Chapter 5
New Concepts for Managing Urban Pollution

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5.1 Introduction

5.1.1 Chapter Goals

Most current pollution management in cities is based on treating pollution at the end-of-the pipe, after pollution is generated. This paradigm worked well for treating municipal sewage and industrial effluents – *point sources* of pollutants. Pollution from these sources has been greatly reduced since passage of the Clean Water Act in 1972. However, the remaining pollution problem in post-industrial cities is mostly caused by *nonpoint* sources – runoff from lawns, erosion from construction sites, gradual decomposition of automobiles (e.g., erosion of tire particles containing zinc and brake pad linings with copper), and added road salt from de-icing operations. The next section of this chapter shows why the end-of-pipe paradigm cannot be the primary approach for dealing with these types of pollution and why new approaches are needed.

 If the traditional end-of-pipe paradigm doesn't work, what will? I will argue that a new paradigm must be based on analysis of the movement of pollutants through urban ecosystems, an approach sometimes called *materials flow analysis* (MFA). MFA can be used to identify where a potential pollutant enters an urban ecosystem, how it is transferred from one ecosystem compartment to another, and ultimately, it enters surface or groundwater to become an actual pollutant. As we will see, MFA can be used to guide the development of novel approaches for pollution management: reducing inputs of potentially polluting materials to urban ecosystems, improving the efficiency by which they are utilized for their intended purposes, and recycling them. MFA can also be used to develop strategies to mitigate legacy pol-

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lution. The second goal of this chapter is to develop the basic concepts of MFA and demonstrate its application in case studies.

The new paradigm for urban pollution management must also recognize the role of individuals and households in generating pollution – and in reducing it. In modern, post-industrial cities, much of the pollution is generated by the activities of individuals and households, and reducing pollution requires that people change their behaviors. Therefore, the third goal of this chapter is to examine several conceptual models that social scientists use to understand environmental behaviors and several case studies to illustrate how "soft" policy approaches can succeed in reducing pollution or achieving other environmental goals.

Finally, the new paradigm for urban pollution management will make greater use of *adaptive management*. Adaptive management is the concept of using feedback from the environment to managers (individuals; government agencies, etc.) to modify ongoing management practices. Expanded use of adaptive management, made possible by advances in sensor technology and by vast increases in our capacity to acquire, transmit, and store data, could lead to much greater use of adaptive management for managing urban pollution. The final goal of this chapter is to examine the application for adaptive management for managing urban pollution.

Several case studies – managing lawn runoff, reducing the legacy of urban lead pollution, and managing road salt – are developed to illustrate how these concepts can be applied to problems of urban water management and pollution.

5.2 Limitations to End-of-Pipe Pollution Control

5.2.1 Success at Treating Point Sources of Pollution

The traditional focus of urban water pollution management in cities has been treatment of point sources of wastewater – mainly municipal sewage and industrial wastes. Modern wastewater treatment plants are essentially high-speed biogeochemical reactors where pollutants are degraded or transformed into manageable end products, such as sludge or harmless gases (Table 5.1). Physical and biological processes remove pollutants within a few hours in sewage treatment plants, whereas a similar level of pollutant conversion would take days to weeks in a river, during which time pollutants would impact the river. Some pollutants are actually degraded by biological processes. For example, organic matter (measured as *biological oxygen demand*, or BOD) is converted to CO_2 (Table 5.1). Many other pollutants do not actually disappear, but are "removed" only in the sense that they are transferred from the polluted water to sludge (*biosolids*) by sedimentation. The resulting sludge then contains the pollutants.

Fifty years ago, many sewage treatment systems would have been some version of sewage ponds, sometimes aerated. These were moderately effective at reducing the BOD in sewage, but did little to remove nutrients (Table 5.1). Sewage lagoons are still common in many small towns in rural areas of the United States and in

Table 5.1 Treatment reactions, end products, and typical treatment efficiencies for several types of municipal sewage treatment

Pollutant	Reaction	End product	Typical treatment efficiencies, as % of inflow concentrations		
			Sewage ponds[2]	Typical secondary treatment[3]	Advanced treatment[3]
Biological oxygen demand (BOD)	Respiration	CO_2	50–95	95	95
Nitrogen	Sedimentation, mineralization, nitrification-denitrification[1]	Sludge N_2 gas	43–80	50	87
Phosphorus	Concentration by microbes or chemical reaction with alum	Sludge	50	51	85
Suspended solids	Sedimentation	Sludge	85	95	95
Metals	Chemical precipitation and sedimentation.	Sludge	Variable	Variable	Variable

[1]Mineralization converts organic nitrogen to ammonium (NH_4^+); nitrification converts NH_4^+ to nitrate (NO_3^-); and denitrification converts nitrate to nitrogen gas (N_2). All three processes are mediated by bacteria.
[2]Values for lagoon systems are from Metcalf and Eddy (1991) and Reed (1995). Variability reflects wide variations in types of sewage pond (lagoon) designs.
[3]Values for BOD, N and P removal are averages for secondary and advanced treatment systems in the St. Paul-Minneapolis metropolitan region. Suspended solids removal is a "typical" value.

larger cities in lesser developed countries, but the majority of wastewater systems in U.S. cities use at least "secondary" treatment, high tech systems that can remove up to 95% of organic matter. What was once called "advanced treatment" – additional processes used to achieve higher removal efficiencies for nitrogen and/or phosphorus – is becoming standard for large wastewater treatment plants that discharge to waters susceptible to eutrophication.

Industrial waste treatment employs a broader range of treatment technologies, depending on the type of pollutants in the waste stream. Some common treatment technologies include ion exchange, reverse osmosis, filtration, floatation, and sedimentation. Industrial wastewater containing toxic or non-biologically degraded contaminants is generally treated on-site, before it is discharged to public sanitary sewers or waterways. This pre-treatment is necessary to protect sewage treatment

plants from toxic chemicals, and to prevent transfer of toxic chemicals to effluent or sludge.

