 289
Sentiment –3 Very unpleasant 0 Neutral +3 Very Pleasant	1.57 (1.38)	2.28 (1.02)	0.63 (1.18)
Cost-value ratio –3 Lot more effort than benefit 0 Equal effort and benefit +3 Lot more benefit than effort	2.42 (1.09)	2.46 (0.99)	1.64 (1.48)
Perceived reputation –3 Very negative reputation 0 Neutral reputation +3 Very positive reputation	0.91 (1.10)	1.56 (1.08)	0.72 (0.87)
Perceived difficulty 0 Not difficult +3 Very difficult	1.11 (1.19)	0.95 (1.23)	0.55 (0.89)
Intention 0 No intention +3 Very high intention	2.75 (0.56)	2.65 (0.65)	2.23 (0.84)

However, compared with the other recycling practices, reuse tends to be seen as less pleasant and the readiness to pursue it is more limited. This may be due to the fact that it is perceived as less worthwhile and less reputation-enhancing. In the case of separation and composting, the public displays a high level of willingness but regards them as more difficult to put into practice. According to the survey, this is due in particular to the lack of containers and space within the home for separate storage of materials.

A Need for More Recycling and Composting. The overall conclusion to be drawn from our findings is that the volume of waste arising in the households of Santiago de Cuba could be reduced through increased separation efforts and the introduction of composting. Promoting reuse within the household, however, would not be advisable.

In the second phase of the project, now under way, strategies for the promotion of waste separation and composting are being tested:
► Individual commitment: households can make a conscious commitment to waste separation and use a notice to signal this – "Wastes are separated in this household".
► Reminders: notices providing guidance on sorting can be displayed wherever waste materials are to be separated.
► Information: people can be familiarized with the principle of composting.
► Provision of infrastructure: for example, readily accessible compost bins can be installed.

Finally, in a third phase of the project, the successful strategies are to be applied across the entire city of Santiago de Cuba. If it proved possible to reduce the amounts of waste generated by promoting simple behavioural changes at the household level, this would be a major achievement. Even though the inhabitants of Santiago de Cuba are already quite proficient at recycling, every additional tonne of waste that does not end up in a landfill can be accounted a success. ○ ○ ○

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Monika Schaffner, geographer and doctoral student, and Irene Wittmer, environmental scientist and former master's student in the Department of Water and Sanitation in Developing Countries (Sandec)
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The Tha Chin River is Overloaded with Nutrients

Increasingly intensive farming practices have led to a dramatic deterioration of water quality in the Tha Chin River in Thailand. One major problem is the high level of nutrients. According to our model – based on material flow analysis – intensive aquaculture accounts for a large proportion of the nutrient inputs.

The Tha Chin River, with its numerous natural and artificial channels, flows slowly and heavily regulated through intensive rice and sugarcane farming areas, fruit and vegetable plantations, piggeries and fish farms, and finally through the periurban region on the western margins of Bangkok. Along its course, the river is exposed to high levels of nutrient inputs. In 2002, alarmed by a mass fish death, the government and civil society came together to formulate an action plan for the improvement of the river's water quality. Although ambitious measures were envisaged, it is not clear what should be tackled first and how the limited financial and human resources could be most effectively used. As part of the NCCR North-South research programme [1], Eawag is currently developing a material flow model for the relevant nutrients.

Intensive fish farming is one of the main contributors to nutrient overload in the Tha Chin River.

I. Wittmer, Eawag

This model allows the identification of the main sources of nutrient pollution and the definition of possible mitigation measures.

A Material Flow Model for the Tha Chin River. Our study is based on an analysis of material flows in the Tha Chin catchment (Fig. 1) [2], with nitrogen and phosphorus selected as indicators of nutrient overload. In the first step, the processes leading to an accumulation of nutrients in the Tha Chin River are identified. The main contributory activities are:

- Agriculture – production of rice, sugar cane, vegetables and fruit;
- Livestock production – pig, poultry and fish farming;
- Industry;
- Households.

The model is then formulated based on knowledge of the system acquired through field observations, literature review and discussions with the public and experts. Data for the model parameters are obtained from national and international statistics and literature, and regional research projects. In cases where no data are available, estimates are initially used to fill the gaps, and later replaced by more precise information. The data collection is an iterative process: data are continuously refined and updated until the model calculations produce a sufficient degree of accuracy. The basic model developed for the whole catchment (Fig. 1) can subsequently be applied to lower-level spatial units as required. This is an advantage, since landuse is not homogeneously distributed across the Tha Chin River basin, and specific regional conditions can thus be more accurately represented.

Preliminary modelling results suggest that aquaculture is responsible for the release of large quantities of nitrogen and phosphorus into the Tha Chin. Pig farming and intensive agricultural practices also contribute significantly to the nutrient balance.

Aquaculture on the Tha Chin. To provide a more in-depth understanding of material flows in fish farms, we elaborated a

