Chapter 5
Agriculture and Karst

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Abstract This chapter provides a review of the impacts of agriculture on karst terranes, and on management approaches to minimize such impacts. It discusses the range of agricultural activities with potential impacts on soil and water in karst regions, including deforestation, changes in grazing intensity and changes from pasture to tillage, application of fertilizers, and pesticides and storage of farm wastes. Case studies of impacts on soil and on water quantity and quality are presented, with a particular focus on water quality issues including suspended sediment, nitrate, phosphorus, pesticides, and microbial pathogens. The particular vulnerability of karst regions to such impacts is discussed, including the occurrence of point recharge in closed depressions and swallow holes, the thin, patchy soil cover found in many karst areas, the presence of epikarst and the occurrence of conduit flow within karst aquifers. Methods of risk evaluation are reviewed briefly and management strategies to minimize impacts of agriculture are discussed, including the use of Best Management Practices, community-based agri-environmental initiatives, and various legislative controls.

5.1 Introduction

Of all the human activities that have a potential impact on karst terranes, agriculture is perhaps the most ubiquitous. A few karst regions have undisturbed natural vegetation, but the vast majority have some form of agricultural activity. Karst plateaux sometimes have low-intensity agriculture because of the constraints imposed by the rocky terrane, shallow soils, and scarcity of water. However, where higher-intensity agriculture occurs, the risk of problems such as soil erosion and water contamination is generally much greater than in other terranes.

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P.E. van Beynen (ed.), *Karst Management*, DOI 10.1007/978-94-007-1207-2_5,

Agricultural activities in karst regions have wide-ranging implications for soils, water, and landscape, for ecosystems and biodiversity, and for social and economic sustainability. It is not possible within the scope of this chapter to review all of these areas, and so the following discussion is focused specifically on the impact on soils and water, particularly on water quality, and on management approaches to minimize such impacts. However, it is acknowledged that any changes to soil and water quantity and quality will have implications on other aspects of the natural and human environment, and that any management strategies must take these linkages into account.

One of the greatest problems associated with land clearance for agriculture and agricultural intensification in karst terranes is the risk of soil erosion. Karst areas are particularly prone to this, both because limestone soils are typically shallow (as the rock from which they are derived yields little insoluble residue) and because the open joint systems facilitate the washing underground of soil material (Williams 1993). Intensification of land use, including irrigation and drainage schemes, may also bring about hydrological changes to karst aquifers, including changes in timing or amount of aquifer recharge or discharge and flooding problems. Alterations to water quality may arise from land use change, from the use of fertilizers and pesticides, and from point sources of contamination such as badly stored farm wastes. Karst aquifers are particularly vulnerable to chemical and microbial contamination due to the occurrence of point recharge via sinking streams and dolines, the presence of an epikarst zone, and the existence of both conduit and diffuse flow within the aquifer itself (Field 1989; Smith 1993). Changes in water quality may have implications for human health and for ecosystems, including cave communities and surface water ecosystems fed by karst springs.

The range of agricultural activities with potential impacts on soil and water in karst regions is outlined in Sect. 5.2, while case studies of actual impacts are presented in Sect. 5.3. Case examples are mainly drawn from the last 15 years; for additional earlier studies, the reader is referred to the review by Coxon (1999). Methods of risk evaluation and management strategies to minimize impacts of agriculture are reviewed in Sect. 5.4.

5.2 Activities

5.2.1 Land Use Change

Deforestation of karst regions results in a loss of biodiversity; the vegetation changes in turn cause increased soil erosion, and the combination of changes in evapotranspiration and in soil cover will result in hydrological changes. Increases in grazing pressure and the conversion of pastureland to tillage may also increase soil erosion rates and have hydrological impacts. Land use changes are also likely to have impacts on water quality, particularly on suspended sediment and nutrients.

Fig. 5.1 Grazing of recently deforested land in the Vaca Plateau, Belize (Image © M Day)

Prehistoric and historic occurrence of soil erosion due to deforestation has been reported from many karst areas. For example, agricultural development by the Maya people in the Yucatan Peninsula of Mexico, Belize, and Guatemala from 4,000 to 3,000 BP onwards gave rise to soil erosion in karst areas; soil conservation measures, including extensive terracing, appear to have been effective in reducing soil loss, but a further period of soil erosion followed (Beach et al. 2002). Deforestation continues to the present day in the karst of the Caribbean region (Day 1993, 2007; Fig. 5.1). It is also an important issue in many other tropical and subtropical karst areas, notably in a large area of subtropical China (Yuan 1993; Wang et al. 2004). Soil erosion due to deforestation has also been widespread since prehistoric times in Mediterranean karst areas (Gams et al. 1993) and in karsts of cool temperate climatic zones (Drew 1983). Soil erosion problems are discussed in Sect. 5.3.1.2, while hydrologic impacts of deforestation are reviewed in Sect. 5.3.2.1 and suspended sediment is discussed in Sect. 5.3.3.2.

Forest clearance may give rise to other water quality changes besides suspended sediment. Lichon (1993) found that the release and leaching of forest nutrients, following deforestation of Tasmanian karst, resulted in elevated nutrient loading of karst streams and contamination of water resources, while Ellaway et al. (1999) note that springs and cave streams from uncleared native forest catchments in Buchan, Australia, differ in chemistry from those with catchments of cleared agricultural land. Jiang et al. (2006) document changes to major ion concentrations of groundwater in the karst Xiaojiang catchment in Yunnan province, China, between 1982 and 2004, due to deforestation and agricultural intensification.

Intensification of agriculture on existing farmland, such as increased grazing pressure or a change from pasture to tillage, may also provoke soil erosion and hydrological and water quality changes. Problems associated with land clearance and intensification are documented from the Burren karst plateau, Ireland, by Drew and Magee (1994), and from Murgia, Southern Italy, by Canora et al. (2008). In the latter area, a dense network of drystone walls had an important role in reducing soil erosion and retarding runoff, but wall clearance, agricultural mechanization, and a change from grazing to tillage from the 1980s onwards caused changes to the soil and hydrology of the region. Figure 5.2 shows the contrast between the karst landscape unaltered by clearance and the cleared, tilled land.

A decrease in agricultural intensity, often associated with rural depopulation, may also cause environmental problems, albeit of a different nature. In the Burren plateau, Ireland, a decrease in winter livestock grazing in recent years has led to increasing encroachment of hazel scrub vegetation with loss of characteristic world-renowned arctic-alpine flora designated as priority habitats under the E.U. Habitats Directive (Dunford and Feehan 2001; BurrenLIFE 2006). Efforts to tackle this issue are discussed in Sect. 5.4.2.

5.2.2 Irrigation and Drainage

Soil water content is frequently altered to facilitate agriculture, with moisture levels being either increased by irrigation or decreased by land drainage operations. This is likely to have an impact on groundwater resources, with changes in amount and timing of recharge and discharge, and such impacts will be particularly marked in karst areas where surface waters and groundwaters are so closely interlinked.

Irrigation of agricultural land may cause a hydrological impact at the source of the irrigation water or at the irrigation site. In karst aquifers, the lowering of the water table due to irrigation water withdrawals may be very uneven and difficult to predict. The irrigated land may then provide a new source of recharge to the karst aquifer, with potential problems of salinization noted below. Problems may also arise with damming for irrigation purposes, e.g., Gillieson and Thurgate (1999) record damage to the Texas cave system in Australia due to the building of an irrigation dam. Land drainage operations carried out with the aim of decreasing soil moisture levels to improve agricultural productivity may also have significant hydrological impacts. For example, in the carboniferous limestone lowland areas of Western Ireland, channelization to relieve flooding of agricultural land has resulted in a lowering of water tables and a change to the flooding regime of ecologically important seasonal karst lakes (Drew and Coxon 1988) (see Sect. 5.3.2).

Irrigation or drainage of land is generally accompanied by agricultural intensification and increased use of fertilizers and pesticides, resulting in changes to soil water and groundwater quality. Irrigation may also provoke groundwater quality

