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CHAPTER 3. AGRICULTURAL POLLUTION SOURCES AND PATHWAYS

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Historically, the analysis of negative impacts on aquatic ecosystems (e.g. dead zones) or on human health (e.g. blue baby syndrome) has focused attention on the nature and probable sources of the causative pollutants (e.g. nitrate from agriculture). Further investigation, often through formal research projects, helps to determine the correlations between likely contributing agents, loads and load dynamics (timing, frequency and duration) and their concentrations in water. Finally, remedial actions can be identified and implemented, although perhaps not in time to forestall substantial negative impacts. This approach can be improved if the links between pollution loads and their impacts are better understood, so that decision-makers can take preventive actions before pollution loads are sufficient to threaten human health and ecosystems. The particular challenge of agricultural pollution is to determine the source(s) of pollutants (which are frequently diffuse) and their actual contributions to the loads experienced in a lake, river, estuary or coastal zone.

This chapter introduces key concepts related to agricultural water pollution and describes the main types of pollutants arising from agricultural sources and their pathways to water. Subsequent chapters (Chapters 4-8) review specific pollutants more thoroughly and will provide global data on loads and impacts when available. Chapter 9 discusses how modelling can help to link the causes of water pollution from agriculture to their effects (i.e. links between drivers, pressures, state change and impact) and how models can be used to plan and inform policies.

3.1 Clarifying terms and concepts

Agricultural pressure on water quality is defined here as a direct effect of agriculture expansion and intensification that can cause a change in the physicochemical characteristics of water. Pressures include the increased load of chemicals, sediments or pathogens that enter water bodies through runoff or percolation. Loads are determined as the product of concentration and flow rate, and are calculated in terms of mass per time unit (e.g. kg/day). Because loads are determined by flow and concentration over time, both components must be measured or modelled. Water abstractions and the consumptive use of water by agriculture can also affect water quality, as they reduce water quantity in rivers, lakes or aquifers, therefore increasing the concentration of existing pollutants.

The state of a water body is normally defined in physical (e.g. temperature) and chemical (e.g. concentration of nitrate) terms. The metrics of state document pollutant concentrations, pH, turbidity, temperature and similar parameters. Other metrics record the state of an ecosystem, usually through indexes that rely on indicator species. Indicator species are chosen for their sensitivity to environmental conditions. For example, frogs and toads are good indicator species because the skin of the adults is moist and permeable, allowing numerous pollutants entry into their bodies. If the chosen indicator species declines in numbers or health, it is a sign to look for detrimental influences. Nevertheless, some authors consider these indicator species to be indicators of the impact of a water quality change on ecosystems (Ferreira *et al.*, 2011; Sebastian *et al.*, 2012; UNEP, 2016). The European Commission suggests different steps to analyze the link between pressures and state change in water bodies (see box 3.1).

This book defines impact as the effect water pollution on the environment, human health and economic activities. Examples of water pollution impacts are given in Table 3.1. State and impact are separate concepts that are often combined or confused. One reason for this is that many of the impacts are not easily measurable, thus state is often used as an indicator of impact. While it is possible to determine the state of receiving waters (such as lakes, wetlands, etc.) by measuring certain indicators, it is harder to quantify the actual loads of pollution to water bodies and to link them to state and impact. Despite different attempts to quantify them through measuring or modelling (e.g. Schwarzenbach *et al.*, 2010; UNEP, 2016), the links between cause and effect are sometimes elusive, or counter intuitive.

The quantification of agricultural pollution loads, while seemingly simple, poses considerable practical challenges. National statistics (e.g. on the use of N fertilizers) can be employed to estimate pressures in broad terms. However, they would need to be sufficiently disaggregated across land use type (e.g. cropping, horticulture, pasture) to avoid presenting a misleading picture. Even when we can identify an extreme use

BOX 3.1 Pressures and state change analysis for water pollution: the European Union case

A European Commission guidance document on pressures and impacts for the Water Framework Directive (European Commission, 2003) focused on how to define and implement a work program to identify pressures, monitor their behavior and determine how to mitigate them. The document requires the integration of different sources of water pollution, in addition to agricultural sources. It notes that only significant pressures should be considered and monitored, but recognizes that investigation and research are needed to identify which pressures are actually significant, and that development of indicators and some modelling (even with inadequate data) may be required in conjunction with selective and improved monitoring.

The recommended work programme involves the following steps:

1. Screen all available information on pollution sources:
   a. collate information;
   b. produce a short list of likely key pollutants responsible for observed impacts.
2. Test for relevance:
   a. estimate concentrations in water bodies by monitoring or modelling;
   b. compare measured concentrations with benchmarks, including Environmental Quality Standards, where they exist.
3. Safety net: check if a small number of pollution sources can have a significant combined effect, or whether trends are increasing, even if a standard has not been breached.
4. Prepare a final list of relevant pollutants and their actual and target loads and concentration levels in specific river reaches, lakes and estuaries.