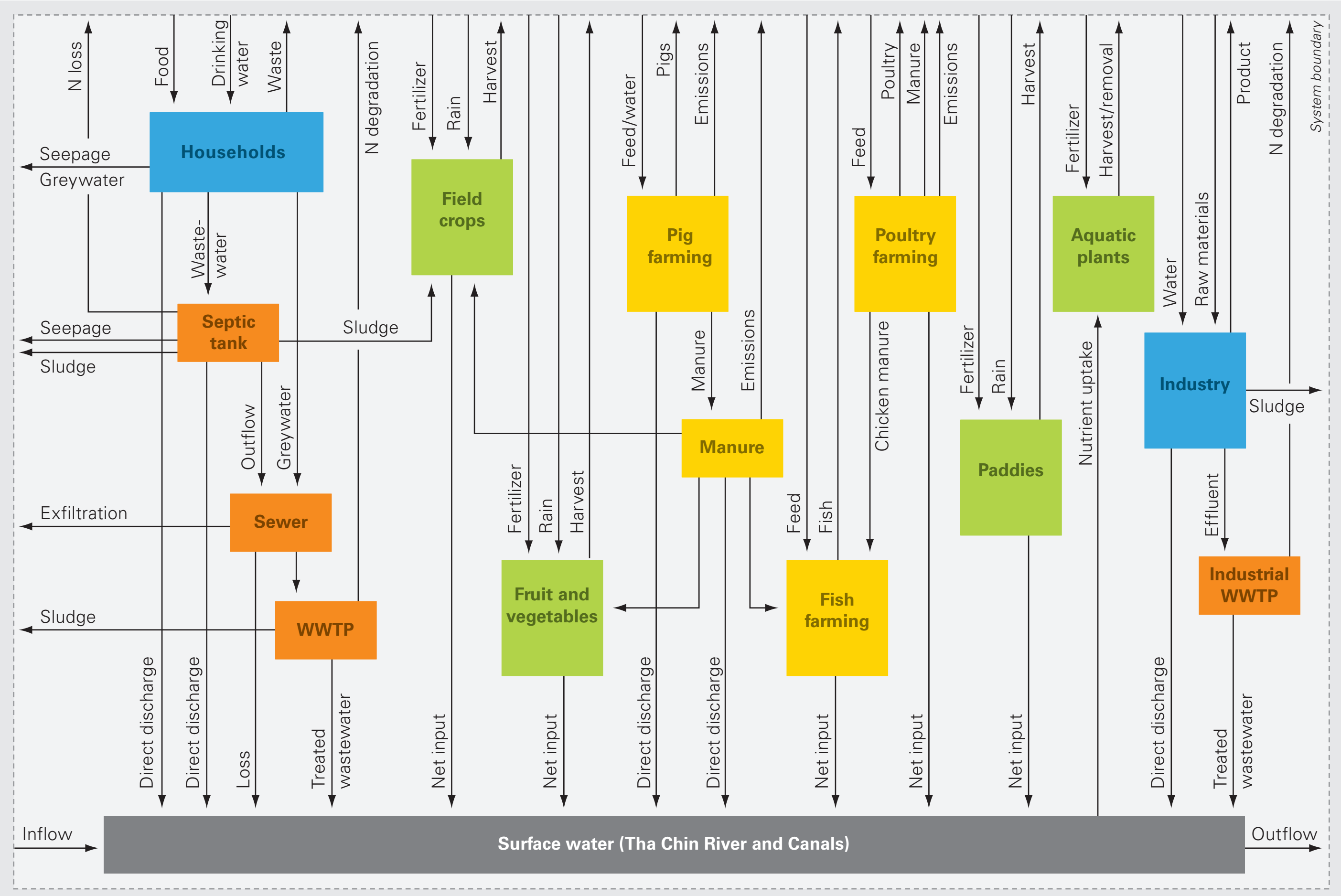

Fig. 1: Schematic system analysis for the Tha Chin River basin: boxes = processes influencing the nutrient load in the Tha Chin River; arrows = nutrient flows.

detailed sub-model [3]. In the Tha Chin River basin, fish ponds are a conspicuous feature. Often, several ponds – each with an area of 1–4 ha – are clustered together, separated only by narrow strips of land. The fish raised here include cichlids of the genera Tilapia (Nile tilapia, also known as St Peter's fish, *Oreochromis niloticus)* and Channa (snakehead, *Channa striatus),* as well as catfish *(Clarias bartrachus)* and tiger prawn *(Penaeus monodon).* Although only a small number of ponds in the Tha Chin region are used for raising catfish, twice as many catfish are produced by weight as tilapia. Intensive catfish cultures can easily be recognized by the smell of the feed used – old, low-quality sea fish. Shrimp farming is also practised on a large scale: more than 30% of Thailand's total tiger prawn production is based in the Tha Chin area. In contrast, production of snakehead is relatively small-scale.

The aquaculture rearing process is cyclical. Once the fish are ready for sale, they are harvested and the water is pumped into the nearest canal. Via this route, the nutrients finally enter the Tha Chin River.

The material flow model was developed so as to be applicable to any kind of fish culture. The aim was to quantify, in approximate terms, the amount of nitrogen and phosphorus introduced into the system with the feed, taken up by the fish and phytoplankton, and the proportion finally discharged into the river. Some of the required input data was collected by means of interviews: we carried out site visits and asked the fish farmers how much feed they used and how they managed their ponds. We learned, for example, that a proportion of the water in the prawn and catfish ponds is renewed every day. In the tilapia ponds, however, only the water lost by evaporation and seepage is replenished. The remaining data were taken from local statistics or scientific literature.

Aquaculture: a Significant Contributor to the Tha Chin Nutrient Load. As nutrient flows in the fish farms of the Tha Chin catchment vary widely, separate calculations were performed for each of the main cultures – catfish, tilapia, snakehead and prawn. To illustrate the results, the nitrogen and phosphorus flows associated with a catfish culture are shown in Fig. 2. Only a small proportion of the nitrogen feed input is ingested by the catfish, while the bulk (11 of 14 t/yr) is washed directly into canals that are connected to the Tha Chin. To calculate the total nutrient load discharged to the Tha Chin River from catfish cultures, the

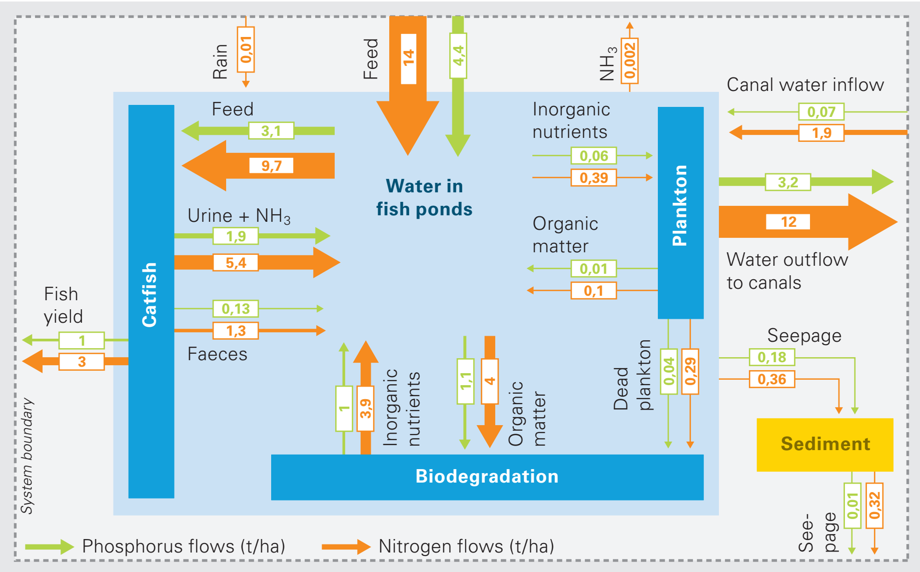

Fig. 2: Nitrogen and phosphorus flows for the catfish culture subsystem.

figures were extrapolated according to the total cultivated area in the catchment. The results show that a vast amount of around 10 000 t of nitrogen and 3000 t of phosphorus are released into the Tha Chin River from catfish farming per year. Of the total annual nutrient load from aquaculture in Tha Chin Basin – 15 000 t of nitrogen and 3600 t of phosphorus – catfish farms thus account for the largest proportion.

