Mitigation Measures for Water Pollution and Flooding

23

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Abstract

This chapter discusses the range of measures that can be used to mitigate the impacts of water pollution and flooding. It makes a distinction between source measures which aim to reduce the amount of water or pollutant initially mobilised, pathway interventions which seek to slow the flow of pollutant enriched water once it has become mobilised and methods to protect receptor water bodies which are intended to reduce peak flows or prevent pollutants moving further through a catchment. In many European countries the policies and programmes used to increase the adoption of such measures are heavily influenced by EU obligations stemming from the Floods, Nitrates and Water Framework Directives. Typical approaches used involve a combination of regulation, financial incentives and advice provision. There are also a range of tools that can be used to model the potential effects of mitigation measures and a number of research programmes generating findings that may be of value to the landscape planner.

Keywords

Mitigation measures · Source-pathway-receptor paradigm · Water framework directive · Regulation · Financial incentives · Advice

23.1 Introduction

Intensification of agriculture and extensive urbanisation have resulted in environmentally-sensitive freshwater systems across Europe becoming degraded by nutrient and sediment enrichment, pesticide contamination, overexploitation,

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the introduction of invasive species and through a simplification of hydromorphology. With human resource demands exerting pressure on both water quality and water quantity, catchment water resources experience an array of detrimental ecological and economic impacts which threaten the sustainable ecosystem functioning of this essential natural resource. Under national and international legislation, such as the EU Water Framework Directive (2000/60/EC), governments have legal obligations to ensure that water bodies achieve good ecological and chemical status. Nevertheless, many freshwater systems across Europe are still failing to achieve recommended water quality standards due to continuing poor land management practices contributing to the delivery of contaminants from the terrestrial environment. Mitigation measures are therefore required to help reduce land-to-water pollutant transfers, however for these to be targeted effectively, it is essential to understand catchment functioning and the provenance of pollutants. This chapter builds upon the catchment water resource concepts presented in Chap. 11 by exploring a range of commonly applied mitigation methods for tackling water pollution and flooding, considering both the physical performance of these options as well as the policy and economic drivers to incentivise uptake. It focuses heavily on mitigation measures employed in agricultural settings due to the dominant role of agriculture in contributing to the degradation of European freshwater environments (Box 23.1).

Box 23.1: Definitions and Concepts

Mitigation measure: Term used to describe any process or feature designed to prevent, reduce and/or remediate the impact of pollution upon a water body. Measures are classified via the source-pathway-receptor paradigm (see Chap. 11) and largely seek to minimise the terrestrial-to-freshwater transfer of nutrients, sediments, pesticides, heavy metals and organic contaminants. In other chapters of this book the overarching term **response measure** is used in a similar sense.

Critical source area (CSA): An area within a catchment where elevated *pollutant availability* and good *hydrological connectivity* coincide to facilitate the rapid and efficient land-to-water transfer of pollutants. This term can refer to transfer into surface water bodies or leaching of pollutants into groundwater. CSAs are most commonly discussed in the context of soil erosion, where there exists high antecedent soil moisture conditions and an abundance of readily mobilised nutrient-rich soil. These CSAs include silage storage areas, field gateways, infield tramlines, compacted headlands, intensive pig and poultry units, road and river crossings, livestock paths, farmyard hardstanding and animal feeding stations. It is typically more cost-effective to target mitigation efforts on CSAs that cover a small part of the catchment yet are responsible for a majority of the pollution than to distribute mitigation efforts across the entire catchment (Thompson et al. 2012).

(continued)

Box 23.1 (continued)

Pollution swapping: A term used to describe the paradox when a land management measure introduced to mitigate one type of pollution inadvertently results in an increase in another type of pollution, thus *swapping* one pollutant for another. This necessitates the adoption of a holistic approach to the implementation of mitigation measures to ensure the most effective site-specific options are chosen from both an economic and environmental perspective (Stevens and Quinton 2009).

Hydromorphology: a WFD legislative term that encompasses fluvial geomorphology and hydrology and which describes the physical factors that govern river ecosystems.

Green infrastructure: A network of new or existing green space (i.e. vegetation) in rural or urban areas that supports the natural functioning of ecosystem processes and is integral to the health and wellbeing of communities. An example would be the use of *sustainable urban drainage systems (SUDs)* to reduce surface water flood risk by increasing the infiltration rate of rainwater into the soil in towns and cities (Ellis et al. 2002), as well as possibly contributing to urban biodiversity and recreation. This contrasts with *grey infrastructure* which entails artificial ecosystem modifications to control natural processes for human needs (e.g. the building of concrete dams to reduce downstream flood risk and provide hydroelectric power).

23.2 Types of Mitigation Measure

A wide range of mitigation options are available to address the threats of flooding and water pollution to ecosystem services and these can be classified according to their primary function with respect to the source-pathway-receptor paradigm. Source measures are options which aim to reduce the amount of water or a pollutant initially mobilised (e.g. by reducing soil erosion). Pathway measures are options which seek to slow the flow of pollutant enriched water once it has become mobilised (e.g. through intercepting surface runoff). Lastly, receptor measures are options deployed in or around water bodies which aim to reduce peak flows or prevent pollutants entering and moving further through the catchment. Examples of commonly used mitigation measures are presented in Fig. 23.1 and Table 23.1. A number of studies have sought to compile inventories of measures, including details of their applicability, cost and effectiveness, with examples including Kania et al. (2014), GWP/INBO (2015) and NWRM (2017). Selected measures are discussed in more detail in the following paragraphs.

