4 Bioenergy-related water quality issues

Water quality is a measurement of the physical, chemical and biological characteristics of water against certain standards that can be ecological or specifically related to human needs. The production of bioenergy feedstocks and their conversion to solid, liquid and gaseous biofuels for heating, power and transport can drastically affect water quality in aquatic ecosystems, with impacts on biodiversity and human health. Depending on how a bioenergy system is located and managed, it can lead to deterioration or improvements in water quality. This chapter focuses on the impacts of bioenergy production on water quality, and how to measure and reduce these impacts.

4.1 Sources of water pollution in bioenergy production

Water quality needs to be considered in an integrated manner. According to Perry and Vanderklein (1996), it should be seen as part of a wider picture, including hydrology, chemistry, biology, geology, land use, demographics, public attitude and policy. Water quality may be affected by physical, chemical, biological and thermal pollution of aquatic systems from bioenergy production. It may also be affected by natural events (e.g. volcanic eruptions) and by human activities. The following sections review these impacts, from agricultural and forestry practices to the processes used in bioenergy feedstock production and conversion.

4.1.1 Agricultural inputs and impacts on water quality

The impacts on water quality of cultivating conventional crops as feedstock for first generation biofuels are the same as those of cultivating other farm crops. Direct impacts on water quality arise from pollution owing to run-off from intensive agricultural production employing pesticides (e.g. herbicides, insecticides, fungicides) and fertilizers, together with other undesirable agricultural practices such as tillage of unsuitable soils.

a) Pesticides

Pesticides can have a profound effect on aquatic life and water quality. As pesticide residues are carried to ponds, rivers, lakes and other water bodies by surface run-off or spray drift, they can cause acute poisoning (e.g. fish kills) as well as chronic poisoning when wildlife is exposed to pesticide levels that are not immediately lethal. Negative effects on fish that receive repeated sub-lethal doses of pesticides include reduced fish egg production and hatching, lower resistance to disease, decreased body weight and reduced avoidance of predators. The overall consequence can be lowered population abundance. There are also risks of secondary poisoning when predators consume prey that contain pesticides. This can be a particular concern in relation to persistent chemicals that bioaccumulate and move up the food chain. Indirect effects may also occur when habitats or food chains are modified, for instance when insecticides diminish insect populations fed on by fish and other aquatic animals.

Pesticides stored in sub-standard conditions pose a threat to both human health and the environment, particularly when they are stored in urban areas or near water bodies. Farmers with insufficient knowledge of pesticide management commonly use older, more toxic and environmentally persistent chemicals (Ecobichon, 2001). This may be a particular problem in some developing countries. Absence of stringent regulations, or lack of enforcement of existing regulations, contribute to the problem (Eddlestoon et al., 2002).

b) Fertilizers

Fertilizers are used to increase agricultural yields. In particular, nitrogen and phosphorous may end up in waterways and aquifers, where they can have significant impacts on the quality of river water and groundwater and result in eutrophication of wetlands and water bodies (Ongley, 1996). High nutrient concentrations stimulate growth of algae, leading to imbalanced aquatic ecosystems. These ecosystems may experience phytoplankton blooms, production of excess organic matter and increased oxygen consumption, leading to oxygen depletion and the death of benthic organisms that live on or near the bottom in aquatic habitats.

For example, the Baltic Sea[17] is surrounded by nine countries. Five more countries are in its drainage basin, but do not border on it. Fertilizer run-off to the Baltic Sea from surrounding agricultural land contributes to a large nutrient load, primarily via river discharges[18]. This run-off has changed it from an oligotrophic clear-water sea into a eutrophic marine environment experiencing summertime algal blooms. Blue-green algae that are potentially toxic to humans and animals are a particular problem (Figure 4.1). Similarly, nitrogen run-off to the Mississippi River has resulted in algal blooms and an anoxic "dead zone" in the Gulf of Mexico[19] (Bianchi et al., 2000; Finni et al., 2001). The Black Sea[20], which is an inland sea, provides a third example of the occurrence of large annual phytoplankton blooms. During the last decades, increased nutrient loads from human sources, together with other forms of pollution and over-harvesting of fisheries, have caused a sharp decline in water quality in the Black Sea.

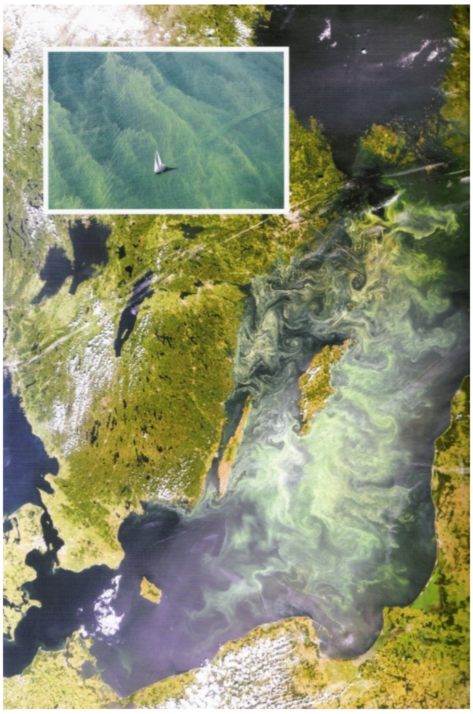


Figure 4.1: Algal blooms in the Baltic Sea. Photo credit: SMHI, Sweden.

c) Manure and sludge from wastewater treatment

Wastewater treatment can be a valuable source of nutrients and contribute to maintaining/improving soil carbon content and productivity. Nevertheless, especially when spreading takes place on frozen ground, high nutrient run-off can result in high levels of contamination of receiving waters by pathogens, metals, nitrogen and phosphorus. Groundwater may also be polluted, specifically by nitrogen.

[17] The Baltic Sea is not a freshwater body as defined in Chapter 1, footnote 1

[18] All sources of pollution of the Baltic Sea were made subject to the Convention on the Protection of the Marine Environment of the Baltic Sea Area (the Helsinki Convention), which was signed in 1974 and entered into force in 1980. A new Helsinki Convention, signed in 1992 by all bordering states and the European Union, entered into force in 2000.

[19] The Gulf of Mexico is not a freshwater body as defined in Chapter 1, footnote 1

[20] The Black Sea is not a freshwater body as defined in Chapter 1, footnote 1

d) *Irrigation*

The impacts of irrigation include run-off of salts (leading to salinization of surface waters), run-off of pesticides and fertilizers to surface waters (causing ecological damage), and bioaccumulation of hazardous substances in edible fish species (Ongley, 1996). Box 4.1 presents a case study from the Republic of Senegal, where the irrigation of thousands of hectares of sugarcane fields requires millions of cubic metres of water per year (pumped directly from the Senegal River and Lake Gouiers) with environmentally harmful effects.

e) Tillage

Unsustainable agricultural practices such as the tillage of unsuitable soils can lead to sediment run-off to water bodies, causing physical impacts (e.g. water turbidity and siltation of river beds) as well as chemical ones (e.g. through the absorption of organic chemicals like phosphorus, and of pesticides, on sediment particles) and consequently loss of habitats including spawning grounds (Ongley, 1996). These impacts should also be considered in regard to harvest residue extraction for bioenergy production, which encourages erosion (Section 4.1.2).