Table 3.1 I Examples of potential negative impacts on human health, the environment and economic activities due to water pollution from agriculture (crops, livestock and aquaculture)

Impacts on:	Examples of impacts
Health	Increased burden of disease due to reduced drinking water quality
	Increased burden of disease due to reduced bathing water quality
	Increased burden of disease due to unsafe food (contaminated fish, vegetables, etc.)
Environment	Decreased biodiversity (e.g. as a result of pesticide toxicity)
	Eutrophication and dead zones
	Visual impacts such as landscape degradation
	Bad odors (e.g. from manure)
	Diminished recreational opportunities
	Increased greenhouse gas emissions

Impacts on:	Examples of impacts
Productive activities	Reduced agricultural productivity (e.g. by the use of saline drainage water)
	Reduced market value of harvested crops, if pollution acknowledged
	Reduced number of tourists in polluted areas
	Reduced fish and shellfish catches

Source: Adapted from Hernandez-Sancho *et al.*, 2015.

of a potential pollutant, say nitrogen fertilizer, it does not necessarily follow that it is a significant pressure. For example, in some water-scarce areas, due to necessarily high levels of water control, the export of soluble nitrate to groundwater or surface water is limited despite the intensive use of fertilizers because deep percolation and runoff volumes are small (Duncan *et al.*, 2008; Molden *et al.*, 2010).

3.2 Types of pollutants and agricultural sources

The chief agricultural contributors to water pollution (and the main targets for water pollution control) are nutrients, pesticides, salts, sediments, organic carbon, pathogens, heavy metals and drug residues. The relative contribution of different types of agriculture pollutants to water quality degradation is presented in Table 3.2. The importance of different types of agricultural pollution can vary, depending on the circumstances. Negative impacts, such as eutrophication, arise from combinations of stressors, which can include sediments, nutrients and organic matter. Significant portions of nutrient load may be carried by sediments into surface waters, whereas groundwater pollution results mostly from dissolved pollutants (with perhaps the exception of pathogens).

Water quality monitoring programs typically record key pollution indicators, such as concentrations of ammonium, nitrate, phosphate, oxygen (or oxygen demand), salts, pathogens (e.g. E. coli) and suspended solids, and sometimes also pesticides and heavy metals, although these are expensive to measure. Other indicators, such as temperature or pH, are recorded because they impact biota directly, or because they mediate the impacts of pollutant loading. For example, temperature plays an important role in the occurrence of algal blooms in conjunction with nitrate and phosphate loadings; it also affects the solubility of oxygen in water and high temperatures can induce anoxic waters. Many indicators need to be measured in groundwater as well as in surface water; these have historically received greater attention when that water is used by humans for drinking.

Cultivation practices can impact both surface and groundwater quality. For surface water, two types of impacts are of most concern: the loss of topsoil as a result of erosion,

Table 3.2 | Categories of major water pollutants from agriculture and the relative contribution from different agricultural production systems

Pollutant category	Indicators/examples	Relative contribution by:		
		Crops	Livestock	Aquaculture
Nutrients	Primarily nitrogen and phosphorus present in chemical and organic fertilizers as well as animal excreta and normally found in water as nitrate, ammonia or phosphate	***	***	*
Pesticides	Herbicides, insecticides, fungicides and bactericides, including organophosphates, carbamates, pyrethroids, organochlorine pesticides and others. Many, such as DDT, are banned in most countries but are still being used illegally and persistently	***	–	–
Salts	Ions of sodium, chloride, potassium, magnesium, sulphate, calcium and bicarbonate. These are measured in water, either directly as total dissolved solids or indirectly as electric conductivity	***	*	*
Sediment	Measured in water as total suspended solids or nephelometric turbidity units – especially from pond drainage during harvesting	***	***	*
Organic matter	Chemical or biochemical oxygen-demanding substances (e.g. organic materials such as plant matter and livestock excreta), which use up dissolved oxygen in water when they degrade	***	***	*
Pathogens	Bacteria and pathogen indicators, e.g. *Escherichia coli*, total coliforms, faecal coliforms and enterococci	*	***	*
Metals	E.g. selenium, lead, copper, mercury, arsenic and manganese	*	*	*
Emerging pollutants	E.g. drug residues, hormones and feed additives	–	***	**

Source: Author’s descriptions.

and its subsequent deposit in water courses and lakes; and runoff of nutrients (N and P) from an excessive use of fertilizer. Pesticide runoff can be locally very relevant when pesticides are applied incorrectly or when rain washes them away. Another local water quality problem occurs when farmers attempt to desalinize irrigated fields by applying large amounts of leaching water (Cañedo-Argüelles *et al.*, 2013). In addition, pumping of groundwater can induce saline intrusion in coastal aquifers or the migration of low quality water from underlying aquifers (IGRAC, 2009).