Key Factors Influencing the Nutrient Load. With the aid of a sensitivity analysis (see the Lead Article on p. 4), in which the input values were varied, we determined the key factors influencing the nutrient load from the aquaculture subsystem.

► Feed quantity: In aquaculture, overfeeding is a common practice in order to maximize yields. However, as the fish can only take up a certain percentage of their current bodyweight, the surplus feed is washed away. To ensure appropriate feeding levels, owners would need to determine the weight of their fish periodically and be aware of approximate stock numbers.

► Nutrient content of feed: If the culture is dependent on fresh products, the nutrient composition cannot be modified. In contrast, if artificial feed is used, the phosphorus content could be drastically decreased. Thus, according to our calculations, the phosphorus load from tilapia cultures which are fed on manure rather than on artificial dry feed could be reduced from 30 kg to 3 kg per tonne of fish. On the other hand, the nitrogen concentrations cannot be changed, as these are determined by the required protein content.

► Drainage of ponds for harvesting: At harvest time, the ponds are usually drained to allow farm workers to climb in and collect the fish. As a result, the nutrient-rich sediment is stirred up. Finally, it is deliberately pumped into the nearest canal, together with the remaining water. This is done to prevent the accumulation of sediment in ponds. Thus, the Tha Chin River is exposed not only to continuous nutrient inputs but also, periodically, to peak discharges of nitrogen and phosphorus. The nutrient load could be substantially reduced if, for example, the sediments were spread on agricultural land rather than being released into the canals. However, it is not clear whether it is possible to change this practice.

Stakeholder Involvement in Planning. In order to make best use of the material flow analysis results for the studied area, society and business need to be involved in designing measures to improve water quality. Accordingly, representatives of all the concerned groups will be invited to participate in round-table discussions at a workshop. On the basis of the estimated material flows and the key factors identified, specific measures can be determined and evaluated. Stakeholders can thus jointly define the most suitable and effective measures, given the conflicting pressures of water pollution control, practicability and socioeconomic concerns.

Extension of MFA to Other Pollutants. While our study quantifies nutrient flows in the Tha Chin River basin, it does not address other substances – such as heavy metals, pesticides or hormones – that certainly also make a significant contribution to the pollution of the river. In discussing appropriate measures for improving water quality, however, it is essential to consider all problematic substances. It would therefore be advisable to extend the analysis to include pollutants that have not yet been studied. ○ ○ ○

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The National Centres of Competence in Research (NCCR) are research instruments of the Swiss National Science Foundation. The NCCR North-South is co-funded by the Swiss Agency for Development and Cooperation (SDC).

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Closing the Phosphorus Cycle

In Hanoi, Vietnam, waterbodies are polluted by high levels of nutrients, which are discharged in wastewater. At the same time, the region's agriculture uses artificial fertilizers. Our new planning tool indicates where to set priorities to sustainably manage nutrient resources – and reduce water pollution.

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Co-authors: Roland Schertenleib, Hasan Belevi

"The river is so heavily polluted", according to an official at the local authority of Dong My on the outskirts of the Vietnamese capital, Hanoi, "that it will soon no longer be possible to draw water supplies for fish-rearing ponds from this source". In fact, eutrophication of surface waters is one of the region's main problems. But what can be done to reduce the nutrient loads in rivers and lakes? In collaboration with partner organizations in Vietnam, we have developed a mathematical model for predicting the effects of possible measures on water and nutrient flows. This model, which is generally applicable to urban regions in developing countries, incorporates data from the water supply, liquid and solid waste management and agricultural sectors. It was tested in a case study of the Province of Hanoi, focusing in particular on phosphorus flows.

Water Pollution Due to Population Explosion. In recent decades, Hanoi's population and economy have grown dramatically, with rapid industrialization. These processes are closely associated with increases in resource consumption and environmental pollution. Discharges of wastewater into waterbodies have increased and, at the same time, the expanding population is dependent on food supplies from periurban agriculture. As a result, use of artificial fertilizers has risen, leading to increased consumption of phosphorus. If current rates of extraction continue, however, known global phosphorus reserves are likely to be depleted within 50–100 years [1].

Using our model, we therefore aimed to produce a detailed analysis of phosphorus flows in this system (Fig. 1) and subsequently to demonstrate the effects of selected extreme scenarios on phosphorus inputs into surface waters and on phosphorus recovery for agricultural use. For this purpose, we studied the effects of various parameters, such as the number of inhabitants, type of sanitation system, area under cultivation and livestock population. The model is designed to provide support for local actors in the development of appropriate measures.

Filling Data Gaps by Eliciting Expert Judgements

In developing countries, reliable data is not always readily accessible. In addition, the resources available are often inadequate to permit systematic measurements. In order to avoid misinterpretation, it is therefore essential to allow for uncertainties. One promising method of filling data gaps involves the elicitation of subjective expert judgements. The probability distributions obtained in this process describe the state of knowledge concerning a given value. Bayesian statistical techniques show how the uncertainty thus described can be reduced on the basis of new findings (e.g. results of subsequent data collection efforts) [2]. Parameters that cannot be quantified using existing data can thus be estimated by eliciting expert judgements. In this project, the phosphorus transfer coefficient value for the "septic tank" process was approximated by means of expert elicitation.

A sprawling city: peripheral areas of Hanoi combine rural and urban features.