Box 4.1: Sugarcane production in Senegal

The Senegalese Sugar Company (Compagnie Sucrière Sénégalaise, or CSS) is located in northern Senegal on the Senegal River. The largest agro-industrial unit operating in the Senegal River basin, it has a production potential of more than 8 000 hectares of sugarcane with an average yield of 120 tonnes/hectare, using water from the river and Lake Guiers. The company employs 3 000 permanent workers and 2 000 seasonal ones. In 2008, it inaugurated a new bioethanol plant with an annual production capacity of 10 to 12 million litres of ethanol from the distillation of molasses. Ethanol production covers the company's energy consumption and supplies the Senegalese market with clean fuel as an alternative energy source for households and sectors such as pharmaceuticals, alcohol and alcoholic drinks.

Irrigating some 8 000 hectares of sugarcane fields requires approximately 188 million m^3 of water per year, which is pumped directly from the river and Lake Guiers. The lake, the country's largest reserve of surface freshwater, is connected to the Senegal River by a canal. Its hydrological regime was subject to fluvial rising, but is now regulated by dams on the river. The lake's main uses include irrigation of sugarcane and drinking water supply. In the future, Lake Guiers could be the starting point for a 250-kilometre canal to Dakar, the capital, which would supply the city with water. From the Ngnith station pumps, the lake already provides Dakar with over 100 000 m^3 of drinking water per day.

Irrigation using water from the lake and river has environmentally harmful impacts. Those associated with sugarcane production involve the use of chemicals, especially mineral fertilizers and pesticides. Studies have been conducted to assess water pollution of the river and lake (in terms of quantity and quality) due to sugarcane production. Effluent quality has been measured at different points, upstream and downstream of the receptor point and of the surface near where water is pumped, in order to take the diffusion of water pollution into account. Concentrations of nutrients from fertilizers (e.g. nitrogen and phosphorous) appear to be low. The lake is more polluted than the river, where water is moving. However, the deeper lake water is less polluted than that at the surface.

Source: Cogels, 1994; OMVS, 2002.

4.1.2 Forestry inputs and impacts on water quality

In addition to impacts associated with cultivation, other practices related to bioenergy feedstock production (e.g. harvest residue extraction) can lead to negative impacts, including soil erosion (causing sedimentation of water bodies) and reduced ability of precipitation to penetrate the soil and replenish groundwater supplies.

Increased demand for lignocellulosic biomass can change the way bioenergy production affects water quality. Although removing lignocellulosic harvest residues may have negative impacts, some positive impacts on water quality can be expected if increased demand for this biomass leads to shifts in land use towards a larger share of perennial herbaceous plants and woody plants (e.g. willow, poplar, eucalyptus) being grown in multi-year rotations. Such short rotation coppice plantings are generally considered more beneficial for water quality in a given area due to less intensive management practices (e.g. use of weed control only during the establishment phase, tillage only before the establishment phase, and lower inorganic fertilization than in the case of conventional food/feed crops) (Box 4.2).

Box 4.2: Water quality impacts of cultivating short rotation coppice (SRC) plants

Most studies of the impacts on water quality of cultivating short rotation coppice (SRC) plants have been concerned with nitrogen and phosphorous leaching to groundwater. Reports of considerable differences in nitrogen leaching between SRC and conventional food/feed crops can, in some cases, be attributed to the smaller amount of fertilizer applied to SRC plantings. However, results for SRC plantings intensively irrigated with nutrient-rich wastewater (usually nitrogen, but also phosphorous) suggest that in general nitrogen leaching from these plantings in comparison with that of arable crops is significantly lower and a shift from arable crops to SRC can lead to improvement of groundwater quality and, consequently, of surface water quality in a certain area. Similarly, results from experiments involving applications of municipal sewage sludge to willow and poplar can provide insights into the effects of SRC on phosphorous leaching.

Today, application of sludge to SRC is a common practice in Sweden and the United Kingdom, where it compensates phosphorous losses in newly harvested fields (Sagoo, 2004; Dimitriou and Aronsson, 2005). Here, studies also point to low phosphorous concentrations in drainage water when there is a relatively high phosphorous input. Phosphorous is usually bound to soil particles. Its leaching patterns differ from those of nitrogen, which in most cases are related to water drainage. However, future phosphorous leaching cannot be excluded if sewage sludge is applied over a number of years at high rates.

Source: Dimitriou et al. (2011).

Energy production from wood has a life cycle that produces environmental burdens and impacts on hydrologic systems at various stages (Malkki et al., 2001; Neary, 2002). Most concerns have been focused on forest operations, including road networks, site preparation, herbicide use, fertilization, harvesting, ash recycling and regenerated site preparation (Ranney and Mann, 1994). These operations are transitory and are generally well-dispersed throughout watersheds. They can affect hydrological processes and pollute water directly or indirectly through the use of pesticides and fertilizers, among other activities. Their impacts include:

a) Hydrological processes

Hydrological processes can be affected, for instance, by harvesting. The hydrological cycle quantifies interactions between the atmosphere, geosphere, biosphere and hydrosphere (Table 4.1). Since water is a primary driving force in ecosystem processes and fluxes, water quality reflects the net effects of those processes and disturbances that occur in watersheds.

A generalized breakdown of the inputs, fluxes and outputs in undisturbed forested watersheds in humid regions was described by Hewlett (1982) and Neary (2002). The percentage distribution of water movement changes somewhat depending on whether arid shrub, grassland or woodland ecosystems are being studied, and it can vary considerably in watersheds disturbed by climate change, harvesting, burning, insect defoliation, windthrow, land use conversions, mining and agriculture. Precipitation inputs consist of rain, snow and sleet. Fluxes, or the movement pathways of water within watersheds, consist of interception, evaporation, transpiration, stemflow, throughfall, infiltration, surface run-off, interflow, baseflow and stormflow. They convey variable amounts of dissolved or suspended solids, which constitute the physical component of water quality (Swank, 1988).

Table 4.1: Changes in hydrological processes in forests after harvesting. Source: Adapted from Neary and Hornbeck (1994) and Neary (2002)

Hydrologic process	Type of change	Specific effects
1. Interception	Reduced	Moisture storage smaller Greater run-off in small storms Increased water yield
2. Throughfall	Increased	Baseflow increase Soil moisture increase
3. Evaporation	Increased	Baseflow decrease Soil moisture decrease
	Decreased	Baseflow increase Soil moisture increase
4. Litter storage	Litter reduced	Less water stored (0.5 mm cm^{-1})
	Litter not affected	No change
	Litter increased	Storage increase
5. Transpiration	Temporary Elimination	Baseflow increase Soil moisture increase
6. Infiltration	Reduced	Overland flow increase Stormflow increase
	Increased	Overland flow decrease Baseflow increase
7. Streamflow	Changed	Increase in most ecosystems Decrease in snow systems Decrease in fog-drip systems Decrease depending on conversion process
8. Baseflow	Changed	Decrease with less infiltration Increase with less transpiration Summer low flows (+ and -)
9. Stormflow	Increased	Volume greater Peakflows greater Time to peakflow shorter
10. Snowpack	Changed	Cuts <4 ha, increase in snowpack Cuts > 4 ha, decrease in snowpack Snowmelt rate increase Evaporation/sublimation greater

b) Erosion and peakflows

When a watershed is in good condition, rainfall infiltrates the soil and baseflows are sustained between storms. Well-vegetated watersheds in good condition generally do not suffer from damaging peakflows (flash floods). The term "watershed condition" describes the ability of a watershed system to receive, route, store and transport precipitation without ecosystem degradation (Brooks et al., 2007).