Treating municipal and industrial point sources was a necessary but not sufficient pollution management strategy. The Clean Water Act of 1972 encouraged, through regulation and economic subsidies, massive improvements in sewage treatment throughout the United States (see Chapter 9). From 1968 to 1996, the amount of BOD entering rivers from sewage treatment plants was reduced by 45%, even as the sewered population increased by 50 million (USEPA 2000a). Industrial wastewater treatment, also mandated by the Clean Water Act, has reduced the inputs of many toxic pollutants to surface waters.

5.2.2 The Nonpoint Source Problem

Sewage treatment has probably had relatively little impact on nutrient inputs to rivers, partly because municipal sewage is a fairly small source of nutrients to rivers, accounting for roughly 6% of the total N and 4% of the total P inputs to U.S. surface waters (Puckett 1995). Even without sewage treatment, point sources probably never accounted for more than 10–15% of N and P inputs to U.S. rivers. The rest comes from *nonpoint sources*, such as urban stormwater and agricultural pollution. Nonpoint sources are also the major sources of salts, sediments, lead, pesticides and many other pollutants. According to the EPA (USEPA 2000b), 45% of all assessed lakes, 39% of rivers and 51% of coastal waters are classified as *impaired*, meaning that these waters do not meet one or more *designated uses* under the Clean Water Act, with most of this impairment caused by nonpoint sources of pollution. We now need to contend with a broad set of problems for which new solutions are needed.

Urban stormwater: Nearly all large, older U.S. cities originally developed *combined sewers* that accepted both urban drainage and sanitary sewage (Chapter 1). The problem with combined sewers is that the volume of water that enters them during rain events is so large that it can't be treated in sewage treatment plants and was often discharged directly into rivers during peak flow periods (*combined sewer overflows*), severely polluting rivers. Over the past 40 years, most cities with combined sewers have re-built their sewage infrastructure into separate sanitary sewers and storm sewers.[1] Even so, until recently, urban storm water, though highly polluted, was not treated. Starting in the late 1990s, large U.S. cities were required to seek permits for discharging stormwater into rivers under the National Pollution Discharge Elimination System (NPDES). This has spurred the construction of thousands of end-of-pipe *best management practices* (BMPs) such as detention ponds, infiltration basins, constructed wetlands and rain gardens to treat stormwater. Pollution removal efficiencies are typically 30–80%, depending on the pollutant and

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[1]Despite this effort, there are still more than 700 sewage systems serving 40 million people in the U.S. which still have combined sewer systems. Most of these are in older cities in the east and mid-west (see http://cfpub.epa.gov/npdes/cso/demo.cfm)

type of BMP (Weiss et al. 2007). They are particularly ineffective (<50% removal) at removing salts, soluble phosphorus, and bacteria. None are sustainable for prolonged periods without maintenance that generally involves transporting polluted sediments to a disposal site. Finally, the overall costs of structural BMPs (capital costs + operation and maintenance costs) are quite high. Weiss et al. (2007) estimated that the total operation and maintenance costs of wet ponds located in the Minneapolis-St. Paul area is $10,000 to 15,000 per hectare of watershed (values are expressed as "current worth"). Analysis of pollutant inputs to streets indicates that source reduction has considerable potential for reducing urban stormwater pollution (Baker 2007).

The upstream problem: In the lexicon of modern industrial ecology, pollution generation occurs in the *pre-consumption system*, the *consumption system*, and the *post-consumption system*. Some of the pollution caused by urban living is generated in the pre-consumption agricultural systems that provide food and other materials to be consumed in cities. For example, in an analysis of N flows through the Twin Cities, runoff and leaching of N in the upstream agricultural system needed to provide protein to the city was four times higher than the amount of N discharged as treated sewage (Baker and Brezonik 2007).

Agriculture is the main source of N and P to surface waters in the United States today. Over the past several decades, reduction of erosion and more efficient use of phosphorus has probably reduced P loading to rivers, but the recent surge in corn production, driven by ethanol demand (and subsidies!) may reverse this decline. Nitrate concentrations in U.S. rivers have generally increased in recent decades (Smith et al. 1994, Goolsby and Battaglin 2001).

Salt pollution: Salt pollution has emerged as a major urban pollution problem that is not amenable to end-of-pipe treatment. In cold weather regions, road salt has become a major urban pollutant. Road salt use was not used much prior to the 1960s; its use has more than doubled since the 1980s, resulting in widespread salt contamination in the Northeastern United States (Kaushal et al. 2005). In the arid Southwestern United States, some urban landscapes are becoming contaminated with salt from irrigation water (Miyamoto et al. 2001, Baker et al. 2004).

Resource conservation: Finally, resource conservation will become an increasingly important driver for pollution reduction. Of particular concern may be phosphorus, which is obtained almost entirely from mining of scarce phosphate deposits. Several analyses (Hering and Fantel 1993, Smil 2000) have suggested that exhaustion of phosphate deposits over the next 100 years may be problematic for human food production. Although the main goal of reducing P pollution has been to ameliorate ecological effects of P enrichment of surface waters, conservation of P via recycling may become an even more important objective in the foreseeable future. Even now, recycling of many metals is driven as much by high prices caused by resource depletion as by pollution reduction goals.

Legacy pollutants: Finally, we need to deal with legacy pollutants in cities – pollutants that were widely used and released to the environment in earlier times and remain today, either in soils (such as lead, creosote, and other persistent organic chemicals) or in groundwater (such as organic solvents).

