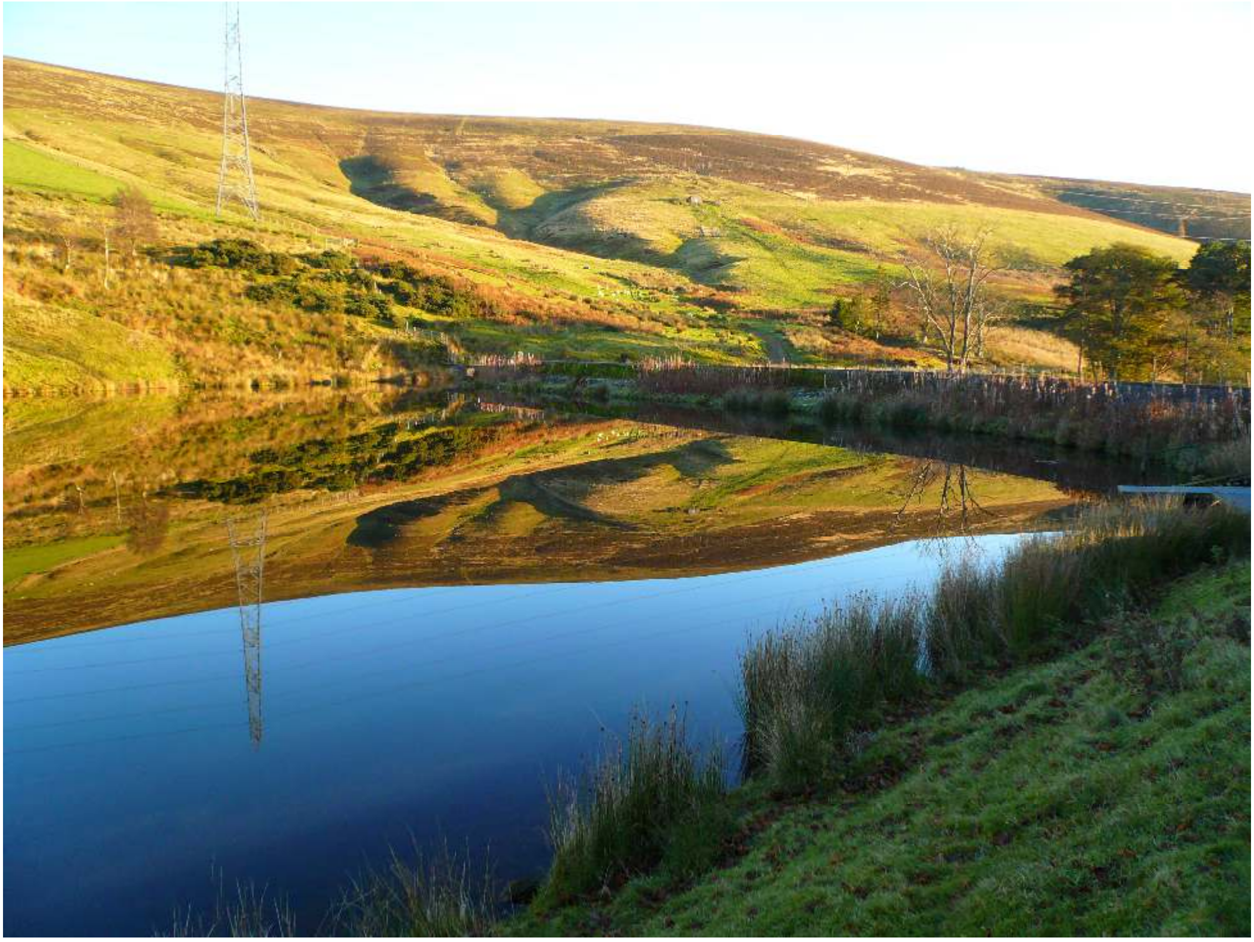
CLIMATE-POSITIVE FARMING REVIEWS

Climate-positive integrated water management systems: Water and wastewater decisions on upland farms



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Executive Summary

The uplands in the UK are a vital source of water, providing 70% of the drinking water supply, which in turn provides dilution for downstream pollution. The farming situation in the uplands is distinctive by virtue of often harsh climate, high elevation, high rainfall, long winters, short growing seasons and areas of poor-quality soils. This review focuses on the integration of natural water cycles, managed waters on-farm including wastewaters as part of integrated farm management in the uplands, both in terms of current and future pressures.