In some regions of the world destructive streamflows are common irrespective of watershed condition. Nevertheless, severe fires, poor harvesting practices, over-grazing, conversion to agriculture and urban uses, and other disturbances may alter the watershed condition, reducing it to a moderate or poor level. In the case of poor watershed condition, the percentage of infiltrated rainfall is reduced significantly and the result may be erosion and flooding. Moreover, sometimes the loss of organic material through severe burning, harvesting, respiration, oxidation, site preparation or other disturbances can bring about adverse changes in hydrologic conditions.

c) Chemical pollution

A number of studies have examined the effects of forest harvesting on water quality (Bosch and Hewlett, 1982; Neary and Hornbeck, 1994; Neary, 2002; Andreassian, 2004; Bruijnzeel et al., 2004). The water quality parameters typically examined by these studies are nitrate-nitrogen (NO_3-N), ammonia nitrogen (NH_3-N), total nitrogen (N), total phosphorus (P) and orthophosphate (PO_4-P), cations such as sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg), micronutrients, sediment and temperature. These parameters are of concern for streams being used as water supplies, and for their potential impact on aquatic biota, particularly threatened and endangered species.

The changes in water quality parameters discussed here are mostly taken from studies treating entire watersheds uniformly. These studies have rarely examined situations in which forest harvesting was carried out within much larger catchments, so that most of the area could not be treated at the same time. Due to dilution effects, water quality effects are usually attenuated as the untreated area increases.

d) Nutrients

Nitrate-nitrogen (NO_3-N) levels are often used as an indicator of watershed health and water quality. This is a good integrator and indicator of disturbance (Swank, 1988), as well as a critical water quality parameter for human health. For the most part, large increases in NO_3-N levels have not been observed in streams draining harvested watersheds. The greatest increases in NO_3-N levels reported in the literature (Pierce et al., 1970) were measured where herbicides had been specifically applied to suppress vegetation regrowth, and also where nitrogenous fertilizers had been applied during forest regeneration (Neary and Hornbeck, 1994) or where nitrogen saturation of ecosystems had reached a critical level due to atmospheric deposition (Aber et al., 1989). Severe fire can cause similar nutrient release (DeBano et al., 1998).

e) Fertilizers and wood ash

Compared to agricultural land, even managed forests have much higher water quality. Certainly fertilizer use in the forest bioenergy life cycle is not expected to cause water quality problems, especially when Best Management Practices (BMPs) are used (Aust and Blinn, 2004). Inter-rotation forest fertilization programmes can be a source of additional nutrient inputs to streams, but mitigation practices may limit those inputs (Neary and Leonard, 1978).

A review by Pitman (2006) cautioned that environmental problems associated with wood ash use are less likely to derive from its heavy metal content, which can be partly removed at source when it is burned, and are more likely to be associated with the tree species and type, the nature of the burn process and conditions at the site. The application of the incorrect wood ash may result in higher soil pH, increasing microbial populations, and potential mobilization of nitrogen. Although higher soil pH is potentially beneficial to tree growth on acidic or nutrient-poor soils, it can be accompanied by changes in the ecology and functioning of forest ecosystems.

f) Pesticides

Herbicides and insecticides are sometimes used in the establishment of bioenergy feedstock plantations to reduce weed competition or deal with insect infestations. Analyses conducted in regional environmental impact statements indicate that the low concentrations and short persistence of forestry pesticides in surface and groundwater do not pose a significant risk to water quality, aquatic biota or human health (Neary and Michael, 1996).

g) Sediment increase

Sediment increase during and after forest harvesting is highly variable, depending on factors such as soils, climate, topography, ground cover and watershed condition. Although sediment levels increase after harvesting as a result of the physical disturbance of soil, they are usually transient due to vegetation regrowth. The largest increases documented in the literature have been associated with post-harvest mechanical site preparation, slope instability, road construction, or soils that are naturally highly erosive. The cumulative effects of erosion and sedimentation that occurred centuries ago as a result of agriculture or forestry can present forest managers with many challenges (Terrene Institute, 1993).

Sediment is an important water quality parameter since it can harm aquatic organisms and habitats, as well as rendering water unacceptable for drinking water supply or recreational purposes. The natural variability of sediment regimes in bioenergy forests must be understood before judgements are made concerning the effects of harvesting. Use of appropriate BMPs and carefully planned harvesting can result in minimal or no additions to stream sediments (Neary et al., 2010) (Table 4.2). BMPs are most effective in minimizing sediment inputs to streams or lakes when they are properly planned and implemented prior to, during and after harvesting (Aust and Blinn, 2004).

Table 4.2: Sediment increases due to forest harvesting and related disturbances. Source: Neary and Hornbeck (1994), Neary and Michael (1996), Neary (2002)

Forest type	Location	Treatment	Sediment increase	Sediment increase
			%	mg ha^{-1} yr^{-1}
Harvesting alone				
Northern hardwoods	New Hampshire, USA	Clearcut	769	0.323
Mixed hardwoods	West Virginia, USA	Clearcut	0	0.000
Loblolly pine	South Carolina, USA	Clearcut	655	0.131
Mixed hardwoods	Georgia, USA	Clearcut	154	0.103
Upland hardwoods	Tennessee, USA	Clearcut	2 020	10.600
Loblolly pine	Arkansas, USA	Clearcut	1 875	0.225
Loblolly/shortleaf pine	Arkansas, USA	Clearcut	6 500	0.260

Lodgepole pine	Montana, USA	Clearcut	661	0.119
Douglas fir	Oregon, USA	Clearcut	8 182	0.202
Mixed conifer	Arizona, USA	Clearcut	38	0.003
Beech-podocarp	New Zealand	Clearcut	42	0.182
Beech-podocarp	New Zealand	Clearcut	700	3.003
Beech-podocarp	New Zealand	Clearcut	2 100	2.100
Harvesting and site preparation				
Loblolly pine	Mississippi, USA	Clearcut, bed	2 198	13.630
Slash pine	Florida, USA	Clearcut, windrow	1 100	0.033
Loblolly pine	North Carolina, USA	Clearcut, blade	1 939	9.695
Loblolly pine	Arkansas	Clearcut, shear	653	0.464
Shortleaf pine	Arkansas	Clearcut, windrow	1 926	0.578
Loblolly pine	Texas, USA	Clearcut, shear	750	0.170
Roads				
Mixed hardwoods	North Carolina, USA	Roads	11 900	1.190
Loblolly pine	Georgia, USA	Roads	96 700	3.868
Douglas fir	Oregon, USA	Roads	175	0.930
Mixed conifer	Arizona, USA	Roads	1 012	0.081

h) Water temperature

Water temperature is a water quality parameter that affects stream biota in temperate forests. Forest vegetation shades stream channels from solar radiation, producing stream temperatures that are cooler and less variable than in the case of unshaded sites (Neary and Hornbeck, 1994; Neary, 2002). Temperature increases that result from canopy removal or thinning during forest harvesting temporarily affect physical, chemical and biological processes. The impact on aquatic biota varies considerably, depending on whether individual species are eurythermic and the degree to which stream temperature is controlled by solar heating or stream baseflow.