Photos: A. Montangero, Eawag

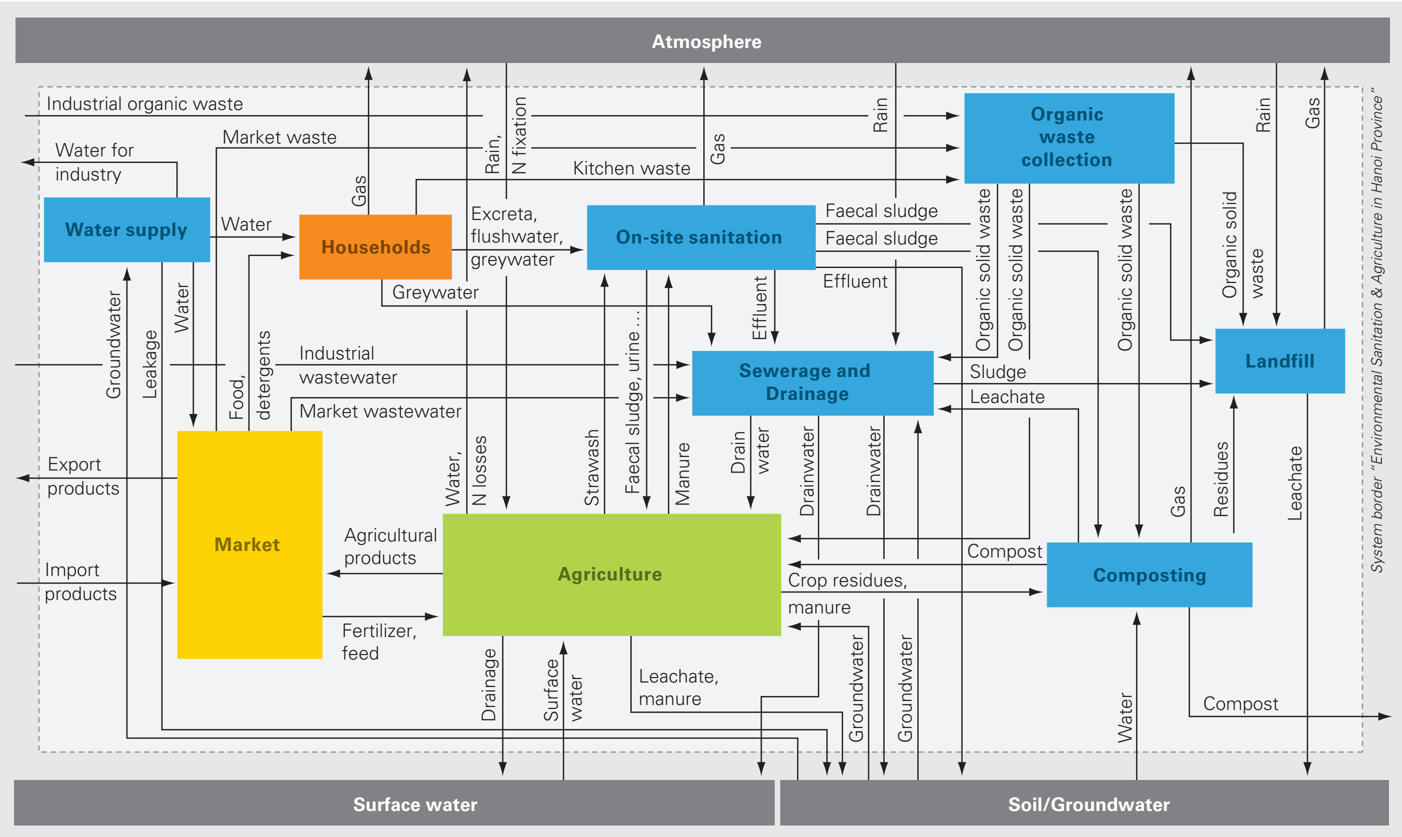

Fig. 1: Processes (boxes) and material flows (arrows) for water supply, sanitation, solid waste management and periurban agriculture in Hanoi Province, together with their environmental impacts.

Domestic Wastewater: Main Source of Phosphorus Inputs. The model seeks to describe the processes and material flows [3] that influence the phosphorus load entering surface waters (Fig. 1). In our calculations, domestic wastewater is identified as the main source: effluent from septic tanks and greywater (laundry, kitchen and bath wastewater) reach surface waters via roadside drainage channels: together, they account for 94% of the total phosphorus load (Fig. 2). This load is decisively influenced by the type of sanitation system. Only a small proportion of this phosphorus load is recovered for use in food production. This is due in particular to the fact that farmers only use wastewater from the drainage channels for irrigation and as a fertilizer during the dry season. During the rainy season (from May to October), the fields do not need to be irrigated and all the drainage water flows unused into the rivers.

Inefficient Retention of Phosphorus in Septic Tanks. In Hanoi, most buildings are connected to septic tanks, which collect wastewater from toilets. These simple domestic sewage treatment systems consist of one or more chambers, through which the wastewater flows. In this process, the solids settle and accumulate at the bottom of the chamber, with some of the organic substances contained in the wastewater being decomposed by microorganisms. The pretreated effluent is subsequently released into the open roadside drainage channels and then enters the nearest receiving waters. The accumulated solid matter should be regularly removed from the septic tanks for treatment. In Hanoi City, this sludge is generally disposed of in landfills, while in periurban areas it is often used as an organic fertilizer.

However, most of the phosphorus is contained in the septic tank effluent. This can be explained by the fact that 50–80% of the phosphorus excreted by humans is to be found in the urine [4], and that urinary phosphorus is water-soluble; as a result, only 11–27% of the total is retained in the septic tank in solid form. The remainder leaves the tank with the liquid effluent.

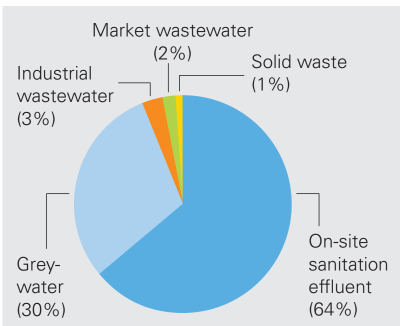

Fig. 2: Relative contributions of various sources to the total phosphorus load in Hanoi's surface waters.