5.3 Materials Flow Analysis for Cities

5.3.1 The Basics

Single compartment model: The concept of a materials balance is fairly simple in principle. First, consider a simple *system*, which may be the whole ecosystem or part of it (a compartment), defined by a distinct physical or conceptual boundary. The movement of material across the system boundary is called a *flux*, measured in units of mass/time (Fig. 5.1). Inputs and outputs are not necessarily equal. Losses of material can be caused by *reactions*. The difference between inputs, outputs and reactions is *accumulation*:

$$\text{Accumulation} = \text{input} - \text{reaction} - \text{output} \qquad (5.1)$$

Accumulation in (5.1) can be positive (the system gains material over time) or negative (the system loses material over time). This definition is different from the colloquial definition, where accumulation is always a gain of material. The term "retention" is used synonymously with positive accumulation. As an example, when phosphorus fertilizer is applied at rates higher than can be removed by crops, some of the excess P will accumulate in soils.

Multi-compartment models: Most MFA studies of urban ecosystems involve more than one ecosystem compartment. Outputs from one compartment may be inputs to another compartment. A given compartment might receive inputs from several other compartments. In turn, outputs from a given compartment may enter any one of several other compartments. Figure 5.2 shows the flow of nitrogen (N) associated with wastewater treatment plants in Phoenix. Inputs to the wastewater treatment plant are lost through treatment (denitrification, producing N_2, and sedimentation, producing biosolids). Wastewater then transports the remaining N to irrigated crops, to a nuclear power plant, where the wastewater is used for cooling, to the Gila River, and to groundwater (via infiltration basins).
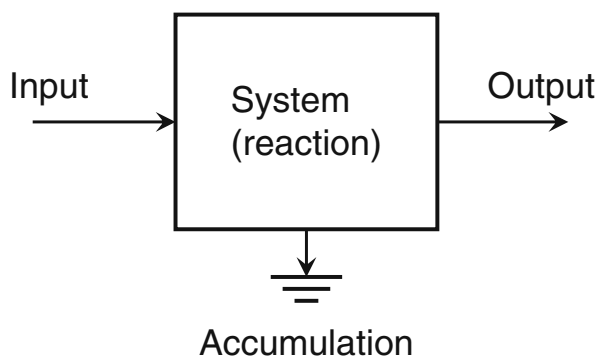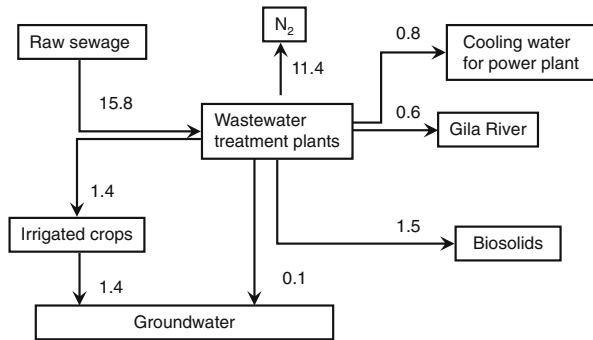

Fig. 5.1 Materials balance for a one-compartment box model

Fig. 5.2 Fluxes of sewage nitrogen in Phoenix, Arizona. Values have units of gG/yr. Source: Lauver and Baker (2000)

Estimating fluxes: Fluxes to and from ecosystem compartments can be estimated in one of several ways (1) by direct measurement of all fluxes to and from a given compartment; (2) by a combination of direct measurements and estimated mass transfer coefficients; (3) by process-based models; and (4) by direct measurement of some fluxes and inferred values for others. Few ecosystem compartments have detailed measurements of all inputs and outputs. A sewage treatment plant might be an exception: Most have continuous records of flow and routine measurements of many pollutants for influent (raw sewage), effluent, and biosolids. Usually, one or more terms cannot be measured and must be inferred by other means. If only one flux value is missing, it can be estimated "by difference". For example, denitrification (conversion of nitrate to N_2 gas) is rarely measured directly in most ecosystem mass balances. In Fig. 5.2, the denitrification flux was estimated as the difference between inputs (wastewater) and measured outputs (biosolids and effluent), on the assumption that there is no net accumulation.

Another common way to estimate fluxes is estimation based on a measured value and a mass transfer coefficient. A simple example is nitrogen inputs from human food consumption in a city. The number of people in a region, by age and sex, can be estimated from Census data. However, measuring food consumption directly (through 24-hour dietary recall surveys) is expensive and requires specialized food composition databases for interpretation. Urban ecologists can take advantage of the fact that national food consumption studies are routinely conducted, providing us with readily accessible data on nutrient consumption rates for each age and sex subpopulation. In this case, the mass transfer coefficient is daily protein consumption, estimated from national studies (Borrud et al. 1996). A simple conversion is then needed to convert protein consumption to N consumption (N = protein/6.25). For each subpopulation, the annual N input from food is:

$$\text{N input} = \text{subpopulation} \times \text{average protein consumption for subpopulation, kg/yr} \div 6.25 \tag{5.2}$$

The total food N input is calculated by summing inputs for all subpopulations.

A third approach is to use outputs from one compartment as inputs to another. For the example of N in human food, we know that about 90% of consumed N is excreted, so the amount of sewage N produced per person is 0.9*N consumption. This output from humans becomes an input to the sewage system.

Detailed process-based models can also be used to develop urban materials balances. Process-based models explicitly recognize biological and chemical processes, and are "dynamic", which means they can represent changing conditions. We are still some years away from a detailed process-based model of an entire urban ecosystem, but process-based models have been used to estimate some processes in urban ecosystems, for example, sequestration of C and N in urban lawns (Milesi et al. 2005, Qian et al. 2003).

Mobility of chemicals in the urban environment: The mobility of chemicals in urban ecosystems is highly variable. Some chemicals are readily adsorbed to soil particles (Table 5.2). For organic chemicals, the tendency to be adsorbed tends to be inversely related to solubility. Readily adsorbed chemicals (like PCBs) are immobilized (trapped) in the upper layer of soils, so they are rarely found in groundwater. However, these chemicals can be transported downstream by erosion and then trapped in sedimentation basins, wetlands, or lakes when the suspended particles settle out. Most metals become adsorbed to some extent. In addition, metals are often immobilized by chemical precipitation, in which metal ions react to form insoluble carbonates, hydroxides and other compounds.