Adverse changes in stream temperature can be buffered by using streamside management zones as a form of BMP. Cumulative effects of stream temperature increases are often moderated as the streamflow from harvested areas merges with that from larger, uncut areas. In some ecosystems, stream temperatures are primarily controlled by the temperature of baseflow inputs. Canopy removal by thinning or whole tree harvesting therefore has little impact on temperature.

4.2 Biomass conversion and impacts on water quality

From a water quality perspective, the biomass production phase represents a diffuse and distributed source of pollution (non-point source pollution). In contrast, the conversion phase can be considered a point source of pollution.

Impacts on water quality associated with *discharges* from conversion plants – the main focus of this section – are caused by chemical, biological and thermal pollution of aquatic systems. Some of the impacts associated with the conversion of bioenergy feedstocks include:

a) Industrial effluents (chemical and physical effects): impacts on rivers, lakes and land of uncontrolled discharges. For example, in Brazil the process of producing ethanol from sugarcane is highly efficient and there is control of discharges. (See Section 4.2.1 below and case study 2.1 in Chapter 2).

b) Application of wastewater in agriculture. Sugarcane vinasse is used as a fertilizer in Brazil and other sugarcane producing countries. This practice needs to be controlled to avoid soil saturation.

c) Wastewater can be a substantial contributor to *greenhouse gas (GHG) emissions.* For instance, palm oil mill effluent (POME) from processing the fruits of oil palm is generated mainly from oil extraction, washing and cleaning. As water quality discharge guidelines and regulations have been implemented (see Chapter 5), POME is now frequently discharged first into open lagoons (without methane capture) where the wastewater is treated. Biological oxygen demand (BOD) is the key measurable parameter of water quality. Microbial activity in anaerobic conditions, a natural process that reduces the BOD, also produces methane (CH_4), a greenhouse gas around 25 times more effective than CO_2 in trapping heat in the atmosphere, according to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (Chalmers and Warden, 2009).

Without the capture of these methane emissions, this stage in the wastewater treatment process is a substantial contributor to GHG emissions. A comprehensive study of emissions associated with various biofuels (JEC, 2008) has calculated that biofuel production saves only 44% of GHG emissions when compared to a fossil diesel if POME emissions are not captured. If the POME emissions are captured and used, GHG savings will be 72%.[21] Methane capture from wastewater treatment for use as a process energy source (e.g. the methane can be used as a gas in boilers) would represent a significant step towards reducing GHG emissions associated with biofuels, and specifically with wastewater.

Some of these impacts are better explained by referring to the different feedstocks and production systems used. The following section focuses on the use of sugarcane for ethanol production in Brazil and the harvesting of feedstock (forestry) in Australia, including some of the impacts mentioned above.

4.2.1 Case study: Use of sugarcane for ethanol production in Brazil

In Brazil, recovery and treatment of industrial effluents from sugar mills and distilleries basically consists in the application of preventive internal controls. Reuse and recycling of effluents to reduce pollution (discharge and physico-chemical parameters), and reduction of water use, have long been carried out in industrial plants. Techniques include recirculation, wastewater reuse, more efficient equipment, less polluting processes, and crop fertigation. The advantages of implementing these techniques include: less use of power and water pumping; better use of raw materials; lower costs; and better management of nutrients (nitrogen, phosphorous and potassium) and organic matter in agriculture, resulting in better yields and soil improvement.

Treatment systems in the sugarcane industry include:

- water washing of the cane: 180-500 mg/litre of BOD_5 and high concentrations of solids. Treatment in sedimentation and stabilization ponds for release to water bodies. For reuse, treatment consists of settling and correction to a pH between 9 and 10;

[21] This assumes a fossil fuel reference of 86 g CO_2 eq/MJ.

- water-cooled multijets and barometric condensers in sugar mills: low pollution potential (10-40 mg/litre BOD_5) and high temperature (~50°C). Treatment by spray ponds or cooling towers before recirculation or release;

- water cooling of fermentation and distillation: high temperature (~50°C). Treatment by spray ponds or cooling towers before recirculation or release;

- use of effluent gas scrubber to treat flue gas from the bagasse-fired boiler in order to retain particulate matter (PM), with low potential for organic matter (range 100-150 mg BOD_5/litre and 200-300 mg/litre COD) and high temperature, reaching 80°C. Treatment is usually by sedimentation-flotation systems for recirculating the gas of the scrubber system. Sludge, containing a great deal of solid (generally referred to as "soot"), is sent to the fields as solid waste;

- stillage (vinasse or spentwash): large volume, ranging from 11 to 12 litres/litre of ethanol, with high organic load (25 000-40 000 mg/litre of COD). The stillage is applied to sugarcane fields with or without wastewater (from washing of floors, purging of closed circuits, excess condensate), promoting fertigation with the use of nutrients.

Table 4.3 summarizes the types of wastewater generated, with its volumes and main features. The characteristics of these effluents and the availability of simple treatment systems allow immediate reuse. The more recalcitrant wastewater – such as stillage (vinasse or spentwash) and purges of reuse systems, with high levels of organic matter and salts – is reused in fertigation of sugarcane.

Table 4.3: Summary of characteristics of wastewater from sugar-ethanol sugarcane mills. Source: Elia Neto and Shintaku (2009)

Wastewater		Physico-chemical characteristics						
		Flow	pH	Temperature (°C)	Settleable solids (mL/L)	COD (mg/L)	BOD (mg/L)	Oil and grease (mg/L)
Sugarcane washing		2-5 m^3/tonne cane	5-6	room	5-10	280-700	180-500	0
Cooling equipment (mills, turbines and turbo generators)		0.665 m^3/tonne cane	7	< 30	< 0.5	0	0	-
Cooling condensers/multijets evaporation and cookers		70-100 L/kg sugar	6-7	50	< 0.2	20-80	10-40	0
Cooling distillery for	Sugarcane juice	30 L/L ethanol	7	< 45	0	0	0	0
	Fermentation	60-80 L/L ethanol	7	< 35	0	0	0	0
	Ethanol condenser	80-120 L/L ethanol	7	50-60	0	0	0	0
	Subtotal	200 L/L ethanol	7	50	0	0	0	0
Effluent gas scrubber, flue gas from bagasse-fired boiler		2 L/kg steam	8	80	50-100	200-300	100-150	-

Condensate of	Steam escape	40-50 L/kg sugar	7	80	0	0	0	0
	Steam juice	50-60 L/kg sugar	5-6	60-80	0	600-1 500	300-800	0
Cleaning of floors and equipment		50 L/tonne cane	5-6	room	< 0.5	1 000-3 000	800-1 500	> 20
Domestic sewage		70 L/person /day	6-7	room	5-20	600	300	-
Stillage (vinasse or spentwash) and flegmass[22]		12-18 L/L ethanol	4-4.5	80	3-5	25 000-40 000	15 000-20 000	8

Note: L = litre

A number of solutions are available to mitigate negative impacts from the different types of wastewater. For example, processing water can be treated and recirculated for further use in the conversion plant, or it can be returned to water bodies. For more information on mitigation strategies, see Section 4.4.