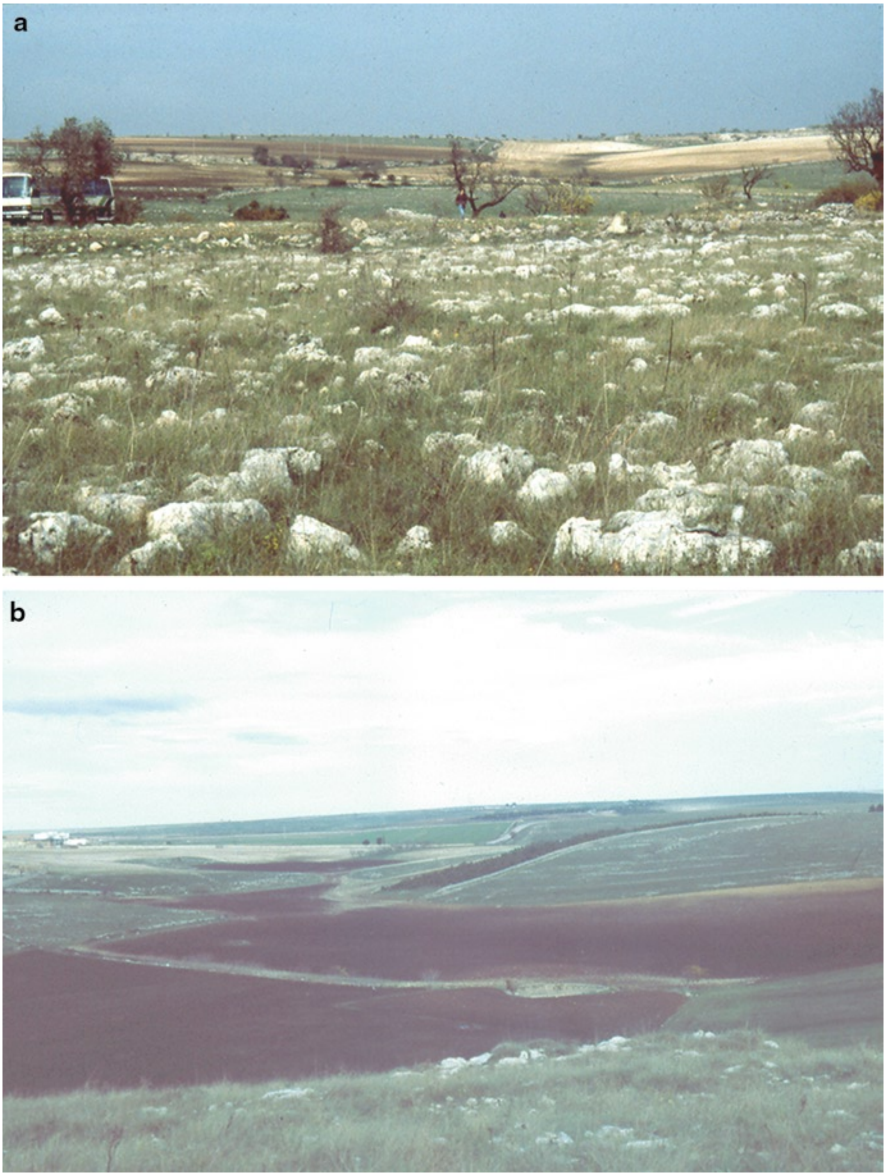

Fig. 5.2 Contrast between (**a**) an unimproved field and (**b**) a reclaimed, tilled doline in Apulia (SE Italy) (Images © D Drew)

changes if it brings about increased leaching of natural or artificial chemical constituents from the soil. Salinization of karst groundwaters due to increased leaching of soluble salts has been documented from several areas, e.g., Puerto Rico (Day 1993). Equally, irrigation with water of a high salinity may have an adverse impact on soil chemistry and productivity, as noted in Southern Italy by Gams et al. (1993).

Drainage operations along river channels may provide entry routes for contaminants to underlying karst aquifers. For instance, in the Clarinbridge catchment in the Western Irish karst lowlands, channel excavation into bedrock resulted in line and point recharge with polluted surface waters, causing a nitrate plume in the karst aquifer (Drew 1984; Fig. 5.3a).

5.2.3 Landspreading of Fertilizers and Pesticides

Over the last few decades, there has been a global increase in the use of inorganic fertilizers, which has led to an impact on groundwater quality, particularly nitrate concentrations. Agricultural land is also landspread with an increasing range of organic material, including agricultural wastes (livestock manure or slurry, silage effluent, farmyard runoff), human wastes (sewage effluent, sewage sludge), and agro-industrial wastes (dairy effluent, blood, offal). Pesticide use has also increased greatly in recent decades in many countries. The resulting water quality problems are widespread throughout both the developed and developing world and are by no means unique to karst areas. However, karst aquifers are particularly vulnerable due to the high aquifer permeability, often combined with thin soil cover. Furthermore, groundwater contamination may not be restricted to the more mobile constituents such as nitrate and chloride; constituents more usually associated with point agricultural sources (e.g., phosphorus, potassium, ammonium, and fecal microorganisms) may also gain entry to vulnerable karst aquifers from diffuse agricultural sources. Similarly, pesticide contamination in karst aquifers may not be restricted to the most mobile compounds, as pesticides adsorbed to colloidal soil particles may gain entry to the aquifer via solutionally widened fissures. Case examples of karst groundwater contamination by nitrate, phosphate, pesticides, and microbial pathogens are given in Sect. 5.3.3.

5.2.4 Rural Point Sources

Agricultural point sources of pollution can range from small-scale inputs of fecal material from groupings of animals at feeding troughs or sheltered/shady locations to larger pollutant plumes originating from badly stored farm wastes such as slurry and silage effluent. These can cause pollution in any vulnerable hydrogeological situation. However, in the case of karst aquifers, there is an added risk at locations of concentrated recharge: contamination is particularly acute where agricultural point sources coincide with karst features such as sinking streams and dolines. Thus, cattle congregating around cave entrances or entering sinking streams can cause severe localized contamination with fecal microorganisms and nutrients (Berryhill 1989). Dumping of animal carcasses into karst-closed depressions is another common source of contamination (Gillieson and Thurgate 1999). Storage of silage on bare limestone pavement in the Burren karst plateau in Ireland has resulted in

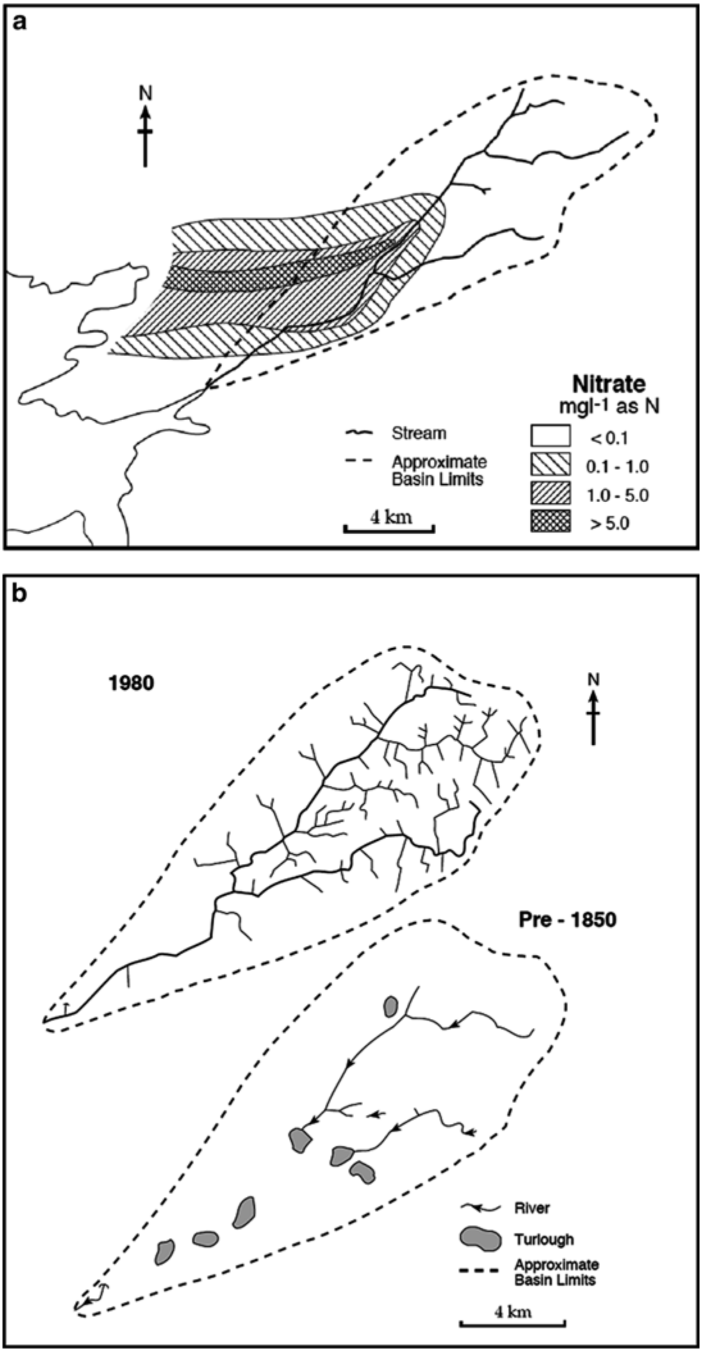

Fig. 5.3 Impacts of agricultural drainage in an Irish lowland karst catchment (Clarin, County Galway), (**a**) Nitrate plume due to line recharge along an artificial river channel, (**b**) Change in drainage density due to agricultural land drainage (After Drew 1984)

Fig. 5.4 Silage clamp on bare limestone pavement on the Burren karst plateau, Ireland, posing a threat to groundwater quality (Image © D Drew)

contamination of karst springs in summer, at times of maximum water demand (Drew 1996; Fig. 5.4).

Another rural point source of contamination is septic tank effluent from rural housing not served by city sewerage systems. While not strictly agricultural, this contaminant source often occurs in close association with agricultural point sources; thus, rural groundwater contamination by fecal microorganisms may be due to a combination of human and animal waste. The presence of thin soils in many karst areas, providing insufficient purification in the percolation area, combined with the rapid transfer of effluent through solutionally widened fractures in the unsaturated zone, means that fecal contamination from septic tank effluent is particularly common in karst regions (Panno et al. 1997).

5.3 Impacts

5.3.1 Impacts on Soil

5.3.1.1 Introduction to Agricultural Impacts on Soil

As noted in the introduction, karst areas are particularly prone to soil erosion due to a combination of shallow, erodible soils and solutionally widened fractures into which soil particles are easily transported. Such erosion is often triggered by clearance of forested land for agriculture or by increase in grazing density or increased cultivation. Examples of such impacts from karst regions around the world are given in Sect. 5.3.1.2 below.

The mechanisms of soil erosion in karst areas are discussed by Hardwick and Gunn (1990). The greatest sediment inputs are associated with sinking streams, particularly where these originate on noncarbonate rocks. Soils may be eroded into karst aquifers by autogenic recharge, particularly where macropores are present and where dolines provide routes of sediment entry. Hardwick and Gunn (1990) also consider that sediment transport through the epikarst or subcutaneous zone is highly likely; they suggest that it is probably very slow but should not be neglected, as they note studies in the Dinaric karst which show suspended load in cave trickles to be of the same order of magnitude as dissolved load. Suspended sediment in karst waters is discussed further in Sect. 5.3.3.2.