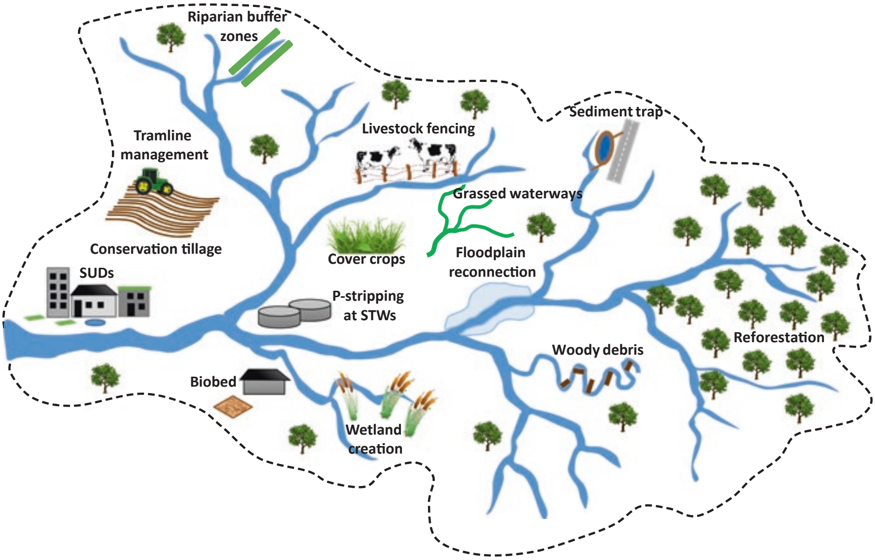

Fig. 23.1 Conceptual model of example land management interventions available to mitigate the impacts of water pollution and flooding to ecosystem services in river catchments

23.2.1 Source Measures

23.2.1.1 Cover Crops

In many conventional farming systems, arable fields are typically cultivated in the early autumn to destroy crop residues and weeds and to prepare the land for sowing of the subsequent crop by loosening compacted soil, incorporating oxygen and bringing nutrients to the surface. Where spring cropping is practiced, this can result in fields being left fallow and devoid of vegetation for 4–5 months during the winter. Under these circumstances, the absence of roots to bind the soil together or leaves to intercept rainfall mean the risk of soil erosion is significantly elevated, resulting in the enhanced transport of sediments and nutrients from the land into surface water courses threatening ecosystem services (see Section 11.4). To mitigate against this issue, a *cover crop* (or *catch crop*) can be sown in the autumn to provide winter ground cover and soil protection (Fig. 23.2). A range of species can be grown, including nitrogen fixing leguminous (e.g. clover, vetch and pea) and non-leguminous (e.g. rye, sorghum and brassicas) varieties. Cover crops have primarily been used to minimise nitrate (NO_3^-) fertiliser leaching into groundwater by scavenging highly soluble residual soil NO_3^- and converting it into relatively immobile organic nitrogen (Snapp et al. 2005). Reported reductions in nitrate leaching under cover crops range from 38–70% (Hooker et al. 2008), 25–60% (Valkama et al. 2015) and 75–97% (Cooper et al. 2017). Cover crops have also been shown to provide a range of other ecosystem service benefits including protecting soils from erosive surface flows, increasing soil organic matter content, improving soil

Table 23.1 Example mitigation measures employed to reduce the impacts of pollution and flooding on the water resources of river catchments

Type	Example	Primary objective	Main impacts on water resources
Source	Cover crops	Soil protection	Reduce nutrient leaching
	Conservation tillage	Soil stabilisation	Reduce soil erosion, lower turbidity
	Biobed	Pesticide degradation	Reduce pesticide concentrations
	Phosphorus stripping	Improving STW effluent	Lower P concentrations
	Reforestation	Water retention	Reduce downstream flood risk
	Rain gardens/soakaways (SuDS)	Increase infiltration	Reduce peak river flows, recharge groundwater
	Green roofs (SuDS)	Increase evapotranspiration	Reduce peak river flows
Pathway	Grassed waterways	Intercept surface runoff	Reduce soil erosion; lower turbidity
	Tramline management/contour ploughing	Disrupt surface flow path	Reduce soil erosion, lower turbidity
	Controlled traffic farming	Reduce number of flow paths	Reduce soil erosion, lower turbidity
	Sediment traps (swales)	Capture mobilised soil	Lower turbidity; lower P concentrations
	Road crossing redesign	Disrupt surface flow path	Lower turbidity; reduce organic contaminants
Receptor	Buffer strips	Intercept surface runoff	Reduce turbidity; reduce N + P concentrations
	Livestock fencing	River bank protection	Reduce turbidity; reduce FIOs; improve morphology
	Floodplain reconnection	Improve water retention	Reduce downstream flood risk
	Woody debris	Meander creation	Improve morphology; slow water flows
	Riverbank stabilisation	Reduce bank erosion rates	Reduce turbidity; improve morphology
	Wetland creation	Water purification	Reduce turbidity; reduce N + P concentrations

STW sewage treatment works, *SuDS* sustainable drainage systems, *P* phosphorus, *N* nitrogen, *FIO* faecal indicator organism

structure, suppressing weeds and enhancing the soil moisture balance (Dabney et al. 2007; Stevens and Quinton 2009). However, some negative aspects of cover crops have also been reported and include the cost of establishment, difficulty in destroying the cover crop prior to sowing the subsequent cash crop, the harbouring of insect and mollusc pests and the complexity of predicting the release of mineralised nitrogen as the cover crop residues degrade (Deasy et al. 2010).