For more information on sugarcane ethanol production, see case study 2.1. in Chapter 2.

4.2.2 Case study: Evaluation of the water quality benefits of Best Management Practices during tree harvesting in Australia

A study conducted in northwest Tasmania, Australia, evaluated the water quality benefits of Best Management Practices during tree harvesting in a streamside management zone typical of tree farming (Neary et al., 2010). A 20-year-old *Eucalyptus nitensm*, growing in a pulpwood plantation along an intermittent stream, was cut according to the Tasmanian State Code of Forest Practice. A machinery exclusion zone immediately adjacent to the stream limited machinery traffic, but tracked harvesters were used to cut and extract tree stems without entering the exclusion zone (Figure 4.2). Ground cover and water quality pre- and post-harvesting were measured to identify major sources of sediment in this headwater catchment, and to determine the effect of tree harvesting.

Figure 4.2: Tigercat tracked harvester delimbing and topping a felled *Eucalyptus nitens* stem during a streamside harvesting study on the effectiveness of Best Management Practices. Note the slash coverage remaining in the harvested area. Photo credit: Daniel G. Neary

[22] Flegmass is a by-product obtained from the rectifying column of phlegm during the process of alcohol production.

The study demonstrated that post-harvesting turbidity levels in streamflow were similar to pre-harvest levels (< 2.5 nephelometric turbidity units, or NTUs) in streamflow exiting the catchment. A road, a dam (accessible to cattle) and a cultivated paddock were much more significant sources of sediment. These sources led to turbidities of about 300 NTUs in Dam 10 immediately below the road, in paddocks, and above the harvested stream reach during a storm in late June 2009 and subsequent winter storms through October 2009. At Dam 13, below the harvesting areas, stream turbidities were mostly below 10 NTUs. The in-stream dams functioned as very effective sediment traps. This study demonstrated how BMPs can be effective in limiting adverse impacts on water quality. It shows that bioenergy-related forest harvesting operations can be carried out without increasing stream turbidity if existing BMPs are followed.

4.3 Key indicators to measure water quality related to bioenergy production

Indicators to measure water quality refer to the chemical, physical and biological characteristics of the water and to its final purpose. In the case of agricultural and forestry systems, indicators tend to be related to the use of agro-chemicals that may pollute surface and groundwater. For this purpose, a number of regulations and international standards and agreements exist, such as the Stockholm Convention on Persistent Organic Pollutants (POPs),[23] the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal,[24] the World Bank EHS guidelines,[25] and the Global Reporting Initiative[26] reporting guidelines on water use and pollution (Smeets et al., 2006).

Water quality indicators can be classified as those concerning drinking water, bathing water, water pollution, and, depending on other uses, agricultural and industrial uses.

The main water pollution indicators have been used extensively for a number of years. They are in effect in most countries, and are enforced using reference maximum permissible levels of pollutants or physical characteristics. These indicators include:

- BOD (biochemical oxygen demand), to determine the oxygen-consuming organic material;
- TSS (total suspended solids), to measure the total amount of suspended matter (primarily inorganic substances from sugarcane and sugarbeet washing water);
- pH, as extreme changes are harmful to water fauna.

The United States Environmental Protection Agency has set some standards for water pollution with regard to best available technologies (Smeets et al., 2006) (Table 4.4).

Other indicators include conductivity and oxygen reduction potential (ORP). Indicators will vary according to the goal or standard of the measurement, and will include physical, environmental and chemical characteristics.

[23] For information on POPs, see: http://chm.pops.int/
[24] For information on the Basel Convention, see: http://www.basel.int/
[25] For information on the World Bank Environmental, Health, and Safety Guidelines (known as the "EHS Guidelines"), see: http://www.ifc.org/ifcext/sustainability.nsf/Content/EHSGuidelines
[26] For information on the Global Reporting Initiative, see: http://www.globalreporting.org

Standards and regulations vary among regions and countries. In the European Union their use is regulated by different directives and rules, including the EU Water Directive (EC, 2000).

Table 4.4: United States Environmental Protection Agency (US EPA) standards for water pollution. Source: Smeets et al. (2006)

	BOD	Volume of suspended solids (indicator)	pH
Raw sugar factory	kg/tonne cane	kg/tonne cane	(-)
Maximim daily value	0.10	0.24	
30-day			6.0-6.9
mean	0.05	0.08	
White sugar factory	kg/tonne raw syrup	kg/tonne raw syrup	(-)
30-day			6.0-6.9
mean	0.09	0.035	
Liquid sugar factory	kg/tonne raw syrup	kg/tonne raw syrup	(-)
Maximum daily value	0.30	0.09	
30-day			6.0-6.9
mean	0.15	0.03	

There are many possible metrics. In the United States, the National Research Council (NRC, 2008) has proposed a metric to compare the water quality impacts of various crops by measuring inputs of fertilizers and pesticides *per unit of the net energy gain* captured in a biofuel. Of the bioenergy feedstocks, corn (maize) has the highest application rates per hectare of both fertilizers and pesticides. Per unit of energy obtained, biodiesel requires just 2% of the nitrogen and 8% of the phosphorous needed for corn ethanol. Pesticide use differs similarly. Using this metric, low-input, high-diversity prairie biomass and other native species would also compare favourably to corn (maize).

NRC (2008) has reported that soil erosion from tillage is another source of water quality impacts. Soil erosion moves both sediments and agricultural pollutants into waterways. Various farming methods can help reduce soil erosion. However, if bioenergy production expands the cultivated area, especially on marginal land that is more prone to soil erosion, erosion problems could increase. An exception would be the use of native grasses such as switchgrass, which can reduce erosion on marginal lands.

The index proposed by NRC (2008), building on inputs of fertilizers and pesticides per unit of the net energy gain captured in a biofuel, requires calculation of the biofuel's net energy balance (i.e. its energy content divided by the total fossil energy used throughout the full life cycle of the production of the feedstock, its conversion to biofuel, and transport). This calculation has been made for ethanol produced from corn (maize) in the United States (NRC, 2008).