The livestock sector is probably the largest source of water pollution, if the land used for feed crops is taken into account (FAO, 2006). The major sources of pollution are animal waste and uneaten feed, land used for feed crops, and tanneries. Animal manure and slurries contain large amounts of pathogens, ammonia and phosphate and have high biological oxygen demand (BOD) (FAO, 2006). The sources of livestock pollution are generally diffuse, but they can be concentrated (e.g. slurry management under zero grazing and feedlots). In many parts of the world, particularly in drylands, overgrazing has caused land degradation and erosion, which has in turn increased sediment loads to water (Doetterl *et al.*, 2012. Heavy metals can concentrate in livestock enterprises (e.g. copper in pig production) resulting in point-source contamination of soils and water.

Pollutants produced by aquaculture, as for livestock, chiefly originate from the use of various inputs, and the excreta and secretions of the aquaculture organism. The major pollutants and pollutant indicators include (Li and Chen, 2013):

- non-ionic toxic ammonia (NH_3), for which the major sources are the faeces of aquatic organisms, feed residues and dead algae;
- nitrite: an intermediate product during the conversion of ammonia into nitrate;
- phosphorus: the major source is phosphorus in feed;
- other chemical residues: bactericides, fungicides and parasite-killing agents, algaecides, herbicides, molluscicides and growth hormones;
- turbidity: suspended particles can be vectors for pathogens and viruses;
- chemical oxygen demand (COD) or biological oxygen demand (BOD): an abundance of organic matter can lead to oxygen deficiency, which can kill fish and cause the release of poisonous or harmful substances, such as ammonia and hydrogen sulfide.

Some important contaminants, such as arsenic (best known in groundwater in Bangladesh, India and Cambodia) or selenium are released from natural sources as a result of extracting large quantities of water (mostly groundwater) for irrigation (Mateo-Sagasta and Burke, 2010).

From a health perspective, the agropollutants of greatest relevance are pathogens from livestock, pesticides and nitrates in groundwater (particularly when the water is used for drinking purposes), trace metallic elements (including arsenic) and emerging pollutants, including antibiotics and antibiotic-resistant genes excreted by livestock. From an environmental perspective, eutrophication due to an excess of nutrients, salinization induced by agriculture and decomposable organic matter (mainly from livestock) in surface waters are probably the most relevant factors (Table 3.3).

3.3 Pollution pathways

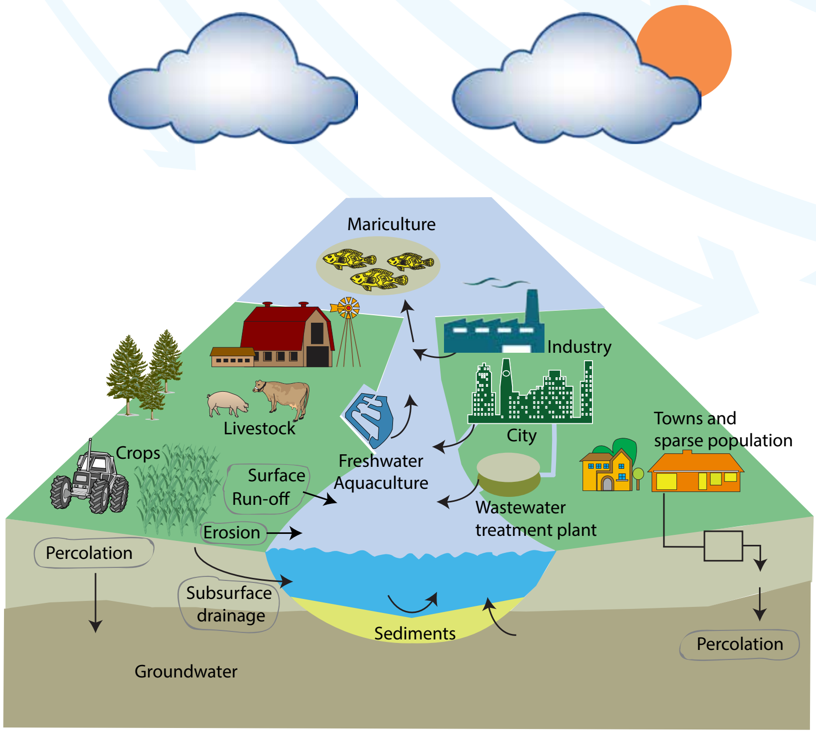
Agricultural and municipal pollution are closely linked to the hydrologic cycle. General sources and pathways for point source (PS) and non-point source (NPS) pollution of water are illustrated in Figure 3.1 below and discussed in box 3.2.