Fig. 23.2 Example mitigation options to reduce water pollution and flood risk. From top: a winter oilseed radish cover crop (*source reduction*); an on-farm biobed (*source reduction*); a U-shaped sediment trap to intercept road runoff (*pathway interruption*); and grassed riparian buffer strips (*receptor protection*)

23.2.1.2 Conservation Tillage

In conventional tillage systems, autumn cultivations typically see the soil inverted to a depth of 10–30 cm using a mouldboard plough prior to secondary cultivation with harrows and rollers to create a seedbed into which the subsequent cash crop is sown. However, such practice damages the soil structure, breaking up soil aggregates and disturbing the natural soil horizons which increases the likelihood of erosion and the transport of soil and associated nutrients into water bodies. The main objective of conservation tillage systems is to improve soil structure and stability by either disturbing the soil to a lesser degree (e.g. shallow non-inversion tillage to a depth of <10 cm using discs or tines) or not disturbing the soil at all, with sowing occurring directly into the residue of the previous crop (e.g. direct drilling) (Morris et al. 2010). By improving soil structure, conservation tillage methods have been shown to reduce soil erosion, improve drainage and water holding capacity, reduce incidences of soil crusting and compaction (thus increasing infiltration and reducing surface runoff), and increase microbial and earthworm activity by preserving the habitat of soil organisms (Holland 2004; Soane et al. 2012). Conservation tillage can also increase soil organic carbon content, an important determinant of both soil fertility and structural stability, by retaining crop residues on the soil surface and reducing the exposure of organic matter to oxygen deeper in the soil profile and thereby limiting aerobic decomposition and its conversion to carbon dioxide. Nevertheless, the lack of soil inversion can increase pest populations in conservation tillage systems as weed seedlings are not mechanically destroyed and surface organic residues provide food to support larger populations of molluscs. These issues can lead to higher pesticide inputs (pollution swapping) or reduced crop yields, both of which have financial implications for the farmer. Under favourable conditions, however, there is increasing evidence that conservation tillage can be financially competitive with conventional farm practice (Kertész and Madarász 2014).

23.2.1.3 Biobeds

Pesticide pollution threatens the sustainable ecosystem functioning of rivers draining agricultural catchments and therefore mitigation measures are required to reduce pesticide transfer into freshwater environments. Whilst diffuse pesticide pollution sources can in part be reduced by behavioural changes, such as timing spraying operations to avoid periods of inclement weather to limit pesticide mobility, biobeds have emerged as an important mitigation strategy for dealing with point source pollution arising from contaminated machinery washings and accidental spillages during sprayer filling (Castillo et al. 2008; Torstensson 2000). The biobed concept originated in Sweden in the 1990s as a way of using microbial activity to degrade waste pesticide residues. A biobed is essentially a moderately sized pit (typically tens of cubic metres in volume) which can be lined or unlined and is filled with a 1:2:1 matrix of compost, straw and topsoil. The surface is covered with grass and onto this the waste pesticide residues are deposited. In principle, microorganisms (e.g. bacteria and fungi) within the biobed matrix chemically and physically interact with the pesticides leading to structural changes and/or complete degradation. To work effectively, the biobed mixture needs to have a high pesticide absorption capacity and be able to facilitate high rates of microbial activity. Therefore, the content of straw, soil and compost is carefully controlled to maximise biobed performance. In lined biobed systems, the leachate is typically collected from the bottom of the biobed and re-used for either irrigation, sprayer washing or as a carrier for further pesticide applications. Biobed pesticide removal efficiencies of 52–100% have been recorded for a wide range of herbicides, fungicides and insecticides in studies conducted across Europe (Cooper et al. 2016; De Wilde et al. 2007), thus demonstrating the success of biobeds as a management tool for protecting the ecosystem services of water resources.

23.2.1.4 Phosphorus Stripping

The effluent discharged into rivers at sewage treatment works (STWs) is rich in biologically available soluble reactive phosphorus (SRP) and is a major cause of downstream freshwater eutrophication. Discharged sewage effluent typically has SRP concentrations of 1–20 mg L^{-1}, values well in excess of the 0.02–0.07 mg L^{-1} river water quality standard considered *'Good'* under the EU WFD (Withers and Jarvie 2008). Due to the continuous nature of sewage effluent discharges, SRP concentrations tend to display a highly seasonal pattern with higher concentrations during summer low flows and lower concentrations during winter high flows due to dilution. Consequently, phosphorus concentrations peak during the ecologically sensitive summer season when the rate of primary production and eutrophication risk are greatest. In order to reduce the toxicity of the effluent, wastewater undergoes numerous stages of processing at STWs, including screening through filters to remove coarse material (*pretreatment*), holding in settling tanks to encourage sedimentation of suspended fines (*primary treatment*) and promoting the degradation of organics through biological oxidation (*secondary treatment*). However, even after these treatment stages the effluent remains rich in phosphorus and requires further treatment to mitigate the pollution risk. Phosphorus stripping is a form of *tertiary treatment* increasingly being installed at STWs in which the effluent is dosed with a precipitant (e.g. iron ammonium sulphate) which causes the phosphorus to precipitate out and accumulate at the bottom of settling tanks where the sludge can be recovered and used as a P-rich fertiliser for agriculture. Such tertiary P-stripping is capable of removing up to 95% of the phosphorus within STW effluent, but the technology is expensive and its application has largely been limited to larger STWs where the benefit-cost ratios are higher.