Transformations and decay: Some nutrients – particularly nitrogen and phosphate – are removed from water by assimilation (nutrient uptake) by algae or terrestrial plants (Table 5.2). These nutrients are also released from plants during decomposition, recycling them back to soils and water. Most natural organic com-

Table 5.2 Major transformations of some important pollutants in urban environments. ●●● = very important; ●● = moderately important; ● = somewhat important; ○ = unimportant

	Decay	Adsorption or precipitation	Assimilation by plants	Gaseous endproduct
BOD	●●●	○	○	CO_2
Surfactants	●●●	○	○	CO_2
NO_3^- (nitrate)	○	●	●●●	N_2
NH_4^+ (ammonium)	○	●●	●●●	NH_3
Phosphate	○	●●●	●●●	○
Sodium	○	●	○	○
Chloride	○	○	○	○
Zinc	○	●●●	○	○
Copper	○	●●●	●	○
Arsenic	○	●	○	○
Cadmium	○	●●●	○	○
Lead	○	●●●	○	○
Glyphosphate (herbicide)	●●●	●●	●●●	CO_2
2,4 D (herbicide)	●●●	●	●●●	CO_2
PCBs	○	●●●	○	○

pounds in urban environments decompose via microbial processes, forming CO_2, and releasing nutrients. Many common herbicides, such as 2,4 D and glyphosphate (Roundup) decay in soils with days to weeks (Table 5.2). Nitrate is readily converted to nitrogen gas (N_2) under anaerobic conditions, which may occur in soils, wetlands, and lake sediments. Note that many pollutants do not decay – they are simply transformed from one form to another (e.g., dissolved in water $\rightarrow$ bound to sediments).

5.3.2 Data Sources

Public data sources: New tools and databases now make the development of materials flow analysis for large urban regions fairly practical. In particular, the widespread use of geographic information systems (GIS) by all levels of government mean that many types of data are readily available on a spatially discrete basis, allowing a facile GIS analyst to create numerous data layers within a selected watershed or other discrete region.

5.3.3 System Boundaries

An important consideration for analyzing materials flows through cities or parts of cities is definition of system boundaries. One commonly used boundary is a watershed, defined by topographic features. One advantage of using a watershed boundary is that it is relatively easy to define the boundaries. However, for analyzing materials flows through cities, there are several disadvantages: (1) water moves across topographically-defined watershed boundaries, particularly through storm sewers and sanitary sewers (Chapter 2), and (2) urban regions are not neatly bounded by watersheds. There also may be significant vertical movement of solutes via groundwater, which may necessitate delineation of a separate groundwater system. Political entities (such as counties or cities) can also be used to define boundaries. These have the advantage that many types of data are organized by political boundaries (Table 5.3), but suffer the disadvantage that political boundaries are generally not closely related to anything that might be considered an "ecosystem". It is not necessary that "boundaries" be spatial. For example, in our analysis of household ecosystems (Baker et al. 2007a), we developed a conceptual boundary that included all activities of household members. By this definition, all driving and air travel done by household members occurred within the boundary of the household ecosystem.

5.3.4 Scales of Analysis

MFA studies can be conducted at scales from individual households to entire urban regions. Vast amounts of publicly available data are readily accessible for materials

Table 5.3 Some types of data used in development of urban materials balances

	Original source of data	Typical unit of government	Common spatial resolution for reporting
Impervious surface	LandSat images	State	$30' \times 30'$
Land cover	" "	State	$30' \times 30'$
Land use	Air photo	State or regional	
Crop production	Surveys of farmers	State agricultural statistics services (also compiled nationally)	County
Agricultural fertilizer use	Surveys of farmers	National Agricultural Statistical Survey	State
Population characteristics	Nationwide census	U.S. Census	Census blocks
Housing characteristics	Surveys	U.S. Census, American Housing Survey	Metropolitan areas
Watershed boundaries	Digital topographic maps		Variable
Sewersheds	Ground-based mapping	Municipality or regional sewage authority	Delineated by individual hookups
Sewage flow and quality	Direct measurement at sewage treatment plants	Municipality or regional sewage authority	Individual sewage treatment plants
Land parcel information	Ground-based mapping and reporting	Local governments	Individual properties
Animal feedlots (type and size)	Ground-based reporting	State government (Minnesota)	Varying – about 30 animal units in Minnesota
Animal production	Ground-based reporting	State government	County
Human nutrient consumption	National surveys based on 24-hour dietary recall	Federal government – Continuing Survey of Foods Study	Federal
Lawn fertilizer use	Lawn surveys (individual studies)	Various (not systematic)	Various

flow analysis, compiled by governments at all levels (see examples in Table 5.3). Some of these data are spatially discrete. For example, land cover data is often based on LandSat imagery, with a resolution of 30×30 feet. Plat data, which contains a wealth of information about individual properties, is now nearly always available in digitized form from local units of government. Other types of data, however, are available only in aggregated form, often compiled at the county, state or even federal level (Table 5.3).

Urban regions: Public sector data are particularly useful for analyzing metropolitan regions ($>1000 \text{ km}^2$). For example, in an ongoing analysis of N and P balances

for the Twin Cities, Minnesota, we estimated the population of all U.S. Census blocks located within the regional watershed, allowing a high degree of precision. Because the watershed comprised a large fraction of five counties, we could also confidently utilize a wealth of data collected at the county level, on the assumption that per capita fluxes collected at the 5-county or regional level would be similar to per capita fluxes within the watershed.

Household scale: We have used a hybrid approach to study fluxes of materials through individual households (Baker et al. 2007a). In this study, we used a combination of an extensive questionnaire, plat data, data acquired from homeowners (energy bills and odometer readings) and landscape measurements. This is probably the only way to collect information needed for materials balances for individual households with a reasonable degree of reliability.