Smeets et al. (2006), reporting on the sustainability of biofuel production in Brazil, stated that the emission standards used to monitor water pollution in that country are different to international ones in most cases, as some have been implemented especially for Brazil. This is the case for BOD and pH standards. The US EPA standards for pH differ from those of Brazil and the World Bank, which have different parameters. (These standards are explained in detail in Chapter 5.) Some certification and standardization schemes also consider the use of agro-chemicals and pesticides linked to water pollution. Examples are GLOBALG.A.P[27] and the Forest Stewardship Council (FSC) (Chapter 6).

Another approach to assessing impacts on water quality is to use the grey water footprint (Box 2.1, Chapters 2 and 3).

4.3.1 Energy and water links with ecosystem services and the Millennium Development Goals

The UNEP Water Quality Outlook (GEMS/Water, 2007) states that water quality management contributes to meeting the Millennium Development Goals (MDGs), particularly Goal 7 on ensuring environmental sustainability, by helping to:

- integrate the principles of sustainable development into countries' policies and programmes and reversing the loss of environmental resources;
- halve by 2015 the proportion of people without sustainable access to safe drinking water and basic sanitation;
- significantly reduce biodiversity loss; and
- achieve significant improvements in the lives of at least 100 million slum dwellers by 2020.

Use of water quality indicators is one way to demonstrate progress towards achieving the MDGs. GEMS/Water (2007) emphasizes that the link between human health and aquatic systems is determined by water's physical, chemical and biological composition.

In the case of bioenergy projects, lack of water availability is probably the most obvious way that achievement of the MDGS could be jeopardized at local level if water is deviated solely for the production of bioenergy crops. Nevertheless, proper land management and use of resources for different agricultural products can contribute to more efficient use of water to produce food and bioenergy crops. Better management of resources, including water, can contribute in general to better ecosystem services.

The possibilities of new bioenergy projects with respect to developing infrastructure at the local level could also contribute to improvements in local water access and quality.

4.3.2 How to measure bioenergy-specific social and economic impacts

One overall challenge in assessing social and economic impacts is that the socio-economic environment is difficult to describe and quantify, and that it is generally a very complex composite of numerous (directly or indirectly) inter-related factors. Several of these factors are poorly understood. Social processes also have feedbacks that are commonly difficult to recognize clearly and to express with an acceptable level of confidence. Identification and assessment of bioenergy-specific impacts

[27] GLOBALG.A.P is a private sector body that sets voluntary standards for the certification of production processes of agricultural (including aquaculture) products around the globe. The GLOBALG.A.P standard is primarily designed to reassure consumers about how food is produced on the farm by minimizing detrimental environmental impacts of farming operations, reducing the use of chemical inputs and ensuring a responsible approach to worker health and safety as well as animal welfare. GLOBALG.A.P serves as a practical manual for Good Agricultural Practice (G.A.P.) anywhere in the world on the basis of an equal partnership of agricultural producers and retailers who wish to establish efficient certification standards and procedures. The GLOBALG.A.P website (http://www.globalgap.org) is a comprehensive knowledge base for all interested parties: producers, suppliers, retailers, journalists and consumers.

adds to the challenge by requiring separation of these impacts, while bioenergy feedstock production can be more or less integrated with other land uses and industrial activities.

4.4 Mitigation strategies

A commonly expressed precondition for large-scale bioenergy production is that the agricultural sector should improve land use efficiency drastically, so as to require less land for meeting demand for food. Nevertheless, increasing yield levels can have negative impacts where further intensification depends on large inputs of nutrients, freshwater and pesticides. Even so, significant potential exists to increase the currently low productivity of rain-fed agriculture in large parts of the world – especially in developing countries – through improved soil and water conservation, efficient fertilizer use and crop selection (including selection of drought-adapted crops), and employment of best practices involving, for instance, mulching, low tillage, contour ploughing, terracing, rainwater harvesting and supplementary irrigation, crop rotation, and reduction of the length of time land lies fallow (Keys, 2005; Badgley et al., 2007; Rockström et al., 2007; Rockström et al., 2010).

Conservation agriculture and mixed production systems (double cropping, combining crops with livestock and/or crops with forestry) have the potential to sustainably increase land and water productivity as well as carbon sequestration, and to improve food security (Kumar et al., 2006; Heggenstaller, 2008; Herrero et al., 2010). Integrated approaches can also be based on combining bioenergy feedstock production with conversion, for instance by producing animal feed that can replace cultivated fodder such as soy and corn (maize) (Dale et al., 2009; Dale et al., 2010) and reduce grazing requirements (Sparovek et al., 2007). Multifunctional systems that provide multiple ecosystem services represent alternative options for production of bioenergy on agricultural land, which could contribute to the development of farming systems and landscape structures that are beneficial for soil and water use as well as for biodiversity conservation.

Examples include systems established to provide specific environmental services, such as trees that form a windbreak to reduce wind erosion or, where integrated into the landscape, reduce water erosion and mitigate flooding (Box 4.4). Plantations of suitable species can also be used to remove cadmium and other heavy metals from cropland soils (Berndes et al., 2004). For instance, certain Salix clones are very efficient at accumulating heavy metals – notably cadmium, but to some degree zinc, as well – which are then removed from the field with the harvest. Other systems provide environmental services of a more general nature, such as soil carbon accumulation leading to improved soil fertility and enhanced climate benefit (Berndes et al., 2008).

4.4.1 Mitigation measures along the supply chain

Mitigation measures for water quality can be incorporated at different stages of the supply chain, from the production of bioenergy feedstock to its conversion.

a) Mitigation measures in feedstock production

Planting short rotation coppice (SRC) for bioenergy development is likely to reduce the problem of nutrient pollution loads since biomass plantations commonly use smaller amounts of inputs. Based on that observation, integration of SRC into the agricultural landscape has been proposed as a strategy to meet the water quality objectives of the EU Water Framework Directive (Jørgensen and

Mortensen, 2000; EEA, 2008; Eppler et al., 2008). On good land, SRC is likely to increase water quality compared with the use of agricultural crops because of its lower agro-chemical requirements. There is some evidence that, in particular locations, nitrate leaching could be a problem due to applications of fertilizers and sewage sludge. However, it has also been suggested that mixtures of trees and grasses used as energy crops could be cultivated along waterways to act as a buffer to prevent nutrient run-off from agricultural land (Hall, 2003). It should be noted that, similarly to when plantations are established to meet feedstock demand for other agricultural and forestry products, the outcomes for water quality can be very different.

Box 4.3. Potential benefits of establishing SRC with poplar and willow in northwestern Germany

The Fuhrberg catchment is situated about 30 km north of the city of Hannover in northwestern Germany. It serves as an aquifer supplying about 90% of Hannover's annual water demand. As in most drinking water catchments, groundwater protection is a major priority and concern about the negative impacts of agricultural land use on groundwater quality has resulted in several measures being taken. These include: *(i)* voluntary agreements with farmers to reduce fertilizer applications to a minimum; *(ii)* initiatives to increase the portion of deciduous forests in the catchment; and *(iii)* set-aside of arable land to reduce nitrate leaching from soils. However, it has proven difficult to keep nitrate concentrations at catchment level below the legal threshold value (50 mg NO_3/litre). Reduced N inputs result in yield losses, but do not greatly decrease nitrate seepage concentrations (Köhler et al., 2006). Even on set-aside land, seepage concentrations above the limit can occur.