23.2.1.5 Reforestation

Forests currently cover 32% (211 million ha) of Europe's land surface, with coverage varying from >50% in Scandinavia to <15% in Ireland and the United Kingdom which have historically high *deforestation* rates (EEA 2015). The clearance of permanent forest to make space for seasonal cultivated crops and intensively stocked livestock pasture has greatly accelerated the degradation of freshwater environments across Europe. Without the protection of above ground vegetation or stabilising subsurface root networks, soil erosion rates increase significantly, enhancing the transport of nutrient rich sediment into surface water bodies and thus promoting the development of eutrophic conditions. The loss of native forest cover also removes the valuable ecosystem services of flood prevention and drought resilience. Although dependent upon the expanse of forest cover, the tree composition, tree density, length of the growing season and complexity of the vegetation structure, forests have the potential to retain excess rainwater, prevent extreme surface runoff during storm events and to reduce peak river flows, thereby mitigating flooding. Research has shown that water retention potential in catchments with 30% and 70% forest cover is 25% and 50% higher, respectively, than in catchments with just 10% forest cover (EEA 2015). Forests also play a key role in buffering catchments against the effects of drought by enhancing soil infiltration, reducing evaporation, restricting soil desiccation and increasing water storage capacity. Overall, *reforestation* can serve as an effective means of enhancing regulatory ecosystem services, but in the context of flood prevention it is important to locate new tree planting quite carefully so as to differentially slow flows in tributaries in a way that reduces downstream peaks rather than just delaying them (Dixon et al. 2016).

23.2.1.6 Sustainable Drainage Systems (SuDS)

In urban areas, the majority of the land is covered with artificial impervious surfaces such as concrete and asphalt as houses, factories, car parks and roads have replaced the natural permeable vegetation cover. These impermeable areas reduce rainwater infiltration into the soil and increase the amount of surface runoff generated, significantly increasing the risk of *flash flooding* during storm events. *Sustainable drainage systems* mitigate this by attempting to replicate, as closely as possible, the natural drainage from a site before it was developed. SuDS are typically designed such that they are able to capture rainfall and/or surface runoff, retain it for a period of time, and increase both water infiltration into the soil and evapotranspiration into the atmosphere (Ellis et al. 2002). The net result of the regulatory services provided by SuDS is a reduction in surface water flood risk. Examples of SuDS include small, landscaped, vegetated areas used to increase infiltration (*rain gardens*); plants grown on the roofs of building to increase evapotranspiration (*green roofs*); detention basins to capture and store surface water (*swales, retention ponds*); and the substitution of impervious materials for permeable surfaces (*porous pavements*, *gravel car parks*). A welcome side effect of such water-related mitigation measures in urban areas is the additional support for biodiversity and urban recreation.

23.2.2 Pathway Measures

23.2.2.1 Tramline Management

Tramlines (or ‘wheelings’) are unvegetated tracks made within arable crops for farm machinery to travel along during fertiliser and pesticide spraying operations without damaging the surrounding crop. Typically around 30–40 cm wide and spaced 18–24 m apart depending on the width of the farmers’ pesticide sprayer boom, tramlines become heavily compacted under the weight of farm machinery, significantly reducing infiltration rates and depressing the soil relative to the surrounding land. With no vegetation cover to intercept rainfall, compacted tramlines can channel erosive surface runoff during precipitation events and act as preferential pathways for the rapid land-to-river transport of nutrient-rich and pesticide contaminated soils (Silgram et al. 2010; Withers et al. 2006). Mitigating this issue is typically focused on disrupting the flow pathway by using tines to loosen tramline soil structure behind machinery wheels and thereby enhance infiltration and reduce incidences of surface runoff. This approach has been shown to reduce sediment and phosphorus concentrations in surface runoff by 72–99% in plot trials (Deasy et al. 2009). Farmers can also fit low pressure tyres to farm vehicles to dissipate the weight and thereby reduce the severity of soil compaction. Furthermore, in areas with steeper slopes, crop management operations can be adjusted to the contour lines, following them instead of ploughing downhill. This measure effectively disrupts flow pathways under conditions of moderately inclined hills and non-extreme rainfall (see Chap. 22).

23.2.2.2 Sediment Traps

Sediment traps, also known as *settling ponds*, *swales* or *constructed wetlands*, are artificial ponds dug to intercept and capture erosive surface runoff before it enters into a water body. Located along a dominant flow pathway, such as the end of field tramlines or next to an impermeable metalled road, fast moving surface runoff is directed into the ponds where it encounters a stationary body of water. The reduction in kinetic energy encourages entrained sediments to settle out of suspension and accumulate on the bottom of the trap. In an *open system*, an outflow then syphons the cleaner water from the top of the pond and discharges it to a neighbouring water course. Conversely, *closed system* traps have no outflow and the captured water is retained and allowed to slowly evaporate and infiltrate down into the soil. The decision on whether to construct an open or closed system, and on the size of the trap required, is dependent upon the volume of surface runoff generated, with larger open systems required to efficiently process high runoff volumes. How effective an open system trap is at capturing and retaining sediments will in large part be determined by the speed at which water passes through the pond, which in turn will partly depend upon the type and amount of vegetation growing within the pond. In general, the higher the plant density, the higher the flow resistance and thus the greater the settling rate. More plants also promotes higher biotic assimilation of nutrients thus reducing eutrophication risk, however too many plants will reduce trap capacity. Retaining 43–88% (69% on average) of sediment inflows, sediment traps and other type of constructed wetland have been shown to be highly effective at removing suspended sediments (Stevens and Quinton 2009), although they can be expensive to construct and maintain (e.g. removing material to prevent over siltation). Where possible, the nutrient-rich sediment should be dug out to maintain trap capacity and used as a source of fertiliser on arable fields, thus supporting crop productivity.