Intermediate scales: Intermediate scales of analysis pose greater problems. For example, small watersheds ($< \sim100$ km^2) may be a small part of a county or regional governmental unit. In this case, it may not be reasonable to assume that average characteristics of the watershed are similar to county to tabulated county or regional characteristics. For example, the American Housing Survey compiles a wealth of data on household characteristics within metropolitan areas, but one could not assume that average values for these characteristics (e.g., household size or energy cost) are averages for a particular study watershed. These problems may overcome in the future, as more and more data are compiled and reported at finer spatial resolutions.

5.3.5 Indirect Fluxes

The issue of "indirect" fluxes of materials presents a problem that requires careful boundary delineation. Indirect fluxes of materials are those that occur outside the system boundary, but are affected by activities within the system. For example, the carbon flux used to manufacture a car may occur outside an urban ecosystem, but is affected by the purchase of cars within the system. Moreover, additional carbon fluxes occur outside the factory that manufactures the car – for example, as food used to feed the workers at the plant. There is no entirely satisfactory solution to this problem, but when indirect fluxes are being included in a MFA, the boundary of indirect fluxes needs to be carefully defined.

5.3.6 Prior Studies

Methodologies for developing urban materials balances and MFA are rapidly improving as more researchers undertake these projects. Table 5.4 shows that most of these studies have dealt with water, nutrients, and salts. Studies on urban metabolism, which generally focus on energy and water, are reviewed by Kennedy et al. (2007).

Table 5.4 Examples of material flow analysis studies in urban ecosystems

Location	Description	References
Phoenix, Arizona	Whole-city N balance.	Baker et al. (2001)
Phoenix, Arizona	Regional salt balance.	Baker et al. (2004)
Five Southwestern U.S. cities	Salt balances for public water supplies.	Thompson et al. (2006)
Hong Kong	N and P balances for Hong Kong.	Boyd et al. (1981)
Sydney, Australia	Whole-city P balance.	Tangsubkul et al. (2005)
Bangkok, Thailand	Partial (food-wastewater) N and P balances.	Faerge et al. (2001)
Paris, France	Early industrial era N balances.	Barles (2007)
Individual households (Falcon Heights, MN)	C, N and P fluxes for 35 households.	Baker et al. (2007a)
Urban residential water systems	Contaminant flows for 12 pollutants in residential water systems.	Gray and Becker (2002)
Hong Kong	Urban N balance.	Boyd et al. (1981)
Gavle, Sweden	P in food and wastes.	Nilsson (1995)
Swedish households	Direct and indirect household energy requirements	Carlsson-Kanyama et al. (2005)
Several U.S. cities	Copper mass balances for municipal water systems.	Boulay and Edwards (2000)

5.4 The Human Element

Studies of MFA often show that much of the generation of pollutants in post-industrial cities occurs as the result of actions by individuals and households, either directly or indirectly. For example, we have estimated that about 70–80% of the N and P entering the Twin Cities region comes directly through households. Other studies have shown that direct energy consumption by households accounts for 41% national energy use in the United States (Bin and Dowlatabadi 2005), an average of 57% of all municipal water use (USEPA 2004) and 28–84% of the salt input to municipal wastewater reclamation plants (Thompson et al. 2006).

Because many homeowner behaviors can not (and most would say, should not) be regulated extensively, we need to expand the use of "soft" (non-regulatory) policy approaches to manage the flow of pollutants through urban systems by changing homeowners' behaviors voluntarily.

Several conceptual frameworks have been used to analyze how environmental behaviors can be changed. Traditional supply-demand economic models have been widely used to develop policies regarding directly marketed goods, either through subsidies, "demand-side" pricing and other means (see Chapter 13). Some environmental psychologists use the framework provided by the Theory of Planned Behav-

ior (TPB) and its derivatives (Ajzen 1991). The TPB seeks to understand underlying attitudes that affect the intent to behave in a particular way. It has been has been used to understand behavioral controls involved in recycling (Gamba and Oskamp 1994), household energy use (Lutzenhiser 1993), urban homeowners' riparian vegetation (Shandas 2006), and lawn management (Baker et al., 2008). Communications theory, which examines how new ideas diffuse from innovation through broad adoption, has also been used to understand the adoption of agricultural erosion (Rogers 1995).

Experience has shown that soft policy approaches can change environmental behaviors. For example, curbside recycling in the U.S. increased from 7% of municipal waste in the 1970s to 32% today (USEPA 2007). Farmland erosion declined by 40% since the early 1980s (USDA 2003). Agricultural P fertilizer use has declined by about 15% since the late 1970s, while yields have simultaneously increased (e.g., corn yields over this period have more than doubled). Many urban water conservation efforts have been successful (Renwick and Green 2000). Most of these programs have included a mixture of policy tools. Typical elements include education, financial subsidies and/or disincentives, outright regulations (e.g. zoning, product bans restrictions) and social marketing. Some also target sensitive areas (e.g., erodible land) or disproportionate consumers or polluters, such as flagrant household water consumers. These examples suggest that in the future, soft policies might also be used to reduce sources of urban stormwater pollution, alter diets to reduce agricultural pollution, and reduce CO_2 emissions.

5.5 Adaptive Management

As we seek solutions for nonpoint source pollution, we will also need new models for decision-making. In the traditional top-down management approach to point source pollution control, the impact of various levels of pollution reduction needed to achieve an environmental goal can readily be predicted using mathematical models. For example, engineers can now readily predict the increase in oxygen levels that will occur in a river as the result of decreased inputs of BOD from sewage. We also have the ability to design sewage treatment plants to precisely achieve a specific BOD load reduction – no more and no less than required to achieve specific oxygen level (usually a legally mandated standard). Decision-making is therefore relatively straightforward, with predictable outcomes and well-defined costs.