Some key aspects of upland farm water management are highlighted in the report:

- Private water supplies and abstractions from streams are the main sources of water supplies on UK upland farms. These may be disrupted during dry periods (amount) and wet periods (contamination). Aspects such as water storage from spring or rain sources are used to buffer periods of low supply.
- Key water demands on upland farms are around livestock management. Crops, dominated by grass and some fodder crops, are rain-fed and subject to variation between seasons and years.
- Managing water flows around the fields and farmyard is essential to minimising fast runoff, flows interacting with pollution sources and for the separation of clean (rainwater) and dirty water (mostly yard runoff).
- Steep topography maximises runoff rates. Measures should be considered to slow and control the movement of flowing polluted water, such as ponds to catch and retain runoff water and sediments, buffer strips to retain nutrients and fencing to restrict animal access to watercourses.
- Septic tank systems commonly serve domestic properties for sewage disposal and need to be in good condition. Dirty water from wider areas of farmyards should be contained and either utilised for returning to soils or treated to a suitable level before discharge.

A range of water management measures have been analysed in the specific context of the James Hutton Institute's Glensaugh farm across broad farm practices related to livestock management, crop and soil management, overall environmental condition, water management in farm infrastructure and the handling of wastes. This synthesis examines their level of suitability, existing implementation and future water management priorities. Opportunities identified for management over the next few years are (in approximate order of priority):

- Improvements in degraded domestic septic tanks not recently already replaced.
- Developing further manure management including wider pre-treatments/handling before spreading.
- Provision of improved structures for the areas where winter feeders are sited for sheep (such as pads and areas where dirty runoff is diverted away from watercourses).
- Several areas of benefits to be integrated with developing woodland expansion, namely: improving winter shelter; developing woodland as runoff interception zones to trap sediment and nutrients between fields and watercourses; riparian planting for overall improvements to river corridor habitat and functions; excluding stock from newly planted wet valley bottoms to reduce incidence of liver fluke.
- Increasing the amount of water storage from the current spring source.
- Considering additional supplementing of chemical fertilisers with soil amendments, subject to concerns about pollution such as micro-plastics that may be brought into the landscape.

1. Introduction

This review is part of a series of reviews that underpins climate-positive farming decisions, with this review focusing on water decisions in natural and managed systems such as upland farms. The review highlights water management, wastewater utilization and farming decisions that could be taken on upland farms in response to climate change and water demand, to help increase resilience without compromising environmental quality or water resources. The review outlines the state of knowledge reported in literature (both academic and grey) for:

- Field and farm pressures on water resources during dry periods.
- The needs for upland farms to become water-holding lands contributing to reducing flooding of downstream lands.
- Reducing fast runoff on sloping lands that can have saturated or degraded soils exacerbating runoff.
- Reducing the presence of pollution sources and their interactions with runoff that transports pollutants to surface waters.
- Stopping the mixing of clean water with dirty water, especially originating from livestock handling and congregating areas.
- Preventing pollutants and sediments from reaching watercourses, removing source areas from close to watercourses and boreholes, and keeping waters clean for a range of usages to minimise energy and chemical burdens of treatment.

This review uses as an example the James Hutton Institute's research farm, Glensaugh, which is an upland farm in the North East of Scotland and the home of the institute's Climate-Positive Farming Initiative.

The review is structured into a series of five chapters, each addressing a question related to water management on upland farms (in particular, linking to Glensaugh).