23.2.3 Receptor Measures

23.2.3.1 Riparian Buffer Zones

One of the biggest threats to surface water resources is erosive runoff during heavy rainfall events transporting nutrient-enriched sediment via overland flow paths off agricultural land and directly into streams, rivers and lakes. Riparian buffer zones (RBZs) are strips of permanent vegetation grown alongside river channels to protect the water course from the impacts of agricultural activities on the adjacent land. Vegetated with grasses, scrubby bushes or trees, RBZs provide a rough, high-friction surface which intercepts surface runoff and slows down the flow of the water. As the flows decrease, entrained sediments are encouraged to settle out and are deposited on the RBZ, whilst the water infiltrates down into the soil. RBZs have been shown to be highly effective at mitigating surface runoff pollution, on average reducing sediment loads into water courses by ~75% and with it ~60% of phosphorus and ~78% of pesticides (Stevens and Quinton 2009). As well as supplying the provisioning service of clean water, RBZs also increase biodiversity by providing ribbons of riparian habitat for species that have been forced out of the surrounding agricultural land. Ultimately, however, the success of RBZs at mitigating water pollution is dependent upon the buffer design, with wider and longer buffers covered in denser vegetation having the greatest potential to inhibit overland flow before it reaches the river. The siting of the RBZ is crucial to ensure it intercepts the dominant flow paths, whilst management may be required to prevent sediment build-up within the strip from reducing longer-term retention ability (Dorioz et al. 2006).

23.2.3.2 Livestock Fencing

The outdoor rearing of livestock, particularly at high stocking densities, can have significant implications for water quality when the animals have free access to a water course. As the animals come down to a river to drink their hooves damage the channel banks in a process termed *poaching*, causing the banks to collapse and rapidly erode, releasing sediment into the river and increasing water turbidity. The problem is particularly acute on dairy and beef farms due to the heavy weight of cattle (500–1000 kg) contributing to a high ground pressure that is capable of causing serious structural damage to riparian soils. Furthermore, livestock defecation within the river can contribute to faecal contamination of the water body and the growth of microorganisms toxic to human health, thus threatening drinking water provisioning services. To protect the riparian zone and mitigate against soil erosion, pastured livestock can be relatively inexpensively fenced off (e.g. using barbed wire) from water courses to prevent unrestricted access and instead be provided with an alternative drinking water source within the field.

23.2.3.3 Floodplain Reconnection

A floodplain is a low lying area of land bordering a river channel that is formed by the lateral erosion of a meandering river within the confines of a river valley (Fig. 23.3). During high-flow conditions, a river may overtop its banks and flood out onto the surrounding floodplain, depositing mounds of coarse sands and gravels close to the river channel (*levees*) and fine silt and clay at a greater distance. This periodic breaching of the river channel is part of a natural process which allows the fluvial system to absorb excess water, dissipating the energy of high flows and helping to transport fertile sediments out of the channel and onto the surround land. Inundation of the floodplain helps to reduce downstream flood risk, increase the fertility of the valley floor, provides a diverse habitat for wetland species, cleans the river of excess sediment and nutrients, decreases riparian erosion and contributes cultural, aesthetic and recreational benefits (e.g. wildlife tourism, wildfowling). However, historically, rivers have been extensively deepened and straightened (i.e. *channelization*) through dredging to speed up the flow of water and enable the floodplain to be more efficiently drained for agricultural use. A direct consequence is that the rivers become disconnected from their floodplains with the river water surface several metres below the height of the surround land and thus preventing overbank flows from occurring. A similar situation arises in towns and cities where, to protect buildings built on the floodplain, authorities install unnaturally high artificial levees (typically made of concrete) to reduce the incidences of overbank flow and thereby mitigate local flood risk. Without this floodplain connection, valuable