Managing the diffuse movement of pollutants through urban ecosystems is more problematic for several reasons: (1) pollution removal efficiencies for BMPs are highly variable (2) mathematical models to represent diffuse pollution are not highly developed, and (3) even if they were, obtaining accurate input data would be expensive and in some cases, nearly impossible (e.g., we have no good way to measure how much fertilizer individual homeowners apply to lawns). One potential solution is *adaptive management*, which involves making environmental measurements over long periods, providing *feedback* to those involved in management, who change management practices in response to feedback (Gunderson and Holling 2002). An

example of adaptive management that we are all familiar with is our weather forecasting system. Our government policy to protect citizens from severe weather is to provide continuous forecasts and measurements. The actual response by citizens is entirely unregulated: Each citizen listening to weather forecasts decides whether to carry an umbrella if the forecast shows a 70% chance of rain. A person may choose not to carry an umbrella when heavy rain is predicted, but over time, most people learn that this is a good idea – they adapt. Generally the response is not based on raw data, but requires some level of interpretation and recommendation. The public is interested in weather forecasts, not real-time barometer readings.

Very little water quality management in cities is currently based on adaptive management, but several technological and cultural developments favor broader use of adaptive management in the future. Some of these include: (1) rapidly improving, less expensive monitoring approaches, including citizen-based programs, to provide feedback; (2) increasing internet connectivity, which allows participants to receive feedback and management recommendations, (3) the advent of "Web 2.0", which allows online dialogues, (4) growing environmental awareness and willingness to change behaviors, and (5) a resurgent interest in citizen participation in governance.

5.6 Applications

This section examines several case studies of pollution management that involve MFA, social tools, and adaptive management to illustrate new directions in management of urban pollution.

5.6.1 Case Study 1: Urban Lawns and P Pollution

Lawn runoff typically contains 0.5–2.0 mg P/L, compared with levels around 0.1 mg P/L that typically result in lake eutrophication. Hence, lawns are probably the major source of P to stormwater in residential areas (Baker et al. 2007b). It would therefore be desirable to develop policies that would reduce P export from residential lawns. Targeted lawn management strategies could be based on MFA of lawn P cycling (Fig. 5.3). Logical system boundaries would be the horizontal borders of the lawn (x–y axis) and the lawn surface down to the bottom of the root zone (z-axis). Some lawn P fertilizer is lost immediately as surface runoff, but this loss is typically <5% of applied P (reviewed by Baker et al. 2007b). Most of the applied P is assimilated by grass or enters the soil. Because most urban lawns have been fertilized with P for many years, many have accumulated a large pool of active P that can be "mined" by growing turf for many years following cessation of fertilizer P inputs. When grass is mowed, some enters streets as P-containing particles and the rest decomposes on the lawn, releasing soluble P, which can become runoff or leach downward, replenishing the active P pool.

One policy option would be to restrict the use of lawn P fertilizers, as the Minnesota and several counties and cities have done. In the first few years since the

Fig. 5.3 Diagram of P cycling in lawns
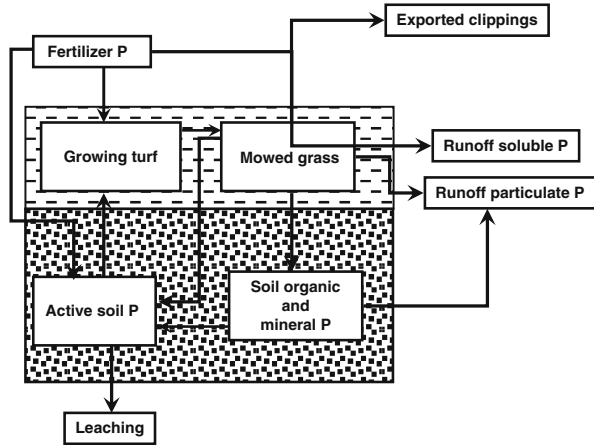
restriction has become law, it appears that P export from lawns has declined ˜15%. Most lawns will continue to mine stored active P. Most of the P assimilated by grass will be recycled, but a small fraction will be exported as grass particles and soluble P to streets. Eventually, the mass of the active P pool will decline. When it gets very low, the amount being mined by grass will decline, and the amount of P in runoff will decline.

One important policy question is: How long will it take to reduce the P concentration in lawn runoff? This depends on several factors: edaphic features of the lawn (slope and soil texture), the initial concentration in the active soil P pool, how fast the grass is growing, and whether the clippings are bagged and removed or mulched in place. Increasing the growth rate would increase the rate at which P is mined from the soil P pool. Ironically, this could be done by adding N fertilizer to stimulate growth! Removing clippings would prevent them from decomposing on the lawn and releasing P. This would reduce P export in runoff and reduce the rate of recycling to the active soil P pool. The fastest way to deplete the soil P would be to fertilize with N *and* remove the clippings. Another consideration is that depleting the active P pool too much could impair turf growth, thereby increasing erosion. An optimum level of P in the active soil pool is ∼25 mg/kg. When soil P falls below this level, grass growth slows down and turf quality deteriorates. Under these conditions, erosion would increase, very likely increasing the rate of P export to streets.

Our analysis indicates that simply restricting P fertilizer inputs would not have a large short-term effect, and may backfire over the long run, if soil P levels fall below the optimum. Furthermore, because lawn management preferences among homeowners vary, strategies for reducing P runoff from lawns should be *tailored* to specific typologies of homeowners. For example, the "casual" homeowner whose soil active P level is below the optimal level for turf growth would be encouraged to add enough fertilizer P to maintain soil P levels high enough to maintain a healthy turf, to reduce the potential for P losses caused by erosion. The "perfectionist" homeowner

with very high soil P levels needs to know that there is no benefit in maintaining the active soil P level above the optimal level. In both cases, P fertilization should be adaptive, based on actual measurements of their lawn's soil P levels. This testing is inexpensive, generally provided by university extension services.