Double-pit latrine with urine diversion (Vietnam): latrine floor with openings to the two chambers for faeces, a urine diversion channel and a urine pot.

Closing the Phosphorus Cycle With Urine Diversion Latrines. Could phosphorus be retained more efficiently by a different sanitation system? We noted that the so-called double-pit urine diversion latrines formerly widespread in North Vietnam offer crucial advantages over septic tanks. These systems consist of two chambers for faeces (used in rotation), a latrine slab specially designed for urine diversion and a pot for urine collection. Ash is regularly added to the faecal matter to promote the drying process and to neutralize odours. When one of the chambers is full, the other is used and the faeces/ash mixture is stored in the first compartment for about a year. During this period, pathogenic microorganisms die off, substantially reducing the health risks associated with reuse of the mixture as a fertilizer in agriculture. The urine, meanwhile, possibly diluted, can be used for irrigation. This latrine system makes it possible to retain all the nutrients, including phosphorus, contained in human excreta – apart from a small amount of nitrogen volatilizing during urine storage. These nutrients could subsequently take the place of some of the artificial fertilizers used in agriculture. This would reduce not only nutrient flows into surface waters but also demand for mineral fertilizers.

Our model also allowed us to quantify the extent to which phosphorus inputs to surface waters could actually be decreased. Assuming, for example, that all the septic tanks in Hanoi were replaced by double-pit urine diversion latrines, the phosphorus load entering surface waters could be reduced from 1570 to 905 tonnes per year, i.e. by 42%. Moreover, thanks to the additional recovery of organic fertilizer, the amount of artificial phosphorus fertilizer required could be reduced from 2800 to 1200 tonnes per year – a 57% decrease.

Need for an Integrated Planning Approach. If scenarios such as that involving urine diversion are to be further developed for Hanoi or for other cities in developing countries, a number of additional questions would need to be investigated, e.g.: How would new sanitary facilities be received by users? What costs would they entail, and to what extent would additional costs be acceptable? Over the longer term, will there be a market for urine and hygienized faecal matter? Our aim is therefore to incorporate the material flow model into an integrated planning approach, which would then be tested for other parameters in further case studies. However, suitable scenarios combining appropriate provision of sanitary facilities with sustainable management of resources can only be implemented if the population, authorities and other stakeholders concerned are included in the planning process. The authorities in the region are certainly prepared to collaborate on pioneering scenarios of this kind, given the pressing nature of the water pollution issue – and the fact that fish farming is one of the main sources of income in many of the region's periurban districts. ○○○

This project was carried out in cooperation with the following partners in Hanoi, Vietnam: *Le Ngoc Cau,* Asian Institute of Technology Center in Vietnam (AITCV); *Viet Anh Nguyen* and *Pham Thuy Nga,* Centre for Environmental Engineering of Towns and Industrial Areas (CEETIA), Hanoi University of Civil Engineering; *Vu Dinh Tuan,* National Institute for Soils and Fertilizers (NISF).

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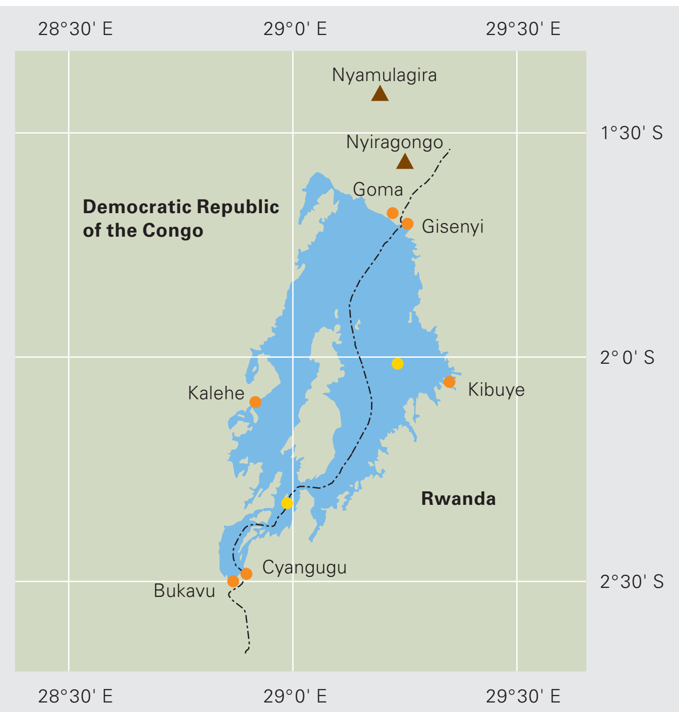
Martin Schmid, environmental scientist and member of the Surface Waters department

Hazardous Build-up of Gases in the Depths of Lake Kivu

The deep waters of Lake Kivu (DR Congo/Rwanda) contain vast amounts of carbon dioxide and methane. If these gases reached the surface, they would endanger the lives of people on the shores of the lake. Measurements carried out by Eawag have now shown an unexpected rise in methane concentrations, spelling an increased risk of a gas eruption.

In Kibuye, Rwanda, there is little to suggest that this is the site of one of the world's most unusual lakes. The landscape is somewhat reminiscent of a lake in the foothills of the Swiss Alps, although banana and cassava plants grow on the slopes, rather than beech and pine trees. In the distance, Mount Nyiragongo can sometimes be made out, towering over the Congolese city of Goma at the northern end of the lake. In January 2002, Goma was largely destroyed by an eruption of Mount Nyiragongo: lava spewing from the flank of the volcano moved at high speed through the centre of the city, with some flows also entering Lake Kivu. In addition to the devastation caused by the lava flows, there were fears at the time that a gas eruption could be triggered. These were based on the fact that the deep waters of Lake Kivu (Fig. 1) contain vast amounts of dissolved carbon dioxide and methane gases. Shortly after the volcanic eruption in 2002, an emergency measurement campaign was organized – with the involvement of Eawag – to investigate the effects of the lava flows on the stratification of the lake. This subsequently gave rise to an Eawag project designed to study gas concentrations in the lake, under what conditions a gas eruption could occur, and how nutrient cycles are related to the development of gases in the lake.