In addition to soil erosion, agriculture can also have a major impact on soil chemistry. Jiang (2006) documents the changes in soil organic matter content and chemical properties due to land use change in a karst agricultural region in Southwest China and notes that the modifications in soil properties were greater in soils developed from carbonate rocks than in soils developed from sandstone. Soil carbon dioxide levels will also vary as a result of landuse change. For example, Day (1999) documents changes in soil carbon dioxide levels arising from "slash and burn" agriculture in the Hummingbird karst of Belize, with a drastic reduction on the day after burning and gradual recovery in subsequent days, and he notes that such changes are relevant to limestone dissolution.

5.3.1.2 Soil Erosion Associated with Land Use Change

As noted in Sect. 5.2.1, deforestation of many karst regions has given rise to soil erosion since prehistoric times, and continues to the present day. One region where soil erosion is particularly severe is in Guizhou Province, Guangxi Zhuang Autonomous Region and Yunnan Province in Southwestern China, where it has been termed rocky desertification (Huang et al. 2008; Fig. 5.5). In this region, land is being lost by the transformation of vegetation – and soil-covered karst landscapes - into exposed rock at a rate of 25,000 km^2 per year; about 40% of the land area is affected by soil erosion, and in addition to causing severe impacts in the eroded areas, this has caused problems of sedimentation of river courses and reservoirs (Wang et al. 2004). Silt transport rates for rivers in this region subject to deforestation and rocky desertification are 208–1,980 tonnes/km^2/year (Yuan 1993).

Soil erosion has occurred in many Mediterranean karst regions since prehistoric times (Gams et al. 1993). Different phases of land exploitation in the karst Venetian Fore-Alps (Northern Italy) are reviewed by Sauro (1993), who notes that forest clearance and cattle and sheep grazing have been responsible for significant soil loss into subsoil karren cavities. Bou Kheir et al. (2008) note that karst landscapes which comprise 70% of Lebanon have thin soils which are prone to erosion due to deforestation, burning, and overgrazing, and they readily succumb to desertification. Gillieson and Thurgate (1999), reviewing karst and agriculture in Australia,

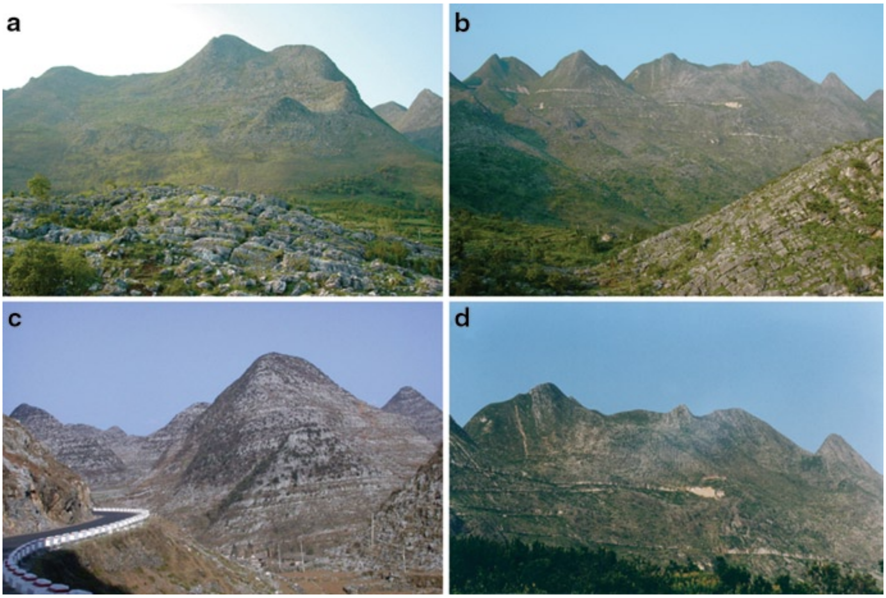

Fig. 5.5 Examples of karst rocky desertification in South-West China (From Huang et al. 2008, p.391, © Royal Swedish Academy of Sciences)

comment that there is a crucial link between landscape stability and vegetation cover in Australian karst; they note that clear-cutting in the Florentine Valley in Tasmania caused the accumulation of 1 m of cave sediment, and they also record evidence of sediment accumulation due to deforestation in the karst of New South Wales. An increase in grazing pressure, particularly in arid and semi-arid areas, may trigger increased soil loss; this is documented for the example in the Nullarbor Plain in Australia (Gillieson et al. 1994). Poor tillage practices may also trigger erosion in karst regions (Berryhill 1989). Intensive vine cultivation in the Entre-deux-Mers karst plateau in Southern France, involving field leveling by bulldozers, has resulted in significant soil erosion, with clogging of drainage channels and development of suffusion dolines (Audra 1999).

5.3.2 Impacts on Water Quantity

5.3.2.1 Changes in Groundwater Recharge

Changes in land use such as deforestation, reforestation, and conversion of grassland to tillage will all have implications for groundwater recharge due to the change in evapotranspiration rates. Lerner et al. (1990) document several case studies of carbonate aquifers where groundwater recharge is related to vegetation cover. Alteration to groundwater recharge due to vegetation changes and resultant changes in evapotranspiration are not, of course, unique to karst areas. However, the recharge mechanisms specific to karst areas may accentuate the change.

Huntoon (1992) noted that in the stone forest karst aquifers of South China, massive deforestation since 1958 has resulted in a major impact on the magnitude and duration of the seasonal recharge pulse. Water that was formerly retained in the forested uplands and gradually released to recharge the aquifers on the lowland now passes rapidly through the system, so that the decline in water level in the aquifers during the dry season has been accelerated. Water shortages due to karst rocky desertification in Southwestern China are also noted by Wang et al. (2004), who comment on a reduction in the retention of surface water and drinking water shortages due to drying up of springs and wells. Similarly, deforestation associated with increasingly intensive slash-and-burn agriculture in the karst area of Batuan on the Island of Bohol in the Philippines is regarded by Urich (1993) as the primary cause of a decline in spring discharges by 40% in a 20-year period. Chandler and Bisogni (1999) also note that forest clearance in karst areas of the Philippines has resulted in an increased frequency of water shortages: in the Leyte uplands, a comparison was made between sites with forest cover, slash-and-burn cultivation, plouwed land, and pastureland. The latter two land uses had reduced infiltration and increased runoff, and it was proposed that disturbance of the soil surface results in progressive plugging of the epikarst. Deforestation may also trigger geomorphological changes with implications for recharge. Kiernan (1989) notes that forest clearance for pasture in Tasmania has resulted in accelerated sinkhole development.

Modification and intensification of existing agricultural land may also result in changes to groundwater recharge. For example, Canora et al. (2008) modeled the hydrological impacts of agricultural intensification on the Alta Murgia karst plateau in Southern Italy (Sect. 5.2.1) and found that cereal cultivation on the reclaimed “shattered stone land” resulted in a significant decrease in recharge to the karst aquifer, which provides an important regional water resource.

Drainage of agricultural land in karst regions will also have an impact on recharge. In the Western Irish carboniferous limestone lowland, channelization carried out from the mid-nineteenth century onwards to relieve flooding of agricultural land has resulted in a decrease in aquifer recharge and lowering of water tables. For example, in the Kilcolgan-Lavally catchment in East Galway, summer water tables have been lowered by 2–3 m, causing previously perennial springs to become ephemeral (Drew and Coxon 1988). In the neighboring Clarinbridge catchment, the drainage density has been increased from 0.2 to 4 km/km^2, and in the lower catchment, an artificial river has been excavated into bedrock (Fig. 5.3b). As a result, surface runoff from the basin has been increased from 0 to 40% of effective precipitation and aquifer recharge has been reduced accordingly. Spatial patterns of recharge and discharge have been altered, with the artificial stretches of channel providing line and point recharge and discharge at different times of year (Drew 1984).

5.3.2.2 Flooding

Flooding problems may sometimes result from deforestation and associated soil erosion, due to increased runoff and blockage of the karst drainage system by the eroded soil and sediment. For example, in a karst region of Kentucky, U.S.A., removal of oak-maple forest cover and cultivation of tobacco and corn in the 1930s resulted in disastrous valley floods known locally as "valley tides." Runoff was increased, and the increased sediment load blocked the already insufficient underground drainage channels, resulting in backing up of runoff and flooding of the valleys upstream of river sinks (Dougherty 1981). Forest clearance in Mole Creek, Tasmania, caused cave conduits to become choked by sediments, resulting in flooding of pastures during the winter months (Gillieson and Thurgate 1999).

Some agricultural changes may cause a decrease rather than an increase in flooding. The drainage operations in the Western Irish limestone lowlands referred to in Sect. 5.3.2.1 have also resulted in the draining of turloughs (seasonal karst lakes; Fig. 5.6); approximately, a third of turloughs have been drained since the nineteenth century (Drew and Coxon 1988). The cessation of seasonal flooding has serious ecological implications (Sheehy Skeffington et al. 2006). Karst poljes, which provide areas of flat, fertile land within rocky Mediterranean karst landscapes, have also been subject to drainage schemes by various means and with varying degrees of success. In recent decades, polje water regulation schemes have been multi-purpose, for hydroelectric power generation and water supply as well as agriculture, and have involved major tunnel construction (Milanovic 2002).

5.3.3 Impacts on Water Quality

5.3.3.1 Vulnerability of Karst Aquifers to Agricultural Contamination

The existence of point recharge to karst aquifers makes it particularly easy for agricultural contaminants to gain access. Swallow holes provide direct access points to the aquifer, with little or no attenuation, so contaminants more frequently associated with surface waters, which would not normally enter by diffuse recharge (e.g., phosphate or pesticides adsorbed to suspended sediment), may enter karst conduits by point recharge. Furthermore, many karst areas have a mosaic of bare rock and thin rendzina soils, and the lack of protective cover combined with solutionally widened fissures in the limestone creates extreme vulnerability to pollution from agricultural sources. The epikarst or subcutaneous zone may allow rapid lateral movement of diffuse contamination to vadose shafts. It can also provide significant temporary storage for contaminants, which may then be released from this zone by flood pulses (Field 1989).