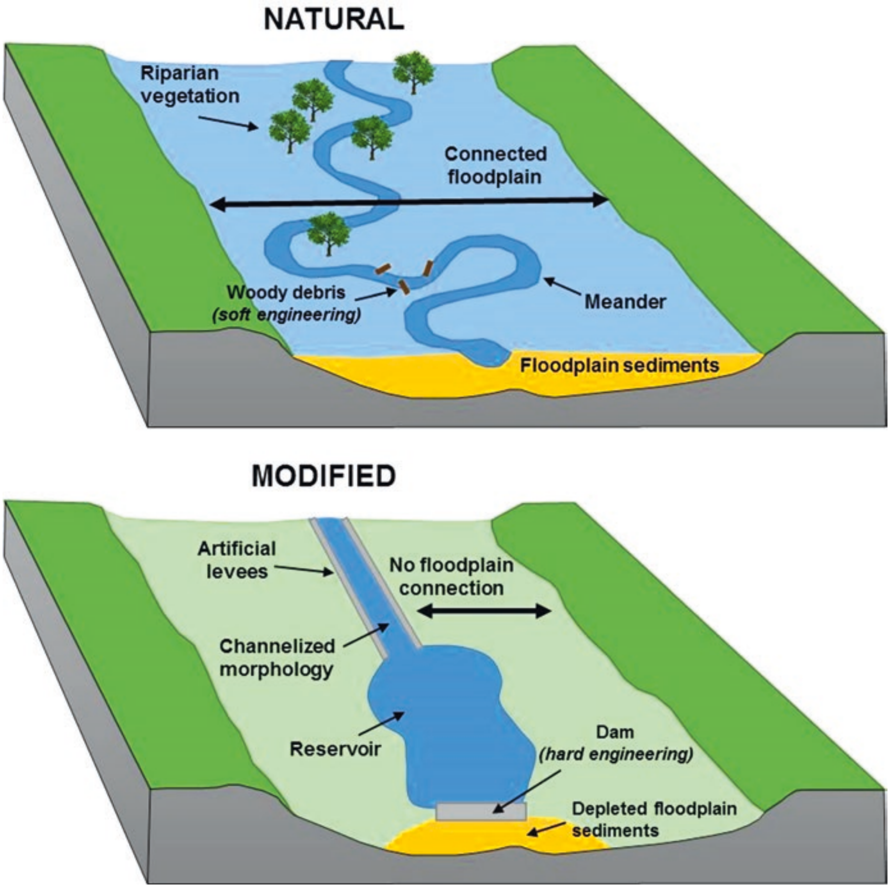

Fig. 23.3 Conceptual diagram of a natural and human-modified river valley. Anthropogenic modifications to a river channel to drain the surrounding land for agriculture or house building can result in the disconnection of the river from its floodplain, even under high-flow conditions

wetland habitat is lost and the main river channel is forced to transport more water during high flows, exacerbating flooding downstream in areas not protected by artificial levees.

Floodplain reconnection aims to restore natural processes by removing artificial flood defences, raising the height of the riverbed and breaching gaps in the river banks to facilitate overbank flow and floodplain retention. Floodplain reconnection is just one example of numerous *soft engineering* mitigation options available termed *natural flood management*, which sees natural processes favoured over *hard engineering* solutions to mitigating flood risk (Fig. 23.3). Another example includes the use of *woody debris* (e.g. felled trees, branches, log piles) strategically placed perpendicular to the direction of flow within straight, homogeneous river sections which acts as a baffle, deflecting the river sideways, increasing flow diversity and encouraging the river to *meander*. The increased *sinuosity* of a meandering river increases its length and reduces its gradient, which in turn slows down the flow of the river and delays peak flows during flood events, thus helping to alleviate flood risk (ECRR 2017). Berms can be used to create narrower sections with faster flowing water and gravel glides can be installed to create a pool-and-riffle type channel morphology. Examples of river restoration features on the River Wensum in eastern England are shown in Fig. 23.4. The left-hand and right-hand columns of photographs are, respectively, prior to (June 2012) and after (October 2012) the implementation of the scheme. From top to bottom in the right-hand column, the river restoration features include: a filled berm to narrow the river width in order to increase flow velocity and the cleaning of river bed sediment; the positioning of woody debris and a gravel glide to decrease the water depth and deflect the river flow in order to increase flow velocity and create a pool-and-riffle type channel morphology; a channel plug to remove a previously straightened section; and a reinstated meander loop following diversion of the river due to the channel plug. Further design information is contained in Natural England (2009, 2012).

23.3 Methods to Incentivise the Adoption of Mitigation Measures

In many European countries the policies and programmes used to increase the adoption of mitigation measures are heavily influenced by EU obligations stemming from a number of EU Directives. These include the Floods (2007/60/EC), Nitrates (91/676/EEC) and Water Framework Directives (2000/60/EC, see Section 11.6). Given the important relationship between agriculture and water resources another key factor is the implementation of the EU Common Agricultural Policy (CAP). All of this means that there is greater commonality across countries in the management of water resources than exists for some other types of natural capital.

Although there are similarities arising from EU-wide policies, there are also differences between countries in the manner that EU Directives and CAP requirements are implemented. In most cases a mixture of approaches has been adopted, commonly with a pyramid of mechanisms (see Fig. 23.5), starting with nationally-applied baseline regulations and codes of good practice, then more regional or local variation in the use of advice schemes or financial incentives. Further legally-enforced restrictions may exist in local water resource protection areas (e.g. around public water supply abstraction points or boreholes).

23.3.1 Examples of Baseline Regulations

CAP Cross-Compliance Financial support to farmers under Pillar 1 (direct payments based on area farmed) of the CAP is linked to *cross-compliance* obligations regarding environmental, animal welfare and food safety standards. If farmers are found not to be meeting these standards during inspections then they can be penal-

Fig. 23.4 Examples of river restoration features at Swanton Morley on the River Wensum, eastern England

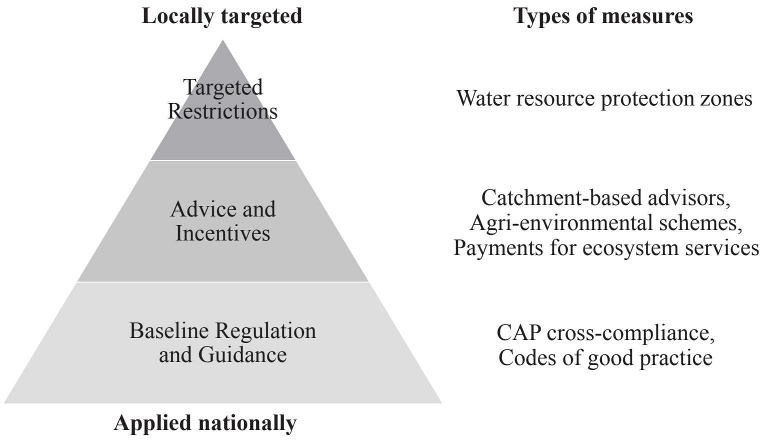

Fig. 23.5 Policy delivery mechanisms for measures to mitigate impacts on catchment water resources. (Source: modified from McGonigle et al. (2012, Fig. 3)

ised a proportion of their Pillar 1 payment. Under the 2013 CAP reforms further *greening* requirements were introduced and linked to 30% of the direct payments (European Commission 2017). The motive for this change was to strengthen the environmental sustainability of agriculture through requirements for:

- diversifying crops (to make soil and ecosystems more resilient)
- maintaining permanent grassland (to conserve soil carbon and grassland habitats)
- dedicating 5% of arable land to ‘ecologically beneficial elements’ (‘ecological focus areas’) in order to protect water and habitats.