2. Where does water come from on upland farms?

2.1. Water for the farm: sources of water supplies on upland farms

At a UK level, water on upland farms can be supplied through one or more sources, predominantly not on the mains water supply: an estimated 25% of farms' private water supplies originate from deeper groundwaters (springs and boreholes) and 31% from surface waters (watercourses and private reservoirs) (DEFRA, 2017). In Scotland, springs outnumber boreholes due to the nature of the dominant geology. Farms in upland areas tend to rely more on private supplies due to remoteness away from available connection to piped mains supplies and in some parts of upland UK mains water will be unavailable across whole regions. The amounts of water abstracted from these private supplies increase with farm size, with greatest volumetric demands for larger cattle farms e.g. dairy farming (DEFRA, 2017). Where a supply is intended for the farmhouse as well as the farm business use, it may be covered by some testing from the local authority (mostly associated with house sales and risk assessment done when seeking improvement grants), but many farmhouse private supplies will have not been tested for many years, if ever. The exception is if the business has paying guest provisions such as self-catering or B&B facilities, then the supply is more regulated for public health. Additionally, private water supplies for farming purposes (e.g. animal drinking water) are not covered by drinking water regulations and the responsibility for acceptable water quality lies with the farmers (AHDB, 2020). Abstraction licencing and constructing boreholes permissions are required from the national Environmental Agencies to prevent the risks of water source contamination and destruction of any buried services such as gas and electric (SEPA, 2005). In addition, water supply availability on the farm can be disrupted during droughts by surface waters drying up or reducing in water quality, or even by restrictions to abstractions during droughts.

2.2. Water flows around upland farms (the natural and managed water cycle)

The ultimate source of the private water supplies relied on for upland farming is rain and snow falling within the catchment area. The interactions of the catchment's hydrological cycle affect the amounts and where this water is stored, its accessibility and quality. Precipitation may infiltrate soils and reside in various groundwater stores; form runoff (i.e. flowing over the land of the farm or in watercourses) and be taken up by vegetation; evaporate; and/or be drawn for farm supply. These hydrological pathways can involve fast rates of water transfers (e.g. storm runoff over the landscape in minutes or hours) to very slow (e.g. infiltration into the ground and exchange between groundwater aquifers over decades). These flows have differing rates and potential for pollution transfers (Fig. 1).

Water flows across the surface as runoff and/or seeps into the soil depending on the wetness and permeability. Soil permeability and infiltration is related to soil texture, superimposed by the effects of landform (e.g. slope) and management (e.g. soil compaction). As well as controlling rates of water transfer, these broad flow path differences can impart opposing influences for water quality. Surface runoff may be energetic and erosive and picks up large loads of sediment and adsorbed agro-chemicals (e.g. phosphorus and pesticides) and microbial pollutants from livestock faeces. Slower infiltration of water through soils can on one hand filter particulate pollutants from flows but may also be the cause of migration of mobile chemicals such as nitrate towards groundwaters. Figure 1 illustrates in general how water flows in a catchment can interact with different aspects of farm infrastructure and practices. Natural water flows have the potential to become faster and/or polluted flows where farm practices have accelerated flow rates or led to contact with pollution source areas. In many areas negative impacts can be mitigated ('best practice water flows'; Fig. 1) by management activities such as ploughing across the slopes, collecting rainwater and providing alternative drinking water for livestock as opposed to allowing their direct access to watercourses. Figure 2 provides further detail on the effects of poor farming practices on pollution and flood risks by illustrating a high-risk field situation for flood and pollution risk. Against this is presented a matrix of the two main contributory factor groups: those of poor soil management and high flow connectivity.