The presence of conduit flow in karst aquifers allows rapid transfer of contaminants through the aquifer, with minimal opportunity for attenuation by adsorption, ion exchange, chemical breakdown, or microbial die-off. The short underground residence time also means that very little time is available for remedial action to avoid contamination of drinking water supplies. In addition, the lack of attenuation

Fig. 5.6 Kilglassan turlough, Co. Mayo, Ireland, a karst seasonal lake in winter, spring, and summer (Many such features in Western Ireland no longer flood regularly due to agricultural land drainage schemes) (Images © P Coxon)

in the karst aquifer can result in groundwater contaminants emerging at springs and having an ecological impact on surface waters to a greater degree than in other aquifer types. However, it should be noted that karst aquifers demonstrate a spectrum of behavior, often reflecting the age of the limestone. In older limestones with secondary permeability only, contaminants in recharge may move through the unsaturated zone extremely rapidly through solutionally widened fissures, while in dual porosity aquifers such as the Cretaceous Chalk, there may also be a very slow recharge component in the primary pore space. In the saturated zone, pollutants may move rapidly along cave conduits, or they may form a more conventional plume where there is a significant proportion of diffuse fissure flow.

In the following sections, some of the most significant groups of agricultural contaminants of karst groundwater are discussed, with case examples from many different regions.

5.3.3.2 Suspended Sediment

The presence of solutionally enlarged joints and sinking streams allows sediment derived from soil erosion to enter karst aquifers to a greater extent than in other aquifers. Suspended sediment may cause problems of turbidity in drinking water supplies, but it is particularly important because it can provide a method of entry for a range of adsorbed contaminants including phosphorus, pesticides, and viruses.

Suspended sediment loads show a large degree of temporal variation. For example, in the Big Spring Basin (Iowa, U.S.A.), an agricultural karst catchment with a rotation of corn/pasture/hay suspended sediment loads in the spring increase during flood events from negligible values to concentrations over 4,000 mg l^{-1}, corresponding to a load of over 87,000 kg h^{-1} (Hallberg et al. 1985). Figure 5.7 illustrates the chemical

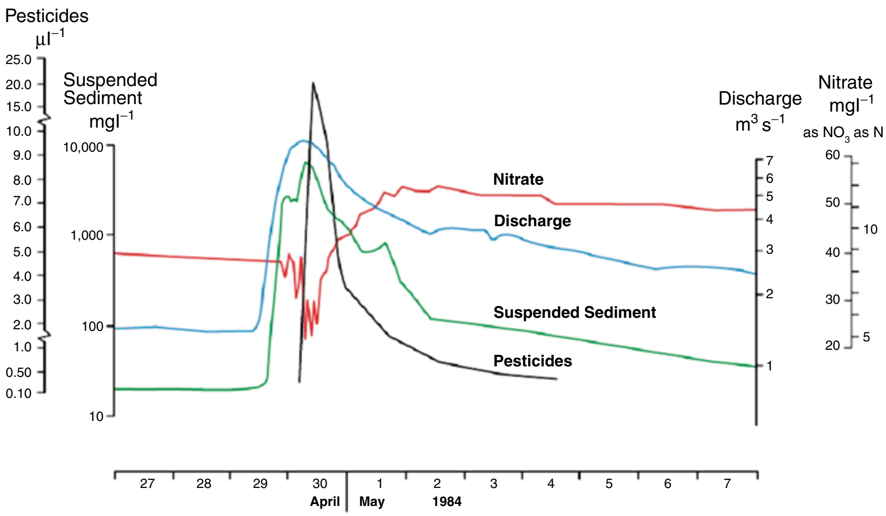

Fig. 5.7 Changes in water quality during a summer discharge event at Big Spring, Iowa, USA (After Libra et al. 1986)

changes associated with summer discharge events at Big Spring; it can be seen that the suspended sediment concentrations mirror the variation in discharge, and the pesticide peak corresponds to the suspended sediment peak. Similarly, Nebbache et al. (2001) note that turbidity peaks in springs, fed by the Brionne Basin karst system in Normandy, France, are short-term events coinciding with heavy rain episodes.

Pronk et al. (2007) studied sediment transport through karst flow systems draining agricultural land in the Yverdon karst system in Switzerland. Continuous monitoring of particle size distribution was undertaken during storm events (Fig. 5.8); the first turbidity peak corresponded to a mixture of coarser and finer particles remobilized within the karst conduit by the flood pulse, while the arrival of the second turbidity peak, consisting of finer particles and coinciding with an increase in total

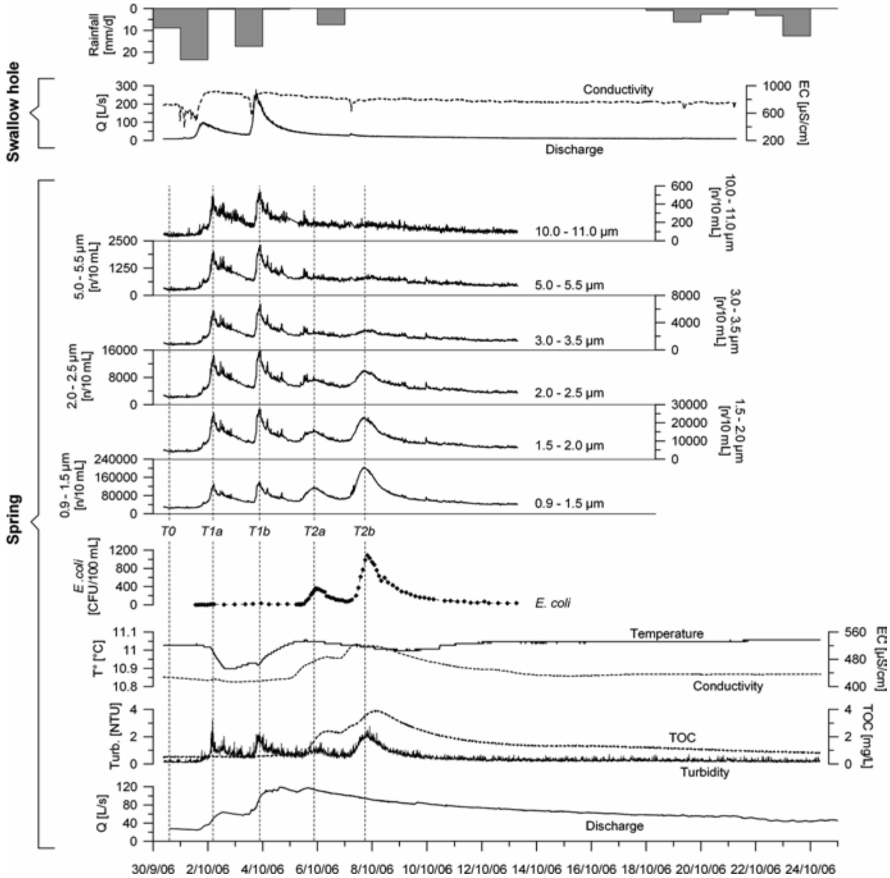

Fig. 5.8 Variation in turbidity and other parameters during a multiple flood event at the Feurtille swallow hole and Moulinet spring, Yverdon karst aquifer, Switzerland. T0 = pre-storm conditions, T1a/b = autochthonous turbidity signals of the first/second flood event, T2a/b = allochthonous turbidity signals of the first/second flood event (From Pronk et al. 2007)

organic carbon, indicated the arrival of swallow hole water at the springs (with larger particles removed by sedimentation within the aquifer).

5.3.3.3 Nitrate

Nitrate contamination of karst aquifers in rural areas can arise from many sources, both diffuse (spreading of inorganic and organic fertilizers and release of soil nitrogen due to land use change) and point (e.g., badly stored farm wastes and septic tank effluent). The nitrate ion is highly soluble and mobile, so nitrate pollution is found in many free-draining hydrogeological situations, but the characteristics of karst regions outlined in Sect. 5.3.3.1 make karst aquifers particularly vulnerable. The shallow, patchy rendzina soil cover overlying some karst aquifers increases the risk of leaching. Where a thicker soil cover is present, nitrate may move slowly through the soil matrix, or macropore flow may provide opportunities for rapid transfer (Iqbal and Krothe 1995; Peterson et al. 2002). The presence of point recharge via swallow holes and dolines may allow nitrate to enter the aquifer with little residence time in the soil. For example, in the Brionne Basin in Normandy, Northern France, nitrate reaches the karst springs both by rapid transfer of point recharge (with short-lived nitrate peaks occurring during heavy rainfall, coinciding with turbidity peaks) and by leaching of diffuse recharge (providing a longer-term sustained nitrate input) (Nebbache et al. 2001). Where the aquifer has secondary porosity and permeability only, nitrate will pass rapidly through the unsaturated and saturated zones (e.g., in the carboniferous limestone of Ireland; Richards et al. 2005), while, if the limestone has dual porosity, there is a possibility of retention in the unsaturated zone for considerable time periods (as in the Cretaceous Chalk; Jackson et al. 2008).