Taken to the next level, quantitative modeling of lawn runoff could be used to determine specific circumstances (slope, soil texture) where runoff P is most likely problematic. Watershed managers could then target their efforts on these areas. Homeowners in these areas would learn that they happen to be located on vulnerable areas. The TPB (discussed above) suggests that this type of specific, credible knowledge would likely cause a greater change in homeowners' behaviors than general guidance. Thus, a homeowner who is asked to change his lawn management practices because his lawn is particularly vulnerable – for example, on a steep slope with clayey soils, where runoff can be 25% of precipitation – is more likely to adopt specific advice than a random homeowner given generic advice.

5.6.2 Case Study 2: Using MFA to Devise Improved Lead Reduction Strategy

Lead has probably been as harmful to human health in cities as any pollutant except perhaps fine particulate matter in air. Prior to the 1970s, two main inputs of lead to urban environments were leaded gasoline and lead-based paints, which together accounted for ~10–12 million tons of lead entering the environment. Both uses of lead were banned in the 1970s, leading to dramatic blood lead levels that parallel the decline in use of leaded gasoline (Needleman 2004). Even so, the Center for Disease Control's latest survey (1999–2002) shows that 1.6% of all children and 3.1% of black children in the United States had blood lead levels (BLLs) greater than the "action limit" of 10 μg/dL. Symptoms of moderate lead poisoning include irritability, inattention, and lower intelligence in children and hypertension in adults. The problem today is largely concentrated in poor, non-white urban populations. For example, more than 30% of the residents (all ages) in Baltimore City, Maryland had elevated BLLs in the early 1990s (Silbergeld 1997). Urban lead poisoning therefore remains a critical human health problem (Table 5.5).

Currently, lead hazard interventions to reduce blood lead levels in children have focused on either abatement (removal of lead-based paint or contaminated soil) or

Table 5.5 Trend in BLLs > 10 μg/dL. Source: Centers for Disease Control

	Percentage of children, ages 1–5, with BLLs >10 μg/dL		
	All races	White, non-Hispanic	Black, non-Hispanic
1976–1980	88.2	–	–
1988–1991	8.6	6	18
1991–1994	4.4	2.3	11.2
1999–2002	1.6	1.3	3.1

interim controls (paint stabilization, dust control). These programs have been only moderately successful, at best reducing blood lead levels by 25% and never reducing them to $\mu 10$ μg/dL (PTF 2000).

A MFA of lead in the urban environment might lead to more effective ways to eliminate lead poisoning. Figure 5.4 shows likely fluxes of lead in cities. The major inputs of lead, paint and leaded gasoline, were phased out in the 1970s. Today, virtually no new lead is deliberately imported into the landscapes of U.S. cities (except car batteries, which must by law be recycled). Declining use of leaded gasoline immediately reduced BLLs, suggesting that much of the lead in gasoline must have been exported from cities quickly. Currently, the main source of "new" lead to urban environments is leaded paint from old buildings, which enters the environment as paint chips. In MFA terminology, this represents a transfer between ecosystem compartments (buildings → soil; Fig. 5.4). Kids probably ingest lead both directly from paint dust in buildings and from external soil and will continue to do so, as long as lead-based paint continues to erode.

There are two likely routes of lead export from the inner city urban environment. One is atmospheric transport. Laidlaw et al. (2007) showed that BLLs of children vary in relation to wind speed, concentrations of fine particles in air (PM-10), and soil moisture. This indicates that fine particles containing lead are dispersed by wind. If this is the case, it is likely that the net direction of lead is outward from inner-urban areas. The reason for this is that soil lead levels are highest in inner-urban areas and lower in the surrounding suburbs and in rural areas (Mielke et al. 1997). The lack of relationship between soil lead levels and land use in Baltimore (Pouyat et al. 2007) also suggests a wind dispersal mechanism. The second export
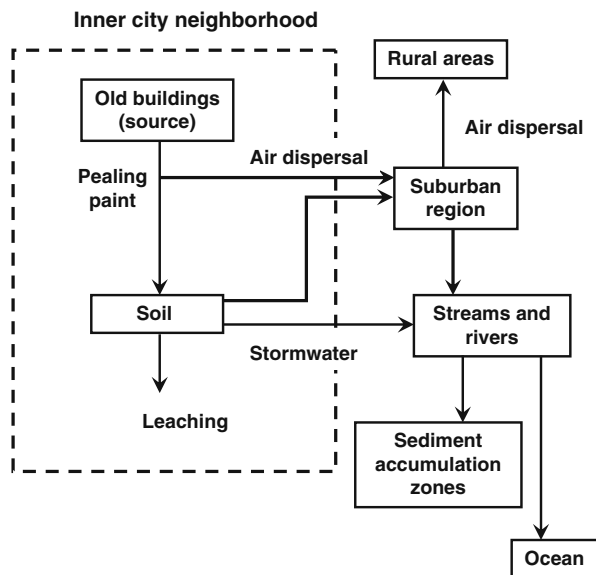

Fig. 5.4 MFA diagram of lead cycling in a city

route is wash-off of wind-blown lead-laden dust that has settled on local impervious surfaces (e.g., streets and sidewalks). Rain events transports lead to storm water drains. Kaushal et al. (2006) found that the mean lead concentration in storm water from some Baltimore streams was 75 μg/L decades after new lead inputs had ceased, indicating that lead is slowly being exported by storm water. Storm sewers would transport lead to low-lying sediment accumulation zones, such as stormwater detention basins and stream riparian areas, where it would be deposited. Particle-bound lead would be transported further downstream during flood events to be re-deposited in regional rivers or transported to the ocean (Fig. 5.4). The one export route that is not likely is downward leaching: Lead is tightly adsorbed to soil and is unlikely to leach.