The explanation is to be found in the history of water and land use here. Since 1960, provision of drinking water for Hannover has lowered the groundwater table, making wet grasslands drier. Large grassland areas containing high levels of soil organic carbon (SOC) were shifted to arable land between 1960 and 1970. The resulting SOC mineralisation has resulted in both CO_2 emissions to the atmosphere and nitrate leaching to groundwater, which still influences groundwater quality since it takes 50 to 100 years for soils to achieve a new equilibrium under present conditions (Springob and Mohnke, 1995; Springob et al., 2001).

Köhler et al. (2006) concluded that setting aside land does not have the desired effect on nitrate concentration levels, and that the only way to reduce N output to groundwater is to convert arable land containing high SOC into forest or continuous grassland. A promising strategy combining groundwater protection and agricultural reactivation of such fallow land might be the establishment of short rotation coppice (SRC) with willow and poplar (Lamersdorf, 2008). These bioenergy production systems might even improve groundwater quality compared to that in fallow areas. SRC with willow and poplar can contribute to groundwater protection, especially through its high fixing potential for nutrients. High biomass production associated with a high fixing rate for nitrogen can reduce the nitrate leaching potential of soils (e.g. see Berthelot et al., 2000 and Aronsson et al., 2000). The establishment of SRC on soils with high nitrate leaching potentials is therefore a promising option for arable land that is about to be set aside for purposes of groundwater protection and compensation.

Source: Paul Schmidt-Walter and Norbert Lamersdorf, Göttingen, Germany (2010)

This section includes two case studies of how bioenergy demand can contribute to water quality improvements through new land use practices. The first one is in Germany (Box 4.3.), and the second in Sweden (Box 4.4). In the Swedish example, there is a shift from conventional food/feed crops to increased production of perennial herbaceous plants and short rotation woody ones as irrigated vegetation filters. Certain types of plantations can be located in the agricultural landscape and managed as buffer strips to capture nutrients in passing run-off water. Expanding these types of irrigated or non-irrigated biomass production systems can help address problems of eutrophication of aquatic ecosystems due to nutrient losses in agriculture.

Box 4.4: Willow vegetation filters for removal of nutrients from pre-treated wastewater in Sweden

In Enköping, central Sweden, which has 20 000 inhabitants, a 75 hectare willow plantation treats and utilizes decanted water from the dewatering of sewage sludge. The water contains approximately 25% of the nitrogen entering the wastewater treatment plant, but less than 1% of the water volume. By treating the water separately, instead of pumping it back into the treatment plant, the total nitrogen load is reduced by 25%.

The relatively limited water volume (around 15 000 m^3 per year, containing some 20 000 kg nitrogen and 600 kg phosphorous) enables storage in ponds during the winter, which is also required in order to reduce the level of pathogens. Between May and September, the water is used to irrigate the adjacent willow plantation using drip pipes laid in double rows, so that harvesting will not be obstructed. To stimulate growth and further improve the wastewater treatment plant's overall nitrogen treatment efficiency, the system is designed so that conventionally treated wastewater is added through the irrigation system. The irrigation load is approximately 250 mm per year, resulting in a load of some 200 kg nitrogen and 10 kg phosphorus per hectare. Ongoing monitoring thus far has shown low nitrogen leaching losses. Thus, the system is apparently capable of transforming the large quantities of added nitrogen.

The municipality covered all costs of the storage ponds, pumps, automatic filters and irrigation pipes (which were lower than the estimated costs of improved conventional nitrogen treatment), whereas the farmer/landowner planted the willows and is responsible for maintenance of the irrigation pipes. The biomass produced is used in the local district heating plant, contributing to the local supply of heat and electricity. Ash from the boiler is recycled back to the willow plantation. This treatment system is therefore an excellent example of how treatment and recycling of society's waste products can be combined with the production of biomass for energy (Figure 4.3).

Figure 4.3: View of the Enköping municipal wastewater plant in Sweden, showing water storage ponds and willows used as vegetation filters

Swedish quality requirements for sewage sludge recycling in agriculture are among the strictest in the world. Nevertheless, most sludge in Sweden is allowed to be used in agriculture. High quality has been obtained through effective and persistent work with, for example, controls on industrial wastewater connected to sewerage, and disconnection of polluted stormwater and landfill leachates. Still, demand for sewage sludge for use in conventional farming is very low. Utilization of the sludge in willow plantations has considerably higher acceptance. The main reasons it is utilized in willow plantations are:

- Willows are not included in food production – they are not eaten;
- Existing routines and equipment for sludge management can be used – it is just another crop;
- To a large extent, sewage sludge replaces commercial fertilizers, especially phosphorus, and increases the soil content of organic material.

Source: Pär Aronsson, Swedish University of Agricultural Sciences, Sweden

Furthermore, more efficient irrigation systems – such as drip irrigation – can help to prevent water pollution and consequent negative impacts on ecosystems caused by the run-off of salts as well as fertilizers and pesticides to surface waters. Figure 4.4 shows examples of such irrigation systems.

Figure 4.4: Drip irrigation pipes (left) and an irrigated poplar plantation (right) in Chile. Photo credit: Dimitriou et al. (2011)

Plantations can be located and managed for reduction of water erosion and for flood prevention. Besides the on-site benefits of reduced soil losses, there are off-site benefits such as reduced sediment load in reservoirs and irrigation channels, as well as less deterioration in river water quality due to the suspended load that accompanies flood waters (formed mostly by run-off).

A specific case of water quality problems, where certain biomass plantations can offer mitigation, is the replacement of forests with pastures or other vegetation types that have lower evapotranspiration rates than the forests, where this results in productivity losses due to soil salinity induced by rising water tables. In such cases, biomass plantations with high water usage can be planted to intercept water moving through the soil and reduce groundwater recharge. When planted up-slope of salt-prone areas, plantations with a high evapotranspiration capacity can contribute to the prevention of salinity by reducing the amount of water reaching recharge zones. When planted within salt-prone areas, plantations can lower the water table and also reduce evaporation losses by providing ground cover.

b) Mitigation measures at the conversion stage

Cleaner production approaches can be very good for business, as they focus attention on maximizing output, minimizing wasted resources of any kind, and recycling and reusing all by-products. Technology change is only one aspect of this approach, and it may be better managed if it is part of a voluntary programme than if it is dictated by legislation. Many actions can be taken to protect the environment and save water resources, such as developing an environmental policies framework (Chapter 5) and minimizing pollution.