Elevated nitrate is found in many karst groundwaters around the world, including Australia (Gillieson and Thurgate 1999), China (Guo and Jiang 2009), Turkey (Davraz et al. 2009), and Morocco (Laftouhi et al. 2003). Nitrate levels are problematic in many European carbonate aquifers. For example, elevated nitrate in the Cretaceous Chalk of Eastern England has given rise to concern since the 1980s, breaching the European Union drinking water standard of 50 mg l^{-1} NO_3 (11.3 mg l^{-1} as N) and creating a challenge for meeting improvement deadlines under the EU Water Framework Directive (2000/60/EC) (Jackson et al. 2008). High nitrate is also found in karst aquifers in the Franconian Alb of South Germany (Einsiedl and Mayer 2006). Such problems were a contributing factor to the introduction in 1991 of the European Union Nitrates Directive (91/676/EEC) (see Sect. 5.4). However, not all European karst regions have such nitrate problems, as in some instances the difficult nature of the karst terrane has meant that agriculture has remained less intensive than elsewhere. In Ireland, the synclinal carboniferous limestone valleys in the south of the country have intensive dairying agriculture, and as a result, there are nitrate problems from both diffuse and point sources (Bartley and Johnston 2006), but the Western Irish limestone lowlands and the Burren plateau have less intensive agriculture, and as a result, nitrate concentrations are significantly lower, as seen from Irish EPA monitoring data in Clabby et al. (2008). A similar contrast can be seen in French karst regions: the Brionne Basin in Central Normandy has undergone agricultural intensification, with increased nitrogen inputs and increased area of arable land, and shows a trend of increasing groundwater nitrate concentrations over the last few decades (Nebbache et al. 2001), but Plagnes and Bakalowicz (2001) note that many French karst areas have a lower intensity of human activity and therefore have groundwater of generally good chemical quality. For example, the Larzac plateau in Southern France has patchy soils and is mainly used for low-density sheep grazing. However, they note that even in this area, agriculture is the main source of nitrate, with a relationship between nitrate flux and amount of cultivation, and they suggest that measures are needed to prevent further increases in nitrate concentration.

In the U.S.A., many papers over the last three decades have documented concerns about nitrate in karst groundwaters. Breaches of drinking water standards for nitrate were recorded in karst groundwaters in Minnesota, Pennsylvania, and Iowa (Berryhill 1989). Nitrate from diffuse agricultural sources is especially well documented for the Big Spring groundwater basin in Iowa (Hallberg et al. 1985; Libra et al. 1986; 1999), where the nitrate problems are linked to nitrogen fertilizer application to corn (maize). Boyer and Pasquarell (1995) found that nitrate concentrations in karst springs in Southeastern West Virginia showed a strong linear relationship with percent agricultural land, with the land being used primarily as pasture for cow-calf and dairying operations. A further study of cave streams in this region (Boyer and Pasquarell 1996) showed that nitrate concentrations were highest in cave streams draining a dairy farm and in a cave stream draining an area of pasture where cattle congregated for shade and water. Management approaches to tackle these problems are discussed in Sect. 5.4.2. More recently, Panno et al. (2001) have used stable isotopes ($\delta^{15}N$ and $\delta^{18}O$ of the nitrate ion) to determine the sources of nitrate in karst groundwater in the sinkhole plain of Southwestern Illinois and to investigate denitrification in the aquifer. Monitoring of nitrate loads from two large karst springs draining this aquifer indicated a loss of ~27 kg N/ha/year, with approximately half coming from background sources and most of the remainder coming from fertilizer (Panno and Kelly 2004).

Temporal variations in nitrate concentration in karst groundwaters will depend on the source of nitrate and the pathway it takes through the aquifer. In many instances, high nitrate concentrations are associated with diffuse recharge, while lower concentrations coincide with major point recharge inputs, when a major input of surface water dilutes the nitrate. For example, in the Big Spring basin in Iowa, nitrate reaches maximum levels during discharge recession when infiltration recharge dominates (Fig. 5.7). Mahler et al. (2008) noted that despite the contrasting hydrogeological characteristics of the Chalk aquifer of Normandy, France, and the Edwards aquifer, Texas, U.S.A., in both aquifers, nitrate was a diagnostic tracer of resident groundwater, decreasing in concentration during storm events, whereas potassium and turbidity were effective tracers of infiltrating storm runoff. The analysis by Guo and Jiang (2009) of temporal variations in the rising of a subterranean river in a peak cluster karst area of China showed that there was a nitrate peak at the start of the rainy season, which was attributed to release of nitrogen which had accumulated in the soil during the dry season from fertilizers, animal waste, and general village waste. Analysis of shorter-term variations during three rainfall events showed that higher nitrate was associated with piston flow from the soil and vadose zone and with arrival of recharge from these zones.

5.3.3.4 Phosphorus

Inputs of phosphorus to surface freshwaters via surface or near-surface pathways have been a concern for many years because this is often the limiting nutrient to eutrophication of rivers and lakes. However, over the last decade, there has been a growing awareness that in some instances groundwater can provide a pathway of phosphorus transfer to ecologically sensitive surface waters, and this is particularly likely to occur in vulnerable karst situations.

Calcareous soils retain significant quantities of phosphorus, due to both adsorption and precipitation reactions. However, leaching may occur where the soils are highly saturated with P or where it has been mobilized by the addition of manure (von Wandruszka 2006). Leaching is particularly likely in karst areas where thin, organic rendzina soils are present, but the greatest reason for concern about phosphorus in karst areas is the occurrence of point recharge bypassing the protective soil cover, combined with rapid passage flow through the aquifer via conduits and discharge to springs which may feed surface water bodies susceptible to eutrophication (Kilroy et al. 2001). Initial lack of evidence for phosphorus in karst springs from studies in the 1980s was at least partly due to poor detection limits in many groundwater phosphorus analyses, reflecting nonexistent or high drinking water limits for P (of the order of mg l^{-1}). Ecological thresholds are much lower, e.g., the OECD phosphorus threshold for eutrophic lakes is a total phosphorus concentration of 35 μg l^{-1} (Vollenweider 1982).

Hardwick (1995) found elevated concentrations of phosphorus in cave waters in a karst aquifer in Derbyshire, U.K., which increased after application of sewage sludge to the overlying agricultural land. Alloush et al. (2003) noted a strong positive correlation between total dissolved phosphorus concentrations in rivers in the Appalachian region of the U.S.A. and the percentage of their catchment areas classified as karst landscape. They found that the total dissolved P concentration and the proportion of dissolved nonreactive P in soil samples increased with the amount of cattle grazing in karst sinkholes in this region. Runoff to the sinkholes contained very high concentrations of dissolved P (several mg l^{-1}), which was dominated by inorganic P, whereas the cave stream contained dissolved P concentrations of the order of 0.2 mg l^{-1} (200 μg l^{-1}), which was dominated by nonreactive P (i.e., organic or colloidal P fractions). These concentrations significantly exceeded U.S. EPA guidelines of 0.1 and 0.05 mg l^{-1} for streams and lakes, respectively.

The western karst lowlands of Ireland contain ecologically sensitive surface water bodies, including rivers, lakes, and turloughs which have close interactions with karst groundwater (Coxon and Drew 2000). Investigations of phosphorus in karst groundwaters in this region (Kilroy and Coxon 2005) showed that mean total phosphorus (TP) concentrations in both springs and boreholes were greater than the

20 μg l^{-1} threshold for eutrophic conditions in Irish lakes. Monitoring of temporal variations in P in eight karst springs showed a peak in P concentrations in response to the first autumnal rains, attributed to release of P accumulated in the soil during the summer following inorganic fertilizer and manure applications. Dissolved reactive phosphorus (DRP) was the dominant P component, but particulate P and dissolved nonreactive P increased to a greater degree than DRP during periods of high rainfall (Fig. 5.9a). This study also provided a case example of the passage of a contaminant plume attributed to the release of silage effluent, resulting in an increase in TP concentration in the down-gradient spring from 42 to 1,814 μg l^{-1} within 24 h (Fig. 5.9b). Such localized pollution incidents may be of particular significance if they impact surface waters in the summer months when groundwater constitutes a high proportion of river flow.

The presence of phosphorus in karst groundwaters contributing to sensitive surface waters can have important management implications. While evaluating the status of Irish groundwater bodies under the E.U. Water Framework Directive (2000/60/EC), one of the factors taken into account was the assessment of adverse impacts of chemical inputs from groundwater on associated surface water bodies and the combination of ecologically significant groundwater phosphorus concentrations. High contributions of groundwater flow to surface waters in Irish karst regions resulted in 101 groundwater bodies occupying 13.3% of the area of Ireland being designated as poor qualitative status. Programs of measures to restore good status are required under the Water Framework Directive, and reducing phosphorus inputs from agriculture to these vulnerable karst systems is likely to have significant social and economic costs (Daly 2009).

5.3.3.5 Pesticides and Other Synthetic Organics

Pesticides vary greatly in their toxicity, mobility, and persistence. However, many have health effects such as carcinogenicity at very low concentrations; therefore, leaching of only a small proportion of applied pesticide can result in violation of drinking water standards. Easily leached pesticides such as atrazine may be found in many aquifer types, but the thin soils and subsoils associated with many karst aquifers together with the potential for rapid movement through solutionally widened fissures will make contamination more likely than in other hydrogeological situations. Less mobile pesticides are readily adsorbed on to soil particles and have a lower risk of entering aquifers but may reach karst groundwater because of the possibility of colloidal particles entering via sinking streams or solutionally widened fissures.