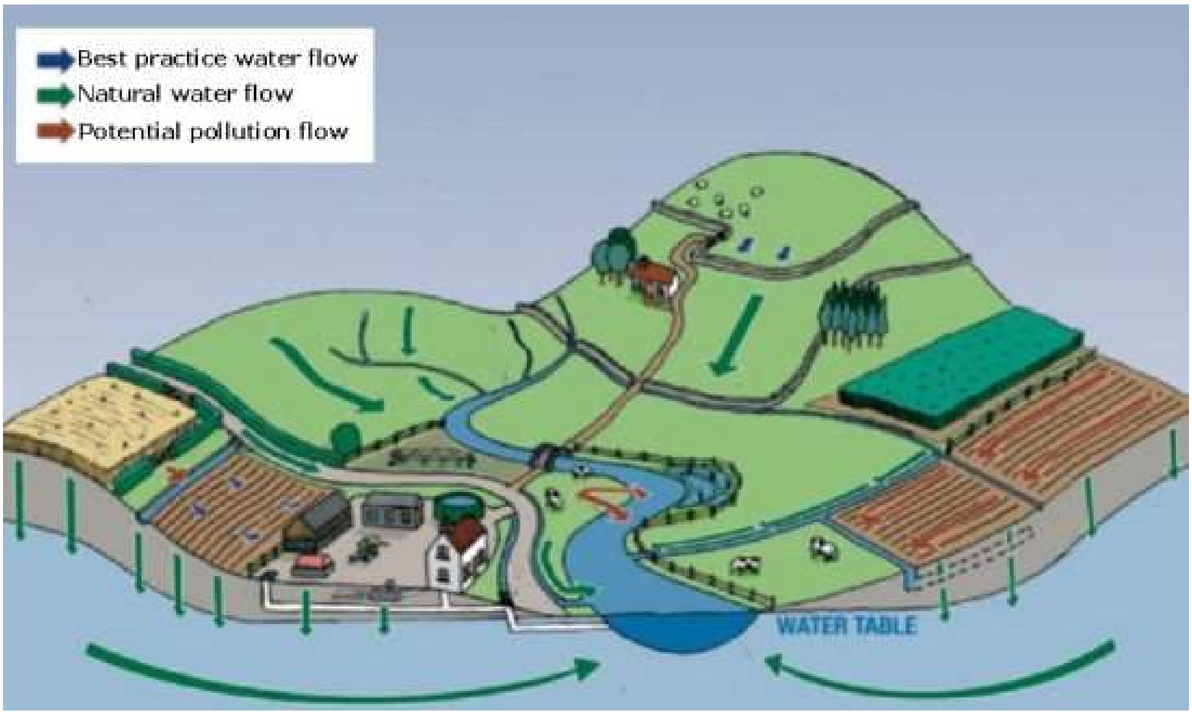

Figure 1: Water flow around the catchment showing potential pollution flow (brown arrows), best practice water flow (blue arrows) and natural water flow (green arrows), after DEFRA, (2012) and Environment Agency, UK, (2007).

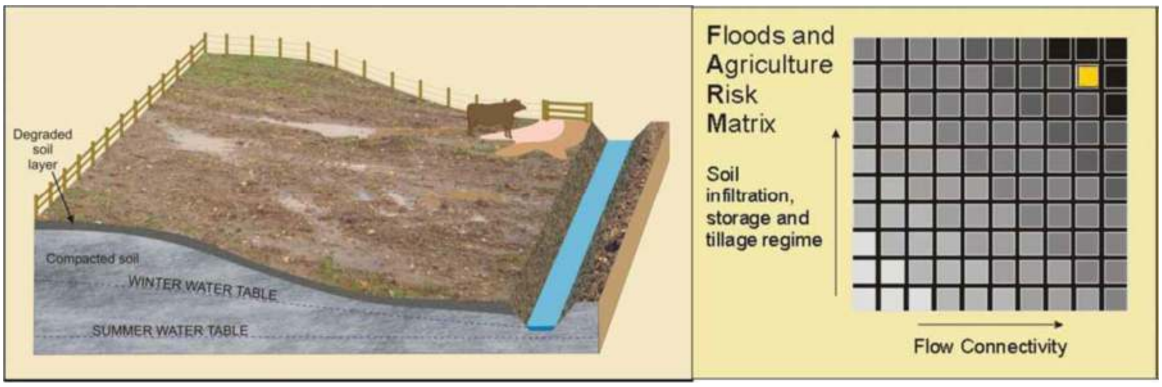

Figure 2: From Wilkinson et al., 2013 – demonstrating that intensive farming that results in compacted soils and highly connected flow pathways increases the risk of runoff generation (and therefore raising several environmental issues).