Fig. 1: Map of Lake Kivu, showing the major cities, the two volcanoes and the location of the moorings installed in the lake (yellow circles).



Gas Eruption: a Major Risk for the Local Population. If water from a depth of 400 m is brought to the surface of Lake Kivu, it effervesces like carbonated water from a bottle that has been shaken before being opened. Such high concentrations of gases can only develop because the stratification of the lake, with a depth of almost 500 m, is extremely stable, so that exchanges between the surface and bottom water are very limited. Gases can thus accumulate in the deep waters over periods of centuries.

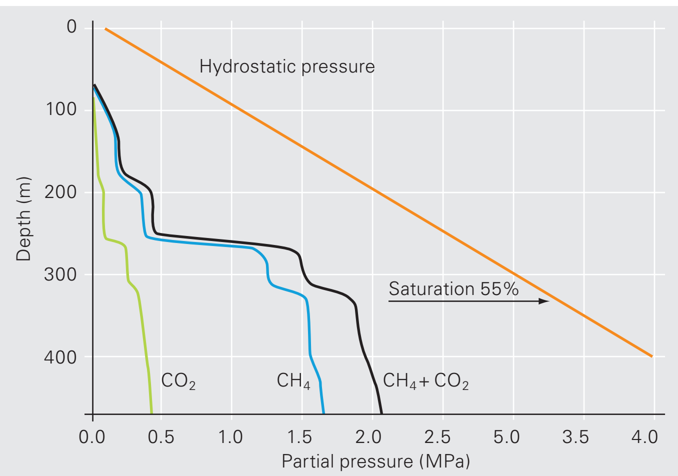
Altogether, Lake Kivu contains around 60 km^3 of methane and 250 km^3 of carbon dioxide. If this gas were distributed on the surface of the lake, it would yield a layer more than 100 m thick. Even if only a fraction of this total were to erupt from the lake, it would be highly dangerous for the roughly 2 million people who live along the shores of the lake. As carbon dioxide is heavier than air, it would form a blanket over the lake, and even concentrations of less than 10% in air breathed by humans are lethal. In August 1986, more than 1700 people were asphyxiated after a gas eruption of this kind from the much smaller Lake Nyos in Cameroon [1]. To prevent a repetition of this disaster, Lake Nyos has been artificially degassed for a number of years [2]. Observations made in sediment samples from Lake Kivu suggest that massive gas outbursts also occurred here several thousand years ago [3].

Gas Eruptions Caused by Disruption of Lake Stratification. Our initial measurements carried out after the volcanic eruption in 2002 revealed no significant changes in the stratification of the lake. We therefore concluded that the heat input from the lava flows was not sufficient to cause mixing of the water layers and thus trigger a gas eruption [4].

But the question remains, under what conditions could gas erupt from Lake Kivu? Figure 2 shows the pressure of the gases in the lake compared with the hydrostatic pressure, i. e. the pressure created by the water column at a given depth. Because methane is much less readily soluble than carbon dioxide, it is the main contributor to the total gas pressure despite the lower concentrations. If the sum of the partial pressures of the dissolved gases is greater than the hydrostatic pressure, bubbles of gas can form and rise spontaneously. Under normal circumstances, this will not automatically lead to a massive gas eruption. However, if an extensive area in the depths of a lake is almost completely saturated with gases, a powerful internal wave – triggered for example by a landslide, rockfall or volcanic eruption – could lift a large volume of water to a depth at which it is oversaturated with gases. The bubbles forming as a result would create additional buoyancy, drawing up further gas-rich water. Within a short time, a chain reaction of this kind could lead to the release of massive amounts of gas from the lake.

At present, the maximum gas saturation level in Lake Kivu is about 50 % (Fig. 2). Water from a depth of 320 m would have to rise by about 150 m for bubbles to form spontaneously. In the current situation, a gas eruption therefore appears to be unlikely. A major intrusion of magma directly into the deep waters of the lake would be required to allow them to rise to the level at which gas would be released [5].

Fig. 2: Pressure of dissolved gases in Lake Kivu compared with the hydrostatic pressure. Currently, the highest saturation – over 50 % – is found at a depth of approx. 300 m.



M. Schurter, Eawag

Westward view over Lake Kivu near Kibuye (Rwanda). The island of Idjwi (DR Congo) can be seen in the background.

Striking Rise in Methane Concentrations. A comparison with measurements from the 1970s [6] shows that methane concentrations have risen by almost 20 % within only 30 years. This observation was surprising since it had previously been assumed that the gas concentrations in the lake are in a long-term steady state – i. e. that the amount of methane transported upwards and consumed by bacteria in the oxic surface layer is roughly equal to the amount produced in the deep waters. Currently, however, methane production appears to be preponderant, so that towards the end of the 21st century a state would be reached in which a devastating gas eruption could occur at any time [7].

Possible Causes: Population Growth and Introduction of a Non-native Fish Species. The causes of the increase in methane are unclear. It is known that methane is mainly formed by bacterial decomposition of organic matter – dead algae – in the anoxic deep waters of the lake. Increased methane production therefore suggests that more organic matter is being exported from the surface to the deeper waters. This can be explained by two different hypotheses:

► In recent decades, the population in the catchment of Lake Kivu has increased sharply. Accordingly, more nutrients now enter the lake from agriculture and urban drainage and as a result of soil erosion.

► In the 1950s, a sardine from Lake Tanganyika was introduced in Lake Kivu; previously, no fish species in the lake had been able to make use of the zooplankton in the open water as a food source. The sardine thrived, and this species now accounts for the bulk of the fishermen's income. However, it has also had a major impact on nutrient cycles in the lake, as it eliminated the daphnia (water fleas) that previously controlled algal growth. Consequently, zooplankton concentrations in Lake Kivu are only half as high as in the other large East African lakes, while concentrations of algae are higher [8, 9].