Atrazine, a herbicide used widely in maize (corn) cultivation and as a general broad spectrum weed killer, has been the most widely reported pesticide in karst groundwater over the last two decades. Karst aquifers in the American mid-west in which atrazine has been recorded include the Big Spring basin, Iowa, where it is the dominant pesticide in the groundwater (Libra and Hallberg 1999; Rowden et al. 2001); two karst catchments in West Virginia, where atrazine and its metabolite desethylatrazine were detected in more than 50% of samples (Pasquarell and Boyer 1996); the Green

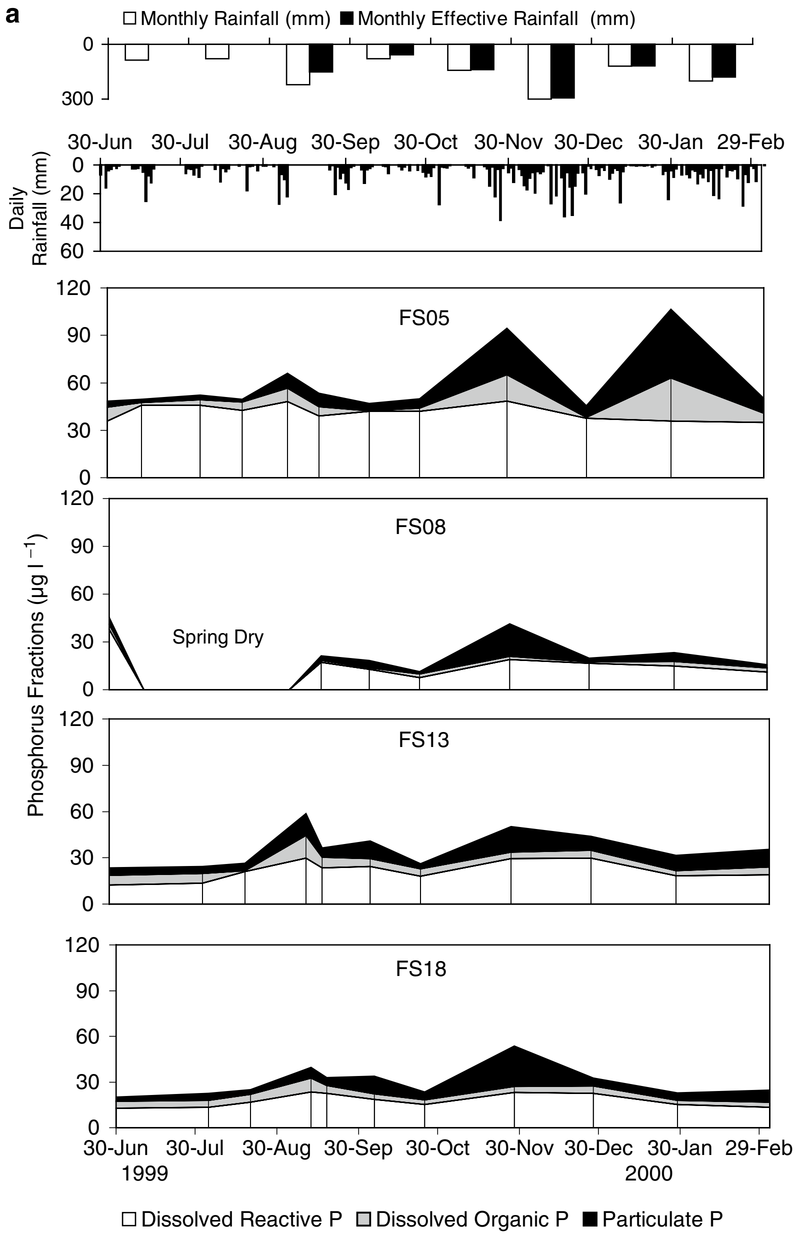

Fig. 5.9 Phosphorus in Irish karst springs (**a**) Temporal variation in different phosphorus fractions at four springs in the Fergus catchment, County Clare (**b**) Short-term variation in total phosphorus at a spring in the Robe catchment, County Mayo (From Kilroy and Coxon 2005)

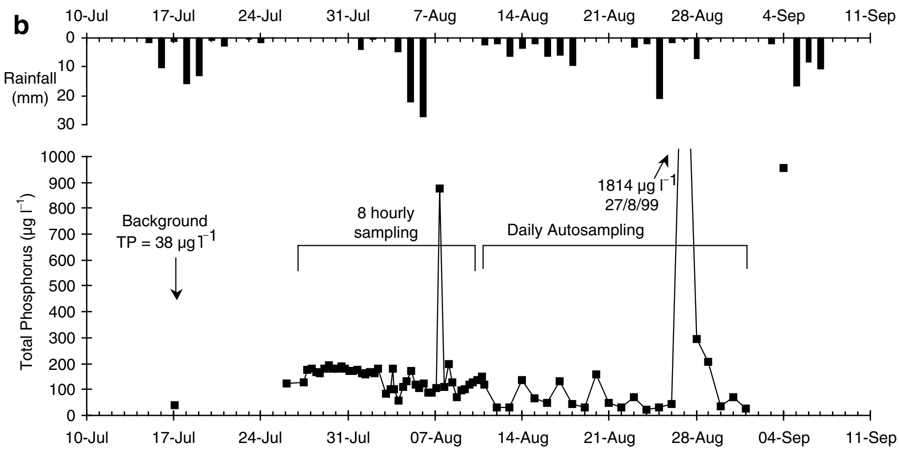

Fig. 5.9 (continued)

River Basin in Kentucky, where it was detected in 100% of karst spring water samples (Crain 2002); the Illinois sinkhole plain, where concentrations ranged from <0.01 to 34 µg l^{-1} (Panno and Kelly 2004); and two karst springs in Northern Alabama (Kingsbury 2008). The drinking water limit for atrazine in the U.S.A. is 3 µg l^{-1} as a yearly average (with higher concentrations permissible in the shorter term), while in the European Union, the limit is 0.1 µg l^{-1}. It has been recorded from a range of European karst aquifers including a Jurassic karst aquifer in Germany (Milde et al. 1988) and a weakly karstified Cretaceous Chalk aquifer in France, where it was present in 83% of samples at concentrations up to 5.3 µg l^{-1} (Baran et al. 2008).

The presence of atrazine continued to be recorded for several years after its use was banned, both in Slovenian groundwater (Gotvajn et al. 2001) and in the French Chalk aquifer mentioned above, where it was recorded 3 years after the ban in 2003 (Baran et al. 2008). Other herbicides recorded in karst groundwaters include other triazines such as simazine (Crain 2002; Debrewer et al. 2008); alachlor, a widely used herbicide particularly in maize and peanut cultivation (Panno and Kelly 2004; Dalton and Frick 2008); and fluometuron, used in cotton cultivation (Dalton and Frick 2008; Kingsbury 2008).

Pesticides which are readily adsorbed on to colloidal particles may enter karst aquifers via sinking streams or solutionally widened fissures. Simmleit and Herrmann (1987) examined the passage of lindane through a karstified Jurassic limestone and dolomite aquifer in Franconia, Germany, and found that transient rises in lindane concentration and loading coincided with increases in suspended solids and in dissolved humic material. Libra et al. (1986) also noted the coincidence between peaks in pesticide concentration and suspended sediment peaks, at Big Spring in Iowa, as shown in Fig. 5.7. Ekmekci (2005) noted that different pesticides of varying mobilities were found in different hydrologic zones of the

Kestel-Kirkgoz karst system in Turkey: lindane and hepta epoxide characterized surface water input to the aquifer via swallow holes, while aldrin and dieldrin characterized shallow groundwater in the polje, and the metabolites of DDT were found in deep groundwater with a longer residence time.

The importance of tracking pesticide metabolites in addition to the primary substance was demonstrated by Pasquarell and Boyer (1996). These authors found that prolonged storage of atrazine in the soil results in loss of its metabolite desethylatrazine (DEA) from the soil to karst groundwater, but atrazine may also be transported more directly to groundwater through dolines and conduits, bypassing the soil desethylation process. Baran et al. (2008) also found DEA occurring as frequently as atrazine in a French chalk aquifer. Similarly, Kingsbury (2008) noted that degradates of the herbicides atrazine and fluometuron were detected at concentrations comparable to or greater than the parent pesticides. In the Floridan limestones of Southwest Georgia, Dalton and Frick (2008) noted that degradates of alachlor and metoalachlor were generally found at higher concentrations than their parent compounds.

Antibiotics are another group of synthetic organic compounds which are a potential cause of concern in karst groundwaters. Landspreading of animal manures in vulnerable karst situations may not only cause problems of nutrient loss and microbial contamination, but may also contaminate water supplies with antibiotics, giving rise to concern about the spread of antibiotic resistance. Dolliver and Gupta (2008) documented a 3-year study of leaching and runoff losses of antibiotics from land application of hog and beef manures in a karst area of Wisconsin, U.S.A.: chlortetracycline was detected in runoff while monensin and tylosin were detected in both runoff and leachate, with detections occurring mainly during the nongrowing season (November to April) following autumn application of manures.

5.3.3.6 Microbial Pathogens

Microbial pathogens are a particular problem of karst aquifers because the lack of filtration within the aquifer and the short underground residence times mean that if organisms manage to pass through or bypass the unconsolidated material overlying the aquifer, they are almost certain to appear in water supplies. The presence of conduit flow within the karst aquifer can allow viable organisms to travel for hundreds of meters or even several kilometers from the point of entry. The microorganisms involved include bacteria, viruses, and protozoan parasites.

Fecal bacteria have been reported from karst aquifers for several decades. The large numbers of bacteria present in human and animal waste, combined with the fact that pathogenic bacteria and indicator organisms such as fecal coliforms and fecal streptococci must be absent from drinking water supplies, mean that the problem is not solved by dilution. Kelly et al. (2009), reporting on fecal bacterial contamination of karst groundwater in Southwestern Illinois from domestic wastewater and livestock manure, noted that there was chemical evidence of substantial dilution of the wastewater, but that this did not lower bacterial concentrations sufficiently to meet drinking water limits. In Ireland, fecal bacterial contamination of groundwater supplies from karst aquifers has been reported since the 1980s (Thorn and Coxon 1992) and continues to the present day (Clabby et al. 2008). Celico et al. (2004) record bacterial contamination of karst springs in Southern Italy resulting from manure spreading, with the highest bacterial numbers found when intense rainfall produced concentrated infiltration of runoff in a swallow hole. Fecal bacterial contamination is also well documented from karst aquifers in North America. Boyer and Pasquarell (1999) compared bacterial contamination in cave streams in a beef cattle area and a dairying area and found that fecal coliforms and fecal streptocci were present in much greater numbers in the dairying area. However, bacterial numbers were much lower where best management practices were in place (Sect. 5.4.2). Kozar and Mathes (2001) found that 32% of wells in a karst limestone and dolomite aquifer in West Virginia contained *E. coli*, with contamination rates being higher where there was nearby agricultural activity.