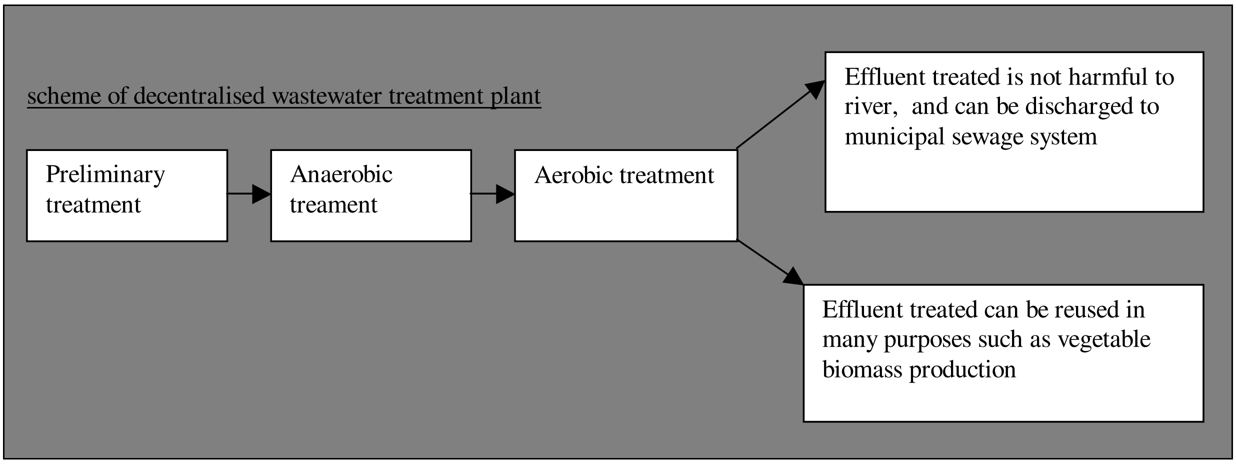
The high organic load and low concentration of chemical products (e.g. sulphate, sodium, copper, iron, zinc) in industrial wastewater justify its use in biogas production (Table 4.5).

Table 4.5: Results of experience with the use of industrial wastewater in biogas production

Type of substrates	Temperature (°C)	Loading rate of volatile solids (kg/m^3/day)	Retention time (days)	Gas yield per kg of COD (m^3/kg)
Sugar refinery waste	35	1.5	5.1	0.76
Molasses stillage	35			0.35
	37	2.2	10	0.12
		5.4	4.1	0.04
		7.5	3	0.02
Rum distillery waste	35	10.4	12-15	0.28-0.29
		8.8	8-10	0.27-0.29
Palm oil mill effluent	35		11-20	0.24
	55		7-13	0.42

Fermentation of wastewater from bioenergy conversion facilities, integrated in a sewage treatment system, is well-developed. However, a conventional type of wastewater treatment plant widely used in developing countries is different, with an anaerobic system of liquid waste treatment (Figure 4.5).

Figure 4.5: Decentralized wastewater treatment plant



To reduce water pollution, it is crucial:

- to know wastewater characteristics, such as flow and physical, chemical and biological parameters;
- to define the objective of treating and reusing water effluent;
- to define the necessary reduction;
- to develop reduction options.

Wastewater characteristics have already been addressed in this chapter. The objective of treating or reusing effluent is to discharge the effluent to surface water without any damage to the environment, to discharge it to the municipal sewage system, or to reuse it in irrigation.

The goal of preliminary treatment is to adjust pH and temperature following flow equalization, and to remove large, heavy solids through collecting, screening and degritting. In anaerobic treatment, where effluent is fermented, about 85% of suspended solids and BOD/COD is removed. At this level, the digester widely used is the UASB (Upflow Anaerobic Sludge Blanket) reactor, which is applied successfully in the municipal and industrial sector. Several advantages are associated with anaerobic treatment, including *(i)* low energy requirement, *(ii)* little sludge produced, and *(iii)* production of methane gas as an energy source. Generally, anaerobic processes are followed by an aerobic second stage that can use conventional activated sludge, extended aeration and rotating biological contactors. With aerobic treatment, organic loads continue to decrease and nutrients such as nitrogen and phosphorus are removed. An aerobic treatment system may consist of one to three oxidation ponds.

Following this treatment, wastewater is no longer harmful to the environment and can be discharged to a municipal sewerage system (if the capacity to do so exists) with the approval of the relevant authority and at the lowest cost to industry. It is important to note that, in wastewater treatment, the first step is "primary treatment" and the combination of anaerobic and aerobic treatment is "secondary treatment".

Advanced or "tertiary treatment" can be applied in the case of liquid waste disposal. A natural system for wastewater treatment, such as constructed wetlands, may be used in tertiary treatment. Constructed wetlands, regarded as an emerging technology for the treatment of industrial effluent, are designed to treat wastewater by using plants such as cattails (*Typha* spp.), reeds (*Phragmites* spp.) and rushes (*Juncus* spp.). Natural systems can provide a huge quantity of vegetable biomass, which may be burned for electricity generation in a sugarcane mill in the same way as solid waste such as bagasse and sugarcane waste.

Finally, in addition to considering technical mitigation measures, water resources management is a way to promote the development of alternatives for bioenergy production. It should be multidimensional and have a sustainable development point of view. Management needs to include: *(i)* an understanding of the resource condition (e.g. levels and types of pollution); *(ii)* goals of the society/community, and/or the decision-maker; and *(iii)* appropriate physical and institutional mechanisms to accomplish these goals. Therefore, the implications of water resources management in terms of policymaking are significant mainly for larger geographical areas and decisions on development and/or regulations (e.g. land use areas with better possibilities for production of bioenergy crops). Failure of water resources management plans has been related to lack of a clear definition of goals, and to ignoring the geological, hydrological and biological realities of water resources (Perry and Vanderklein, 1996).

4.5 Conclusions and recommendations

Water quality related to the production of bioenergy feedstocks and their conversion to solid, liquid and gaseous fuels for heating, power and transport is associated, in particular, with agricultural and forestry activities. The main sources of pollution are clearly related to the use of pesticides and fertilizers, but also to certain co-products (e.g. vinasse) from the industrial pathways of some feedstocks. The impacts of these co-products on water quality depend upon several natural factors, as well as on the severity of the impacts and their effects, including indirect and cumulative ones.

Although the main impacts originate to a great extent from agriculture and forestry, it is not possible to attribute impacts on water quality solely to the production of bioenergy crops.

Innovative forms of integrated production will prove the best way to avoid and mitigate impacts. Water use in processing also contributes to GHG emissions, for example in wastewater treatment in the palm oil industry. Future technologies, probably associated with biorefineries, could incorporate better water quality management.

One of the main constraints in some areas is lack of current data for developing countries, the importance of which is shown, for example, in the case study on water quality in Senegal. Monitoring should be conducted on a regular basis, whereas it may not occur often enough to comply with regulations or with the aim of sustainable production.

Several case studies and examples of research demonstrate that good practices and standards are already available, including affordable measures that can be taken to avoid or mitigate impacts. Examples are provided by the case studies on ethanol production from sugarcane in Brazil; harvesting of short rotation coppice (SRC) in Australia; the potential for using SRC to improve groundwater quality in Germany; and use of willow vegetation filter for wastewater treatment in Sweden.

Finally, considering water resources management as part of policymaking and decision-making can contribute to the mitigation of harmful impacts on water quality and promote better practices with regard to the production of bioenergy feedstock and its conversion to biofuel.