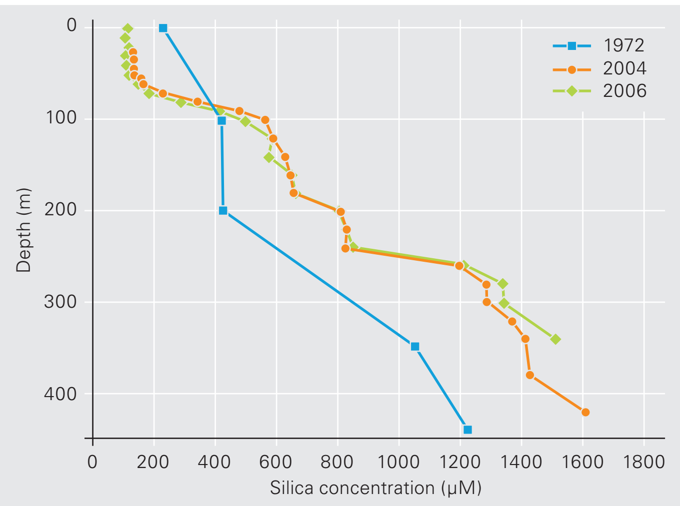
Sediment traps are deployed to collect sinking algae.

Both population growth and the introduction of the sardine could thus have led to increased algal production, thereby causing the rise in gas concentrations.

Evidence of a Rise in Nutrients. The increased input of organic matter into the deep waters is also reflected by a marked rise in nutrient levels. By way of example, Fig. 3 shows the development of silica concentrations in Lake Kivu. Silica is required in particular by diatoms (algae) for shell construction. The decrease of silica concentrations in surface waters and the corresponding rise observed in deep waters indicate that increasing numbers of dead diatoms are sinking to the depths, where they are decomposed. Similar trends have also been observed for other nutrients, such as phosphorus and calcium.

To study the causes of the rise in methane concentrations, Eawag has initiated a new project, financed by the Swiss National Science Foundation. It is being carried out in cooperation with the Institut Supérieur Pédagogique in Bukavu (DR Congo), the National University of Rwanda in Butare and the University of Notre-Dame de la Paix in Namur (Belgium). In May 2006, as part of this project, sediment trap moorings were installed at two sites in the lake (Fig. 1). By collecting sinking algae, it is possible to measure the export of nutrients from the surface layer. In addition, sediment cores were retrieved to permit reconstruction of the historical development of nutrient fluxes. These cores are currently being analysed. Finally, water samples from tributaries and precipitation are to be analysed on a regular basis, so that nutrient inputs from external sources can be estimated. Apart from the purely scientific objectives, the project is also designed to promote research activities at the local universities – in the long term, the intention is that local institutions should be responsible for monitoring conditions in the lake and thus ensuring the safety of the population. ○ ○ ○

Fig. 3: Silica concentrations measured in Lake Kivu in 1972 [10], 2004 [7] and 2006 (N. Pasche, Eawag).



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Forum

The Energy-frugal Building

"The futuristic building", "A step towards the 2000-watt society", "Showpiece of zero-energy architecture" – the Forum Chriesbach has attracted wide media coverage. The theme underlying all the reports was that Eawag, which conducts research on sustainable use of water resources, has now demonstrated its own commitment to sustainable development.

Eawag's new headquarters was officially opened on 1 September 2006. The following day, around 2500 members of the public took the opportunity to have a closer look at the building, which has a striking facade consisting of blue glass fins. On guided tours, the visitors learned a great deal not only about the workings of the building but also about how Eawag's research projects help to tackle current water-related problems.

No Heating Installed. What makes Forum Chriesbach special is the consistent application of available knowledge on sustainable building practices. Essentially, the design involves the integration of established technologies, rather than the radical or experimental use of individual elements. Apart from the ground floor (staff canteen, reception and library), the building requires no conventional heating. With a 45-centimetre-thick outer wall (including a 30 centimetre layer of rock wool) and high-quality windows, it is so well insulated that heat losses are minimal. All sources of heat are utilized, from that given off by computers and lighting to employees' body heat. In the winter, incoming air is pre-heated in 80 20-metre-long underground pipes and further warmed in a heat exchanger, using heat from exhaust air and the server room. Additional heat can be supplied by the hot water storage system. Water is heated by solar collectors on the roof of the building (50 m^2, vacuum tube system) and by exhaust heat from refrigeration units in the kitchen. To meet peak demand during particularly cold periods, heat can be obtained from the Empa-Eawag site network. It has been calculated that supplies from this source will not exceed the equivalent of 2500 litres of oil per year – i.e. barely as much as is required by a conventionally built detached house.

Pleasantly Cool in the Summer. Providing an aesthetically innovative alternative to blinds are 1232 silkscreen-printed glass fins. Along each facade, these are adjusted according to the position of the sun: in the winter the amount of sunlight reaching the building is maximized, and in the summer exposure to the sun's rays is minimized to prevent the windows and interior from heating up. On hot days, the entire building is cooled overnight by the opening of office windows and skylights in the roof. Heat escapes via the atrium as if through a chimney and cool night air enters the offices. Concrete ceilings promote heat absorption, while clay partitions help to regulate interior humidity. Even during the July heatwave, with outdoor temperatures reaching 35 °C, temperatures inside the Forum Chriesbach building remained below 26 °C – without any energy-intensive air-conditioning.

Taking Grey Energy into Consideration. Sustainable construction means that the entire life cycle of a building needs to be

On 1 and 2 September, Eawag celebrated the opening of its new headquarters, "Forum Chriesbach". Regarded as Switzerland's most sustainable office building, it was among the winners of a 2006 Swiss Solar Prize in the "buildings" category. (Photos: Eawag; Roger Frei, Zurich; Sandra Neuhaus, Meilen)

considered, and in particular the embodied or "grey" energy. This fraction becomes all the more important as operating energy efficiency is increased. Accordingly, resource-conserving materials were used, e.g. recycled concrete, wood-clay partitions and magnesite flooring. The use of non-recyclable composites was avoided as far as possible, and more energy-intensive components were required to have a long useful life. A third of the electricity requirement is met by solar panels covering an area of 460 square metres on the roof. After 25 years, this system will have produced about 7.5 times as much energy as was required to manufacture it. With per capita power consumption of around 190 watts for electricity and heat and 240 watts for grey energy, Forum Chriesbach demonstrates that, in the building sector, the "2000-watt society"[1] is no longer a vision but can already be implemented today.

[1] Continuous consumption of 2000 watts per capita relates to all sectors, not just employment. At present, total consumption in Switzerland is 5000–6000 watts per capita..