A current serious concern with fecal coliform contamination is the possible presence of verotoxin-producing *E. coli* (VTEC) such as *E. coli* 0157, which causes dysentery and hemolytic uremic syndrome, which can be fatal (Percival et al. 2004). The presence of VTEC in a karst spring in an agricultural catchment in the Swiss Jura was correlated with high *E. coli* concentrations and with rainfall events: contamination was attributed to local infiltration of polluted surface waters and rapid passage through karst conduits (Auckenthaler et al. 2002). The most serious recorded case of karst groundwater contamination by *E coli* 0157:H7, combined with *Campylobacter jejuni*, took place in Walkerton, Ontario, Canada, in May 2000, when 2,300 people became ill and seven people died. The contamination appears to have come from cattle feces which entered the karst groundwater following heavy rainfall. Tracing experiments demonstrated a significant degree of karstification, with flow velocities 80 times faster than predicted in the initial modeling which had treated the aquifer as an equivalent porous medium (Worthington et al. 2002).

Many viruses are retained in soils by adsorption to soil particles, particularly where the soil has a high clay content (Gerba et al. 1991), but they may gain entry to karst aquifers while adsorbed to such particles. Enteric viruses are recorded in karst groundwaters in the U.S.A. by Berger (2008). Viral transport through karst groundwater has been studied using bacteriophage tracers (i.e., virus infecting bacteria and harmless to humans). For instance, Auckenthaler et al. (2002) carried out tracing experiments in a karst spring in Switzerland using marine bacteriophages H4 and H40 and found a similar breakthrough curve for these as for *E. coli* and enterococci bacteria occurring naturally in the spring.

A recent and growing concern is contamination by protozoan parasites, particularly *Cryptosporidium parvum*, which causes acute gastroenteritis and persistent and potentially fatal disease in immune-compromised individuals. This organism has caused disease outbreaks even where water supplies are treated by conventional chlorination, because it forms an oocyst which is resistant to chlorination; successful removal requires physical barrier treatment, e.g., flocculation and filtration or ozonation (Percival et al. 2004). The first outbreak of cryptosporidiosis linked with karst groundwater occurred in Braun Station, San Antonio, Texas, in 1984, when more than 200 people became ill due to contamination in the Edwards aquifer (D'Antonio et al. 1985). *Cryptosporidium* has been detected in many karst groundwater supplies in the last decade, including springs in West Virginia, U.S.A. (Boyer and Kuczynska 2003), a karst spring in Switzerland (Auckenthaler et al. 2002) and the karst springs which provide the water supply for the town of Ennis in Ireland (Page et al. 2006, p.64).

Microbial contamination in karst aquifers is often ephemeral and not easily detected by routine monitoring at regular wide intervals (e.g., monthly or quarterly). Where even brief exposure to a pathogenic microorganism in a water supply could have serious consequences, the need to predict temporal variations is particularly acute. Soil moisture levels may play a role in controlling temporal variations in fecal coliform numbers, with bacteria stored in the soil zone being released once soil moisture increases and groundwater recharge occurs (Pasquarell and Boyer 1995).

Several authors have noted that peak bacterial numbers often coincide with flow peaks (Thorn and Coxon 1992; Auckenthaler et al. 2002) and with turbidity and sediment peaks (Dussart-Baptista et al. 2003; Boyer and Kuczynska 2003; Pronk et al. 2006; 2007). In Fig. 5.8, it can be seen that the peaks in *E. coli* numbers coincide with the second turbidity peak corresponding to the arrival of allochthonous sediment from the swallow hole.

5.4 Management

5.4.1 Risk Assessment

The first step in implementing management measures to minimize the problems discussed above is to evaluate the degree of risk. This enables appropriate controls to be taken, with the most stringent measures and most rigorous monitoring being applied in the highest-risk situations. The approaches used will differ depending on the nature of the problem, but in many instances, the source-pathway-receptor model of risk assessment is applicable. The source term relates to the agricultural pressure (e.g., animal stocking densities, fertilizer application rates), while the pathway term relates to the transfer route (i.e., the geological pathway through the karst system), and the receptor will vary depending on the nature of the impact being considered (e.g., a drinking water supply or an ecosystem).

While soil erosion risk assessments in most terranes focus on downslope sediment movement, risk of gullying, etc., in karst terranes, the risk of vertical movement into solutionally widened joints and closed depressions must also be taken into account. Nevertheless, Yue-Qing et al. (2008) found that the revised universal soil loss equation (RUSLE) integrated in a Geographic Information System was of value in predicting soil erosion risk in a rural karst catchment in Guizhou Province, China. A remote-sensing and GIS-based model has also been used to assess soil erosion in the Lebanese karst (Bou Kheir et al. 2008).

Risk of groundwater contamination from agricultural sources is commonly evaluated in the context of groundwater protection schemes. These are now widely used around the world, but the extent to which karst is taken into account varies considerably. Groundwater vulnerability assessment methodologies, which take account of karst, include the EPIK method (Doerfliger et al. 1999), the PI method (Goldscheider 2003) and the pan-European method developed in COST Action 620 (Daly et al. 2002). These methods are general purpose assessments of intrinsic vulnerability, while some approaches (Sinreich and Zwahlen 2002) evaluate specific vulnerability to particular types of contaminant. Risk assessments relating to particular substances have also been undertaken in the delineation of nitrate vulnerable zones for the EU Nitrates Directive and in risk assessments for particular groups of chemical parameters for the EU Water Framework Directive (WFD). The Irish WFD groundwater body risk assessments for diffuse source pollutants including nitrate and phosphorus involved an evaluation of agricultural pressures, pathway susceptibility, and receptor sensitivity; the pathway susceptibility took karst aquifers into account, and in the case of phosphorus, the presence of swallow holes was also included in the risk assessment (Working Group on Groundwater 2005).

5.4.2 Management Strategies and Planning Controls

Controls on particular agricultural activities (discussed further below) often form part of an overall land management plan or a groundwater protection policy for the karst region. Groundwater protection policies in karst aquifers incorporate the vulnerability and risk assessment procedures discussed in Sect. 5.4.1, with more stringent planning controls being implemented in the higher-risk zones.

The impact of deforestation can be minimized by good management practices. Planning requirements for timber harvesting in karst areas outlined by Kiernan (1987a) include an inventory of karst features and the designation of karst reserves within the overall karst area where felling is prohibited, while operational measures (Kiernan 1987b) include a prohibition of logging on steep limestone slopes or in the vicinity of sinkholes and cave entrances, and the provision of silt traps in situations where there is a risk of karst stream siltation. Where damage has already occurred due to deforestation, management strategies are required to restore and rehabilitate the landscape. Measures to reverse karst rocky desertification in Southwestern China include programs of reforestation, the planting of economically useful woodland plants, and the development of ecologically sensitive agriculture (Wang et al. 2004).

A major difficulty in implementing planning controls in karst groundwater protection zones is that the nature of karst flow systems means that such zones are much more extensive than in most other aquifer types. Plagnes and Bakalowicz (2001), reviewing groundwater protection in the Larzac plateau in Southern France, note that whereas in nonkarst regions, protection zones typically extend over a few square kilometers, the two springs acting as water supplies in this area have recharge areas of 100 and 110 km^2. Furthermore, karst spring catchments may have large partial contributing areas, where sinking streams contribute a varying proportion of their flow to the spring, as seen in the Western Irish karst lowlands (Coxon and Drew 2000).

Diffuse or nonpoint source pollution is often tackled by a combination of "carrot and stick" approaches: in some instances, farmers are encouraged to implement good land management strategies on a voluntary basis and may be grant-aided or provided with free management advice (as in implementation of Best Management Practices [BMP] in the U.S.A.), while in others, there is an increasing degree of legislative control (such as the European Union Nitrates Directive). Agricultural point sources are somewhat easier to deal with than diffuse sources, given that in many instances they can be eliminated by simple pollution control measures such as constructing adequate storage tanks, rather than requiring fundamental changes to the agricultural system. Point sources have also been addressed in some instances by advice and grant aid, and in others by legal controls.

Initially, agricultural BMPs in the U.S.A. were not specifically geared to karst areas: Berryhill (1989) reviewed BMPs for controlling diffuse pollution in tillage areas (e.g., conservation tillage, crop rotation, reduced input agriculture) and in grazing areas (e.g., rotation of pastures with rest periods to allow regeneration, and fencing animals away from water bodies and areas subject to erosion), and he commented on their relevance to karst areas. He also assessed BMPs used to control pollution from agricultural point sources (e.g., leak-proof feed and manure storage facilities, runoff control structures, and vegetative filter strips for erosion and nutrient control). More recently, BMPs more specific to karst areas have been implemented and have met with a varying degree of success. In some cases, they have been of value in minimizing bacterial contamination of karst groundwaters: Boyer and Pasquarell (1999) found that while a karst stream in a dairying area in Central Appalachia without BMP had more than 4,000 fecal coliforms per 100 ml, a dairying area with BMP for control of animal and milking shed waste was not contributing significant amounts of fecal bacteria to the karst aquifer. However, Currens (2002) found that BMPs implemented in a karst groundwater basin in Kentucky were only partially successful, and Boyer (2005) noted a lack of consistent water quality improvement in two karst study areas in Southeastern West Virginia following several years of implementation of BMPs. He suggested that BMPs should be targeted at well-defined contributing areas that significantly impact water quality (e.g., excluding cattle from particularly vulnerable sinkholes). BMPs subsequently implemented include the use of vegetative buffer strips around sinkholes (Petersen and Vondracek 2006). Boyer (2008) described a sinkhole filter involving filter fabric sandwiched between layers of crushed rock, which was not effective in reducing nitrate concentrations but achieved a considerable degree of success in reducing fecal coliform concentrations; he proposed that it would be a valuable tool in some situations when used in combination with land management measures such as buffer strips.