Knowledge of how water flows interact around the farm allows us to identify overall water-related risks and forms the basis for developing measures for critical water management aims, namely to:

- conserve water;
- reduce the amount and rate of flood runoff and, in doing so, potentially add to aquifer recharge that buffers against periods of drought;
- minimise generation of polluted water, stop this mixing with clean water around the farm (e.g. yard water and roof runoff mixing);
- control the transfer of pollutants to surface-waters and groundwaters.

2.3. Summary of water sources

- Private water supplies and abstractions from streams are the main sources of water supplies on UK upland farms.
- During periods of drought there may be pressures on these water supply sources
- It is important to manage both the natural and managed water cycles to prevent negative environmental issues and promote a healthy water resource that maximises its many uses and minimises energy and resource investment in any subsequent clean-up requirements.
- Consideration should be given to measures that reduce the risk of fast rates of water transfer in the farmed landscape and the risk of clean water mixing with dirty water.

3. How is water used on the farm?

Water on farms is needed for many applications including drinking for livestock, human consumption, cleaning of buildings, hard standings and machinery, slurry thinning, spraying, and other domestic uses. Climate variation, for example extended droughts, can interrupt private water supplies if significant storage is not available in reservoirs or tanks, where boreholes and surface water supplies are susceptible. Drinking water for livestock is generally the largest volume of water used on a farm (DEFRA, 2011). Another major water use at overall UK-level farm industry is irrigation, but this is rare on upland farms where rainfall is generally high and soil moisture deficits currently rare.

3.1. Livestock water usage on upland farms

Farm animals in the uplands can consume 40 or more litres of water per head per day (Table 1, AHDB, 2020), where generally a lactating suckler cow has the largest water need. Limitations in water supply can be costly, inconvenient and in the case of livestock farms cause animal welfare problems. Water footprints are another way of expressing water usage; the water footprint is the amount of water required per production unit. In the case of upland livestock farms, most often this is expressed per kg of meat. The average water footprint across all sectors of livestock farm is estimated at 18 m^3/kg of beef and 58 m^3/kg of lamb in England (AHDB, 2020). Specific beef production figures for upland farming are 16 and 47 m^3/kg for upland and hill suckler beef, respectively, and for sheep are 27 and 135 m^3/kg for upland and hill sheep, respectively. These system values are somewhat complex since they comprise 20-50% and 10% of ‘blue’ water for cattle and sheep, respectively; this being water of a high purity standard for direct animal drinking. The remainder of the water footprint is mostly ‘green’ water in upland farming, that is the rainwater requirement to grow the grass and other materials the animals eat (increasingly large with more extensive agriculture) and a small ‘grey’ water component comprising polluted water embedded in slurry, effluents and crop sprays. It does show that water footprints in upland farming can be large and hence are reliant on large volumes of upland rainfall, but comprise mostly water resources in a clean and natural state. The average annual drinking water requirement is 7.3 m^3 for cattle, 1.8 m^3 for calves, 1.2-1.6 m^3 for sheep and 10.6 m^3 for lambs (AHDB, 2016). Meanwhile, livestock farmers are bound by regulations preventing them from allowing their livestock direct access to watercourses if that results in water pollution (DEFRA, 2012; Holden et al., 2017). This has led to designs of off-stream animal drinking structures, including nose-operated, or solar powered pumps, with challenges for keeping pipes defrosted in winter.

Table 1: Daily water requirement estimates for livestock. Reproduced from AHDB (2016) and (2020).

Livestock	Daily drinking water requirement (Litres)
Beef cow, dry	15-40
Beef cow, lactating	40-70
Fattening cattle	25-75
Growing cattle	15-50
Sow, lactating	15-30
Sheep	4-8

3.2. Water use and crops

Climate change predictions are for more variability in annual rainfall and the consequences of this may be periods of drought, coupled with greater incidence of storms. Upland rainfall generally increases in amount with altitude, relative to lowland farms, but various strong gradients exist across the UK. Whilst water may be stored for livestock and other uses around farm buildings, the crops grown on upland farms are generally directly watered by rainfall. Current requirements for, and use of, irrigation is extremely limited on Scottish upland farms. Hence, a relatively consistent rainfall during the growing season (approximately Apr to Aug depending on latitude and altitude) is important for crop growth. The rainfall provides the soil moisture required by the crop for root uptake. Both soil saturation and soil moisture deficit affect crop performance and yields, the latter occurs when evapotranspiration exceeds rainfall over prolonged periods. An example was the extended dry spring to summer in 2018 where limited growth of fodder and conserved grass led to high feed prices, lack of availability of feed, and farms down-sizing numbers of stock during the following winter.