Nitrate Vulnerable Zones (NVZs) The Nitrates Directive (91/676/EEC) aims to protect water quality across Europe by preventing nitrates from agricultural sources polluting ground and surface waters and by promoting the use of good farming practices. Implementation includes the designation as Nitrate Vulnerable Zones (NVZs) of areas of land which contribute to nitrate pollution and establishment of action programmes of measures which must be implemented by farmers within such zones. In some countries (e.g. Denmark) the entire territory has been designated as an NVZ, whilst in other cases specific zones have been defined (e.g. 58% of England as of September 2017). In England farmers in NVZs are required to meet several obligations including limiting the amount of farmyard manure and inorganic fertiliser applied to fields; keeping records of all nitrate applications within the past 5 years; having closed periods (3–5 months) when fertiliser application is prohibited; not applying organic manure within 10 m of a surface water body or 50 m of a groundwater source (i.e. spring, well or borehole); and providing at least 6 months storage capacity for poultry manures and pig slurry.

Floods Directive (2007/60/EC) The 2007 EU Floods Directive requires member states to assess if all water courses and coastlines are at risk from flooding, to map the flood extent, assets and humans at risk in these areas, and to take adequate and coordinated measures to reduce the flood risk. The directive encourages a coordinated and integrated approach to implementing flood risk measures throughout the entire river catchment to increase their effectiveness, meaning that suites of measures addressing flood risk in upland (e.g. reforestation) through to lowland (e.g. floodplain reconnection) environments are preferred. The directive is implemented in coordination with the Water Framework Directive (WFD), with flood risk management plans being incorporated into the broader river basin management plans (see Section 11.6).

In some European countries, such as Germany, the minimum standards for agricultural practice are defined in environmental laws. Often these make the European Directives more specific at the national level. According to the *polluter pays principle* (PPP) farmers cannot be paid for observing these standards, which may include maximum rates of fertilizer input or limits to pesticide use. Remuneration for water services on farmland will therefore be restricted to – often voluntary – activities beyond the legally-prescribed good practice.

23.3.2 Advice and Voluntary Measures

In addition to complying with the legal standards, an important tool for mitigating threats to water resources, is the establishment of professional *Codes of Good Agricultural Practice* which can be implemented by landowners on a voluntary basis. Such codes aim to provide practical guidance to help farmers and growers to minimise the risk of causing pollution whilst still allowing economic growth within the agricultural sector. Codes typically include advice such as the optimum application rates for fertilisers and pesticides to minimise the risk of unnecessarily applied excess chemicals entering into water courses; guidance on when agrochemicals should and should not be applied in relation to weather conditions to restrict mobility in the environment; and advice on the timings of in-field cultivations to minimise damage to soil structure and reduce the risk of soil erosion. Support given to farmers can also be delivered through government-funded training events (e.g. workshops, demonstrations, farm visits) and access to farm advisers.

Advice schemes exist in many countries and can be funded by central government, local government or industry (e.g. water supply or agri-chemical businesses). In England the *Catchment Sensitive Farming (CSF)* initiative was established by central government in 2006 to raise awareness of diffuse water pollution from agriculture and improve the environmental performance of farms by providing free training and advice to farmers in high priority areas for water quality where WFD targets are not being achieved. The *Voluntary Initiative* (http://www.voluntaryinitiative.org.uk/) is a UK industry-led programme to promote the responsible use of pesticides in order to protect water and the wider environment. There is also an

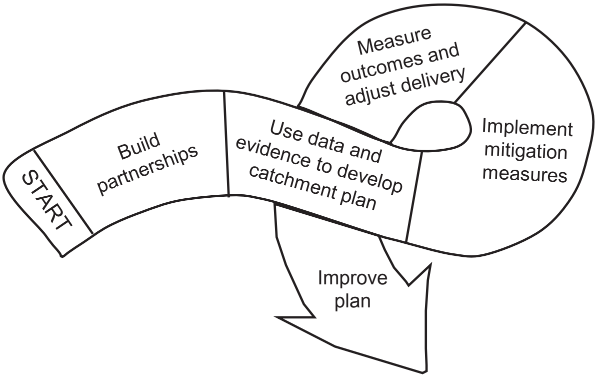

Fig. 23.6 The adaptive management cycle provides a framework for sustainable catchment management and the implementation of mitigation measures to protect water resources at the catchment-scale (US EPA 2008)

extensive literature on factors influencing farmer uptake of advice, see Inman et al. (2017) for a recent review.

Another important change in recent years has been for national governments seeking to implement WFD river basin management plans to shift focus away from national-scale thinking onto a more targeted local-scale '*Catchment Based Approach*' (CaBA 2017) in order to improve the effectiveness of delivery. This catchment-based approach is community led, engaging public, private and charitable organisations from across society to improve water resources, both quality and quantity, through the development of a holistic catchment-specific management strategy. Seeking to integrate economic, environmental and social issues into water resource planning, CaBA adopts the collaborative principles of the adaptive management cycle as a means of incorporating an appropriate combination of regulation, advice, land use measures, incentives and voluntary action to protect water resources (Fig. 23.6).