While catchment controls involving agricultural BMPs may improve the microbial quality of karst waters, they are unlikely to succeed in eliminating microbial contamination. Shutting down of raw water intakes at times of maximum risk, during the passage of flood waves at karst springs, may also be of value. However, reliable prediction of contamination incidents can be problematic. Because analyses of fecal microorganisms take hours or days, they cannot be used for instant monitoring of karst groundwater supplies. As noted in Sect. 5.3.3.6, turbidity is often highly correlated with microbial pathogens, and monitoring a combination of turbidity and total organic carbon, or monitoring turbid particle size distribution, may enable autochthonous turbidity (from remobilization of sediments within the karst conduit) to be distinguished from allochthonous turbidity (representing arrival of swallow hole waters and potential pulses of microbial contamination) (Pronk et al. 2006, 2007; Fig. 5.8). However, Auckenthaler et al. (2002) warn that in some karst systems, microbial numbers may rise several hours before turbidity, so they suggest that spring discharge may be a safer warning parameter. Because of the difficulty of prediction and potentially serious public health consequences, adequate treatment, including treatment to remove microorganisms such as *Cryptosporidium* that are resistant to chlorination, remains of considerable importance.

In the European Union, the Nitrates Directive is implemented by means of mandatory action programs within nitrate vulnerable zones and voluntary codes of practice outside these zones; these are drawn up by individual member states, so the extent to which karst is taken into account varies. The Irish legislation, giving effect to the directive, includes a ban on landspreading of manure within 15 m of karst features such as swallow holes and collapses and a ban on manure storage within 50 m of such features, while spreading of soiled water is strictly limited in karst regions where the depth to bedrock is less than a meter (Stationery Office Dublin 2009). Management measures to reduce nitrate contamination may also involve limits on nitrogen fertilizer application, such as the livestock manure limit of 170 kg N/ha/year imposed in the E.U. Nitrates Directive. However, the time lag between a reduction in fertilizer inputs and a reduction in groundwater nitrate levels can vary greatly; as noted in Sect. 5.3.3.3, time lags are greatest in dual porosity chalk aquifers. Thus, Nebbache et al. (2001) comment that while short-term peaks in nitrate concentration in the Brionne Basin due to point recharge may be addressed on a short-term, local basis, the longer-term trend of rising nitrate over the last few decades will require a longer-term approach, with solutions applied today potentially taking decades to have a tangible effect in this Chalk system.

While nitrate pollution is being tackled by a series of measures including a reduction in fertilizer inputs, in the case of pollution by some pesticides, a complete elimination of inputs is being recommended or enforced. For example, Milde et al. (1988), working on pesticides in German karst aquifers, suggested that substances such as atrazine should not be used in highly vulnerable karst catchments. Atrazine was subsequently banned throughout the European Union, but in parts of the world, where a general ban is not currently in place, a ban on its use in vulnerable karst situations may be justifiable.

In areas where the rocky karst terrane has resulted in low-intensity agricultural systems and where nitrate and pesticides are not currently at problem levels (e.g., the Larzac plateau in France, mentioned above, and some of the Slovenian karst plateaus discussed by Kovačič and Ravbar (2005)), a useful management approach

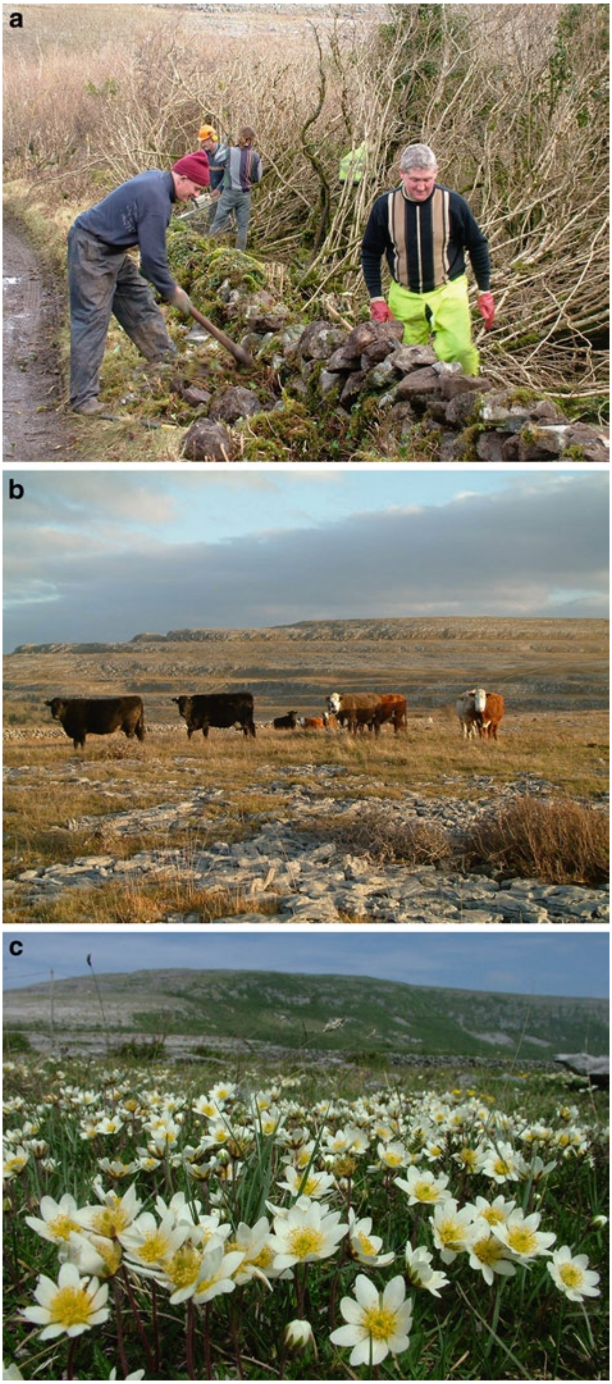

Fig. 5.10 Farming for conservation in the Burren karst plateau, Ireland (**a**) Hazel scrub removal (**b**) traditional winter cattle grazing (**c**) Arctic-alpine flora (*Dryas octopetala*) (Images © B Dunford, BurrenLIFE)

may be to combine catchment controls such as groundwater source protection zones with a positive promotion of the values of such regions. In the karst areas of Croatia, organic sheep breeding involving indigenous breeds of sheep, adapted to the karst environment, is being promoted as a means of economic growth while preserving the traditional way of life and protecting the environment (Radin et al. 2008). In the European Union, whereas earlier schemes funded by the Common Agricultural Policy sometimes exacerbated environmental problems in karst regions (Drew and Magee (1994) and Canora et al. (2008), discussed in Sect. 5.2.1), more recent community-based E.U. projects have had a more positive influence. In the Burren plateau in Western Ireland, the BurrenLIFE project was initiated in 2005 with funding from the European Commission LIFE Nature Fund, combined with national and local sponsorship, in recognition of the importance of farming in protecting internationally important habitats such as limestone pavements and orchid-rich grasslands, which are subject to scrub encroachment as noted in Sect. 5.2.1. This project aims to develop a model for sustainable agriculture, bringing together farmers, scientists, conservationists, and others to develop farming systems and supports to protect the Burren karst plateau (BurrenLIFE 2006, 2009; Fig. 5.10). Another EU LIFE-funded project, the Limestone Country Project, which ran in the upland karst of the Yorkshire Dales, U.K. from 2002 to 2008, also sought to promote sustainable land management and restore limestone pavement and limestone grassland habitats by encouraging a return to mixed farming using hardy upland cattle breeds (Yorkshire Dales National Park Authority 2009).

5.5 Conclusions

From the wide range of research studies carried out over the last few decades, it is clear that agricultural activities can have a wide range of impacts on karst landscapes and karst waters. Clearance of forest vegetation for agriculture gives rise to problems of soil erosion, impacts on groundwater recharge and degradation of water quality. Increases in grazing intensity or a change from pasture to tillage may trigger further soil erosion and impacts on water quality. Irrigation and drainage operations associated with agricultural intensification may have both hydrological and water quality impacts. Landspreading with fertilizers and pesticides can result in water quality problems in drinking water supplies and groundwater-fed ecosystems. Animal wastes, if stored inappropriately or if landspread in vulnerable situations, may give rise to contamination with a range of constituents, with fecal microorganisms posing particular risk to human health.

While such environmental problems associated with agriculture are by no means unique to karst areas, they may occur with particular severity because of the peculiar characteristics of karst: the occurrence of concentrated recharge in closed depressions and swallow holes, combined with the presence of conduit flow and flow in solutionally widened fractures in the aquifer, render karst regions particularly susceptible to soil erosion and entry of contaminants to groundwater. The thin, patchy soil cover found in many karst areas may act as a check on agricultural intensification, but it can further increase the risk of adverse impacts of any agricultural activities that do take place.

Appropriate management measures will vary depending both on the nature of the agricultural systems and also on the nature of the karst region in question. Karst aquifers overlain by significant thicknesses of soil and subsoil are more likely to have intensive agricultural operations such as tillage or intensive animal rearing; in such regions, a combination of approaches may be desirable. This might include a program of education for farmers about the vulnerability of karst systems and on the use of Best Management Practices to avoid problems, combined with appropriate legal controls on application of fertilizers and pesticides and on storage of farm wastes. National programs required to meet national or international legislation, such as the EU Nitrates Directive and Water Framework Directive, may need to be modified to suit the particular needs of karst regions.

Management measures to minimize adverse impacts of agriculture must strike a difficult balance between the need for environmental protection and the need to maintain agricultural activities. In rocky karst plateau regions, maintenance of traditional farming practices may be of importance in preserving distinctive karst landscapes and ecosystems. Measures such as the promotion of indigenous organic sheep production in the Croatian karst and initiatives such as the BurrenLIFE project in Ireland may be of value in preserving distinctive karst flora and fauna and in preventing problems of rural depopulation, while minimizing any adverse impacts on the environment.

Although the quest for an environmentally sustainable solution to the development of agriculture in a particular karst region must take local geological, hydrological, ecological, and socioeconomic factors into account, in many cases, there are valuable opportunities to benefit from work in other similar karst regions around the world, sharing scientific research on environmental processes and impacts and sharing experience of management approaches.

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