Table 3.3 I Major global water quality issues related to agriculture in inland waters and their relevance to human health and the environment

Issue	Environmental relevance	Health relevance	Water body			
			Rivers	Lakes	Reservoirs	Groundwater
Faecal pathogens	+	+++	•••	•	•	••
Suspended solids	++	+	••	Na	•	Na
Decomposable organic matter	+++	+	•••	•	••	•
Eutrophication	+++	+	•	••	•••	Na
Nitrate	++	+	•	–	–	•••
Salinization	+++	++	•	–	•	•••
Trace metallic elements and arsenic	+	+++	••	••	••	••
Pesticides	+	+++	••	••	••	•••
Acidification	++	++	•	•	••	–

Na: not applicable; Health relevance: + (low) to +++ (high); Occurrence of degradation issues: • (low) to • • • (high); –: (rare occurrence).
Source: Adapted from Meybeck, 2004.

FIGURE 3.1 Water pollution sources and pathways



Source: IWMI.

BOX 3.2 Point and non-point source pollution (adapted from FAO, 2013)

We tend to think of environmentally or health-damaging pollution as wastewater that comes from industries, cities, towns and other sources where polluted water is discharged through a pipe or channel. This type of pollution is known as 'point source' (PS) pollution. Because it is discharged through pipes or channels, it can be easily monitored for quantity and water quality (physical and chemical properties) and can be collected and treated before it is discharged into rivers, lakes or reservoirs. Some agricultural systems, such as big industrial livestock farms (e.g. pigs, poultry), slaughterhouses and intensive aquaculture farms, can be considered point pollution sources.

Other types of land-use activities, such as road construction, mine drainage, rainwater runoff from city streets (which is not collected in storm drains), from agriculture and from many rural villages, produce water pollution that does not come from any specific pipe or channel, but instead tends to be dispersed across the landscape. This type of pollution, which cannot be easily measured because of its diffuse nature, is known as 'non-point source' (NPS) pollution, or diffuse pollution.

Although this publication will concentrate on water quality impacts that arise from agriculture, pollution loadings have many sources and follow pathways through air, surface water and groundwater. It is important to note that aerial pathways are significant, and cause secondary concentration in the hydrologic system (Monteith *et al.*, 2007; Howarth, 2008).

In addition to aerial pathways, agricultural pollutants impact aquatic and marine ecosystems as a result of export from farms, transportation along hydrological pathways and concentration in water bodies. Typical water pollution pathways are: i) from soil solution to deep percolation and groundwater recharge; ii) from runoff, drainage water and floods to streams, rivers and estuaries; iii) from natural or human induced soil erosion to sediment-rich streams.

Some pollutants, such as nitrate or ammonium, are highly soluble and are easily lost from the soil profile through leaching or runoff. Other pollutants (e.g. phosphate or some pesticides and pesticide transformation products) tend to be transported by attaching themselves to suspended soil particles, and can thus concentrate where sediments are deposited (lakes, wetlands, estuaries and coastal zones), providing a reservoir of contaminant that can be re-released in episodic or continuous patterns. Hydrology is therefore the link between the source of pollution and state change in a water body.

Surface drainage increases both soluble and sediment-borne transport of nutrients and pesticides by creating a more direct path to waterways. In contrast, by shifting the major pathway for excess precipitation from surface runoff to subsurface flow, tile drainage has been shown to reduce losses of sediment, phosphorus, and pesticides from agricultural land in the north-western USA (Blann *et al.*, 2009). The hydrology of subsurface drainage in conjunction with surface drainage has more complex implications for sediment and nutrient loading.

Animal waste can enter surface and groundwater from communal farms and feedlots both accidentally and on purpose. Rainfall causes animal waste to run off into surface streams and groundwater. Also, some farmers deliberately clean their animal pens directly into rivers and canals (FAO, 2006).

This chapter has introduced some basic concepts that will help to better understand subsequent chapters where, on the one hand, specific pollutants are analyzed more thoroughly – nutrients (Chapter 4), pesticides (Chapter 5), salts (Chapter 6), sediments (Chapter 7), and organic matter, pathogens and emerging pollutants (Chapter 8) – and, on the other hand, water quality models to analyze sources and effects of water pollution are discussed (Chapter 9).

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