The obvious means of reducing lead in the urban environment is careful removal or containment of lead-based paint, or removal or burial of entire buildings. Over time, existing environmental lead would be reduced by export via wind and water. More detailed study of export mechanisms could lead to focused management to accelerate removal of environmental lead. For example, frequent high-efficiency street sweeping and removal of highly contaminated soils might accelerate removal of accumulated lead, while also controlling the export route (to hazardous waste landfills, rather than dispersal to outlying residential areas or to downstream aquatic ecosystems).

5.6.3 Case Study 3: Managing Road Salt with Adaptive Management

De-icing roads using salt has accelerated over the past 40 years, increasing ten-fold since the 1960s. Road salting has resulted in widespread contamination of streams and groundwater in cold regions of the United States (Kaushal et al. 2005). Chloride concentrations in some urban areas can reach several thousand mg/L during peak snowmelt periods, and can remain elevated above 250 mg/L even during base flow periods, exceeding chronic water standards for protection of aquatic life. Chloride also is highly mobile and can readily move through soils, contaminating aquifers. In the Shingle Creek watershed in Brooklyn Park, Minnesota, groundwater chloride concentrations have increased 10-fold, presumably due to road salt. Over the long term road salt could potentially contaminate some urban aquifers to the point that the quality of groundwater would no longer be suitable for municipal water supply. The potential problem with reducing road salt use is increased potential for accidents, so reduction has to be done in a way that assures safe driving conditions. Some common strategies used to reduce the amount of salt applied include the use of pre-made brines rather than dry salt and the use of "pre-wetting" – application of salt or brine to the road before a major winter storm, rather than afterwards. Chloride use can be reduced through the use of alternative de-icers, such as calcium acetate, but these are generally far more expensive and may cause other problems (Novotny et al. 1999).
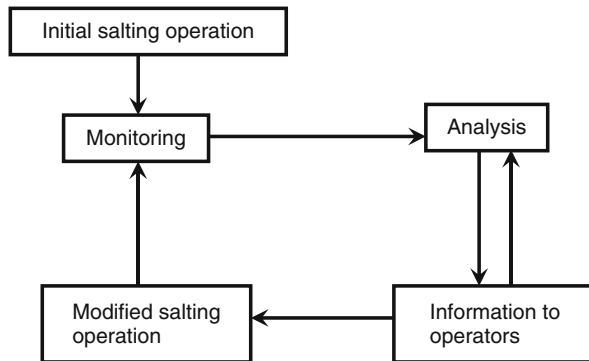
Fig. 5.5 Scheme of adaptive management for road de-icing

Adaptive management might be used to further reduce the amount of road salt used. Management of road salt is well-suited to an adaptive management, for the following reasons: (1) road salt crews are a relatively small, captive audience, which enables frequent communication, (2) because road salt is often overused, there is potential for reduced use, hence savings, (3) several technologies can reduce the amount of salt needed, including pre-wetting, application of brine rather than dry salt and use of non-chloride alternative, and (4) chloride can be readily measured indirectly, as conductivity – a method that is simple, inexpensive, reliable and readily automated, enabling real-time monitoring on pavements, in storm sewers and in streams (Baker 2007). The essential elements of an adaptive management scheme for road de-icing are shown in Fig. 5.5.

Requisite data to guide road de-icing management could readily be obtained via environmental sensors. Road surface temperature and specific conductance (a surrogate measurement for chloride) could readily be measured at the road surface and in streams. Precipitation amount for each event could be interpolated from measured precipitation at weather networks. Newer salting trucks have computerized equipment to record the mass of salt used per mile. Analysis of data from a series of de-icing events might include simple statistical analysis, hydrologic modeling or other methods. In addition, adaptive management often uses human feedback – in this case, the perceptions and knowledge of the salt truck operators. This analysis would be used to guide subsequent de-icing operations, which in turn would result in new data for analysis. This cycle would continue, with the goal of improving de-icing operations until environmental and safety goals are met.

5.7 Summary

Creating sustainable, resilient urban ecosystems requires that we understand and manage the flow of polluting materials through them. From the time of early industrialization through the 20th century, we rarely analyzed the flows of these materials,

often with disastrous, or at least, unpleasant effects. For example, allowing urban lead pollution to occur, and allowing it to persist through the 1970s, will probably be recorded by historians as one of the poorest environmental decisions in the 20th century. Today, MFA methods are sufficiently well developed that they can be used to guide pollution management strategies. As a minimum, we can now develop reasonable a reasonable view of the movement of polluting materials through urban regions. We can also expect that new databases, with more types of data and at finer resolution, will enable even broader applications.

Many of the findings from MFA analysis will likely point toward "soft" and policies to change environmental behaviors of ordinary citizens. To do this, we also need to understand how people make environmental decisions. This will require a new degree of interdisciplinary collaboration to develop transdisciplinary knowledge of social–ecological systems. This type of thinking has largely been missing from most pollution management policy, with the exception of economic cost-benefit analysis. One very promising approach that integrates the biophysical and social realms is adaptive management. New technologies enable a whole new realm of feedback mechanisms to inform policy makers at all levels, including individual citizens. We examined case studies involving lawn runoff, urban lead pollution and road salt to illustrate these concepts.

MFA may have particular importance for cities in arid lands, because contaminants in water tend to be retained in arid cities, rather than flushed from cities, as would be the case for wetter regions. Water conservation measures in general, and recycling of wastewater in particular, tend to exacerbate accumulation of solutes such as salt and nitrate within the urban ecosystem, especially in underlying aquifers (Chapter 4, Baker et al. 2004). Although cities in arid lands have persisted for thousands of years, historical per capita water use rates were probably very low, so accumulation of solutes would have been slow. In the modern, post-industrial city, solute accumulation is accelerated by very high water use, often several hundred gallons per person per day and the long-term consequences have not been studied. Because most of the world's population increase is occurring in cities in arid lands, managing the flow of materials through them may be essential for sustainability.

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