23.3.3 Financial Incentives

Agri-environment schemes funded under Pillar 2 (rural development) of the CAP provide financial incentives for land managers to look after the environment through activities such as conserving and restoring wildlife habitats, implementing flood risk management, reducing widespread water pollution from agriculture, maintaining the character of the countryside, preserving features important to the history of the rural landscape and encouraging educational access. An example is the *Countryside Stewardship Scheme*, the main CAP-funded agri-environment programme in England. Administered by central government (*Natural England*), Countryside Stewardship is a targeted, competitive scheme with a particular emphasis on biodiversity, water quality and flood management for which land managers must submit funding applications. With a budget of £925 million (€1 billion) for 2015–2020, the scheme is split into main three elements:

- **Higher Tier (£380 million):** covers management of the most environmentally significant sites such as ancient woodland, wetlands, wildflower meadows and Sites of Special Scientific Interest;
- **Mid Tier (£412 million):** simple but effective environmental measures carried out on ordinary agricultural land;
- **Capital Grants (£85 million):** larger sums of money available for capital projects such as the installation of biobeds, building settling ponds, improving manure storage facilities or creating new woodlands.

In total, there are 238 agri-environmental options eligible for funding under Countryside Stewardship, with the amount of money available to land managers dependent upon the extent, nature and effectiveness of the scheme. In 2014, 62% of UK agricultural land (10.6 million ha) was registered under some form of agri-environmental scheme. However, it is not just the EU or national governments that fund measures to protect water resources. *Water companies* are increasingly becoming involved in financially supporting pollution and flood risk mitigation measures as a way of protecting water supplies for consumers as part of their asset management programmes and *paying for ecosystem services (PES)*. One example is the Upstream Thinking initiative (http://www.upstreamthinking.org/) run by South West Water in the UK.

23.4 Modelling the Effects of Mitigation Measures

For land-use planners developing on-farm mitigation strategies to reduce water pollution and flood risk, it is useful to consider eight important factors which will ultimately determine the degree of success of measures deployment (Newell Price et al. 2011). These are:

(i) the nature of the problem being targeted (e.g. nutrient enrichment, pesticide contamination);
(ii) the land-use typologies to which the measures are applicable (e.g. intensive arable, lowland dairy);
(iii) the mechanism of mitigation action (i.e. how does the measure reduce pollution/flood risk);
(iv) the potential for applying the measure (i.e. spatial assessment of the area to which the measure could be applied);
(v) the practicality of deployment (e.g. ease of adoption, impact on farm business, resistance from landowners);
(vi) the likely uptake rate (e.g. percentage of farms on which the measure could be adopted given existing economic and legislative drivers);
(vii) the costs of measure deployment (e.g. € per km^2 or € per unit);
(viii) the likely effectiveness of the measure (e.g. percentage reduction in nitrate concentrations based on published research or expert knowledge).

The economic evaluation of mitigation options (stage vii), is a key determinant of whether measures to protect water resources will be pursued. Such evaluation either takes the form of a *cost-effectiveness analysis (CEA)*, where a specified water quality objective is given and the aim is to identify the cheapest set of measures for achieving it; or via *cost–benefit analysis (CBA)*, where the overall costs and benefits of a set of measures are assessed to determine if it should be carried out. In the context of the practical implementation of the WFD, applications of CEA are much more common than CBA. To assist in the assessment process, land-use planners can take advantage of decision-support tools, such as FARMSCOPER (FARM Scale Optimisation of Pollutant Emissions Reduction) or SWAT (Soil & Water Assessment Tool; see Box 11.3), which can estimate baseline pollutant losses and then quantify the effectiveness of combinations of mitigation measures at reducing pollutant losses at the farm- or catchment-scale (Gooday et al. 2014) (Box 23.2).

Box 23.2: Research Programmes for Mitigation Schemes

DTCs (**D**emonstration **T**est **C**atchment**s**): UK government funded initiative to assess the extent to which on-farm mitigation measures can cost-effectively reduce the impact of agricultural pollution on river ecology whilst maintaining food production capacity (http://www.demonstratingcatchmentmanagement.net).

ECRR (**E**uropean **C**entre for **R**iver **R**estoration): pan-European network of national centres, organisations, institutions and individuals linked together to support the development of best management practices for restoring Europe's rivers (http://www.ecrr.org).

NWRM (**N**atural **W**ater **R**etention **M**easures): expert network established to develop a structured knowledge base on the application of natural water retention measures which can be disseminated through the development of web-based practical manuals for supporting the design and implementation of new NWRM schemes (http://www.nwrm.eu/).

REFORM (**RE**storing rivers **FOR** effective catchment **M**anagement): EU-wide project aimed at providing a framework for improving the success of hydromorphological restoration measures to achieve improved ecological status of rivers in a cost-effective manner (http://www.reformrivers.eu).

RESTORE (**R**ivers **E**ngaging, **S**upporting and **T**ransferring kn**O**wledge for **R**estoration in **E**urope): EU-funded project led by the Environment Agency (England) to encourage the restoration of European rivers towards a more natural state that delivers increased ecological quality, flood risk reduction and social and economic benefits (https://www.restorerivers.eu).

RRC (**R**iver **R**estoration **C**entre): a UK-based organisation promoting best-practice river restoration, habitat enhancement and catchment management through knowledge exchange, technical advice and assessment, and training and guidance (http://www.therrc.co.uk/rrc).

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