Irrigation systems have limited importance in UK upland farming and are more a feature of vulnerable, high value crops, such as fruit, potatoes and occasionally cereals, in lowland UK arable farming. A quick review here of irrigation is beneficial though in case it becomes more necessary in upland areas in the future (as in some climate change predictions for parts of Scotland). Currently relatively inefficient gravity fed and drip or sprinkler delivery irrigation systems are prevalent across the world. Gravity irrigation is used in many farms (Frisvold et al., 2018) and requires a reservoir at a high location in the field to collect rainwater or water from an upslope watercourse. Water sources may also be pumped at an energy cost. Sprinkler irrigation is most water-consumptive due to evaporation of fine droplets before the water reaches root depths. Drip irrigation is less water-consumptive due to delivery of drips to the root zone by perforated pipes and porous tubing placed on the surface or under the ground. This method of irrigation can be beneficial in terms of water conservation if future drought periods bring more widespread use of irrigation, since water is directly injected to the root system reducing water losses (Mchugh et al., 2008; Assefa et al., 2019). A shift from the less efficient gravity/sprinkler irrigation to more efficient irrigation application systems coupled with determining the optimal timing of irrigation and the quantity of water for crop growth stages has been the generally promoted best approach where irrigation is practised (Schaible et al., 2010).

3.3. Water management practices

Farms require sufficient infrastructure to ensure that all the water needs for the farm can be met by rainwater and private water supplies throughout the year. It is important in the context of reducing the energy and chemical burden of treatment that water quality is matched to usage requirements. Another important factor is uptake of innovations in water quantity management (e.g. Table 2), especially in relation to climate variability. A survey conducted by DEFRA on water usage management across all farm types (DEFRA, 2011) revealed contrasting decisions taken for efficient water use on a farm (irrigation, spraying, washing down, drinking water for livestock and other agricultural and non-agricultural uses). The actions were categorised as: (i) non-challenging (defined as actions that are easy to implement and at limited cost) versus: (ii) challenging (defined as requiring effort, time and additional costs) (Table 2). This survey revealed that many decisions were financially motivated, also that it was common for the farmer to change management based on his/her experience and knowledge (termed as applying 'operator judgement'). Other management aspects deemed 'non challenging' were use of sprayer and irrigation equipment, use of agronomic advisors and weather forecasts. It was indicated that there are barriers to uptake of water recycling innovations, soil moisture sensing, water balance and decision support tools. In terms of major activities for upland livestock farming of washing down handling areas and providing livestock drinking water there was limited indication of uptake of innovations in the survey. However, the study did not address the perceived or actual need relative to uptake for either generally farming or that specifically in the uplands.

Table 2: Challenging and non-challenging farm management practices for efficient water use (DEFRA, 2011).

Non-challenging water management	Challenging water management practice
High tech spray nozzles	Water recycling
Optimised irrigation systems	Decision support tool implementation
Agronomic advice	Water balance calculation
Other weather forecast / records	In-field soil moisture measurement
Operator judgement	Rainwater harvesting systems

3.4. Summary of water quantity management

- Water on farms is used for drinking for livestock, spraying, washing down livestock buildings and yards, sanitizing animal areas and slurry thinning (as well as for domestic use). On upland farms water for livestock drinking generally becomes a dominant use and alternatives to direct access of cattle to streams are preferred under current regulations.
- Large calculated water footprints for meat production in the uplands show that the livestock sector is reliant on the abundant rainfall in the uplands but that much of the water in the system resides in natural parts of the system, such as soils.