"In-house" Research. Particular importance is attached to the management of water and wastewater. Roof water is stored in a reservoir with a capacity of 80 m^3 and used for toilet flushing. Rainwater from other hard surfaces is allowed to infiltrate on extensively vegetated areas. Urine is separately drained from all toilets and centrally collected for research purposes. Practical experience can thus be gained with the NoMix (urine source separation) technology, and new research questions can be addressed within the building itself (for further information, see the project website: www.novaquatis.ch). In addition, there are plans to rehabilitate the Chriesbach river, which flows through the Eawag site. The entire location, including the new Eawag-Empa daycare facility, is increasingly being transformed into a "sustainable campus".

Not a Luxury Project. Forum Chriesbach was designed by the architectural firm Bob Gysin + Partner, with Implenia serving as the general contractor. The six-storey building accommodates 150 office workplaces, an auditorium for 140 people, two 40-seater seminar rooms, meeting rooms and communication areas. It also houses the joint Empa-Eawag library and the staff canteen "aQa", which has been awarded the "Goût Mieux" label. The building has been occupied since June 2006. Experience to date has been favourable, and isolated weak points or teething troubles, such as defective temperature sensors or incorrect control signals, are being progressively ironed out. The preconceived idea that only the state could afford a construction project of this kind has not been borne out. By deliberately forgoing luxurious interior design and complete energy self-sufficiency (which would not have been economically justifiable), it was possible to keep the project costs significantly below the federally approved credit of CHF 32.7 million. The price per cubic metre – CHF 572 (SIA, BKP2) – bears comparison with conventional construction projects. ○ ○ ○

Andri Bryner, Eawag

Further information and details of public viewings are available at:
www.forumchriesbach.eawag.ch

In Brief

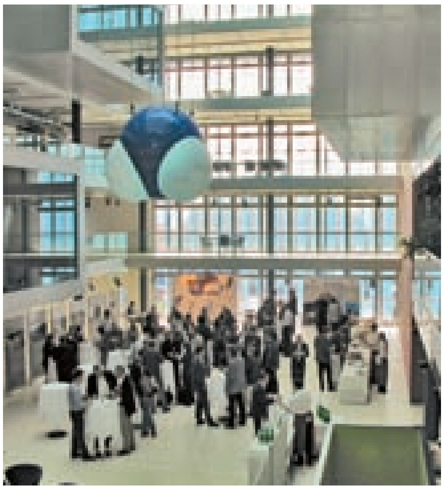
Swiss President Visits Eawag

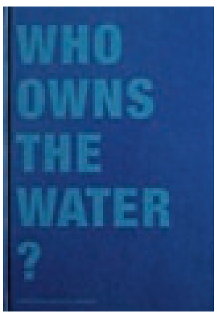
On December 1, 2006, Swiss President Moritz Leuenberger and his staff visited Eawag. Attention was focused on Forum Chriesbach, which is currently considered to be Switzerland's most sustainable office building (see p. 30). This point was taken up by Ueli Bundi in his opening address: as Eawag is working on sustainable solutions for increasingly acute water problems worldwide, it was obliged, he said, to lead the way with its own building. The visitors were impressed by the new building and by the passionate commitment they sensed at Eawag. As was pointed out at the gathering which concluded the event, this is a place where water is not only preached but also drunk (although wine was, of course, also served).

Photos: Eawag

JRC Information Day: Stepping up Collaboration with Europe

Many Swiss researchers are not familiar with the mission and activities of the European Commission's Joint Research Centre (JRC). To raise awareness of the JRC, an Information Day was held at Forum Chriesbach on 16 March. The event – organized by Eawag, the State Secretariat for Education and Research, the ETH Board and Euresearch – offered an insight into the JRC's multifaceted activities. Comprising seven institutes in five countries (the Netherlands, Belgium, Germany, Italy and Spain), the JRC employs almost 3000 staff. Charles Kleiber, State Secretary for Education and Research, described the occasion as "a kick-off meeting to intensify research collaborations between Switzerland and the European Union", underlining the significance of Switzerland's cooperation with the JRC in qualitative and quantitative terms. Roland Schenkel, Director General of the JRC, also stressed that he sees "many possibilities for scientists in Switzerland to play a part in the JRC".





Who Owns the Water?

The new book entitled "Who owns the water" – scientifically and financially supported by Eawag – is already being compared to Al Gore's book and film on climate change. Accessible to lay readers and including disturbing pictures, the work addresses global water issues in depth and asks: "Is water a commodity or is free access to water an inalienable human right?"
CHF 69.90/€ 49.90, available in English or German; published by Lars Müller, Baden, September 2006.

Events

Friday Seminars «Linking Science and Water Management»
On Fridays at 11:00, Eawag Dübendorf

27 April
Membrane Processes for Treatment of Drinking and Wastewater. Overview of the Research Activities
Wouter Pronk, Eawag

4 May
Urbane Wasserinfrastruktursysteme: Nachhaltigkeitsdefizite und Handlungsoptionen
Harald Hiessl, Fraunhofer Institut für System- und Innovationsforschung, Deutschland

11 May
The Water Framework Directive: Characterisation of Surface Waters in Austria
Martin Wimmer, Bundesministerium für Land- und Forstwirtschaft,Umwelt und Wasserwirtschaft, Österreich

25 May
Ecological and Biogeochemical Consequences of Ocean Acidification
Jean-Pierre Gattuso, CNRS-UPMC, Frankreich

1 June
Advective Processes in a Canyon-shaped Mediterranean Reservoir: Ecological Basis for Drinking Water Supply Management
Joan Armengol, University Barcelona, Spanien

8 June
Fast Microbial Analysis of Drinking Water Based on Flow Cytometry: New Methods and their Application
Thomas Egli, Eawag Dübendorf

15 June
Uncertainty Analysis for Urban Water Engineering
Marc Neumann, Eawag Dübendorf

22 June
The new WHO Guidelines for the Safe Use of Wastewater, Excreta and Greywater – from Strict Norms to a Comprehensive Risk Assessment/Management Framework
Robert Bos, World Health Organisation (WHO), Genf

29 June
Climate Change and Water Resources
Glen George, University College London, UK

Details: www.eawag.ch/veranstaltungen