- Disruption to water flow and supply on livestock farms due to droughts can be costly and detrimental to the running of the farm, given that the daily water needs are generally high. Hence, water storage can be good to buffer short periods of drought.
- Cattle and sheep graze on grass and crops in the UK that rely on consistent rainfall during the growing season. Although rain is generally plentiful on upland farms, extended periods of soil saturation and drought can damage crops. There have been notable recent years (e.g. 2018) where soil moisture deficits have severely depleted the farming sector's reserves of feed during the subsequent winter period.
- Upland farm economics under the current Scottish climate do not require irrigation of crops. If prolonged droughts in future cause reduced feed yields overall then irrigation may become necessary and would be most likely be most needed for fodder crops.
- Any future irrigation use should use gravity fed systems (removing the energy input for pumping) and drip delivery direct to root zones (to be water efficient).
- There are real and perceived barriers to uptake of innovation in some potential water efficiency measures amongst farmers. However, in general the plentiful water supply in the uplands does not require water innovations to the same extent as, for example, lowland dairy farms where water scarcity is an issue (and/or metered water is prohibitively expensive).

4. What are the main sources of polluted water on a farm and how do we manage these?

Polluted water may be produced by runoff from fields (bringing sediment, nutrient and agrochemicals to watercourses). Wastewater is an additional contaminant source if allowed to mix with clean water, or discharge to surface waters. Managing wastewater produced on a farm from domestic, agriculture and livestock operations is vital to reduce nutrient and microbial pollution to watercourses. Mixing of wastewater and clean water (as often happens) reduces the potential usefulness of the resulting mix and necessitates energy and/or chemical inputs to purify all the water.

4.1. Pollution sources to water

On an upland farm fast runoff over land or paved surfaces is a major contributor to water pollution both from field locations (so-called 'diffuse' pollution) and the more discrete 'point source' locations such as livestock handling areas. In terms of diffuse pollution, a tendency towards higher rainfall amounts and intensity and more saturated soils can exacerbate erosive and energetic runoff in upland farming areas. These factors that readily drive runoff in the uplands can lead to large pollution loads to surface waters (Holden et al., 2017) when pollution source areas exist on farms, but in contrast can generate large volumes of clean runoff (that may dilute pollution downstream) if pollution sources are absent. Source areas in fields can comprise sloping soils left without vegetation cover, poached areas where animals congregate (for example at feeders) or access-areas at streams for drinking, and fields where fertiliser is excessively applied. The recent trend for chemical inorganic fertiliser use has been a decline in overall amounts used, with better targeting with respect to risky soils and crop requirements. However, poorly timed applications of chemical fertiliser and/or animal manures can still constitute active sources if interacting with runoff (Meyles et al., 2006). This may occur from improper management actions on wet/frozen soils, but more often when a convective rainstorm occurs after cultivation that is difficult to predict. Pollution sources in fields may be worsened by a switch to a riskier crop (e.g. fodder crops) instead of the lower risks associated with (semi-)permanent vegetation cover on soils, such as grassland.

Point pollution sources on the farm can comprise farmyard drains, field drains, septic tank discharges and animals accessing watercourses (Figure 3). These can pose direct pollution risks to adjacent waters by surface runoff and via drains (DEFRA, 2012; Environment Agency, UK, 2007).

Figure 3: Water flow around the farm showing potential pollution flow (brown arrows), best practice flow (blue arrows) and natural flow (green arrows), after DEFRA, (2012) and Environment Agency, (2007).

Figure 3 shows water flow around a farmyard and the measures that can be taken to prevent water pollution. For example, the oil tank is protected, pesticides are secured in a store, rainwater harvesting is used, a reed bed is constructed for cleaning up run-off from the yard, a pond is constructed to separate out the dirty water, and there is a slurry store. In this example, additional protection is needed to (a) divert the farm drain away from the stream, such as a buffer strip, and (b) to prevent livestock from having direct access to the stream, i.e. by erecting a fence.

The following upland farming activities have some associated risks to water quality subject to the stated caveats and control measures:

- Overstocking of livestock can be an issue. Despite overall declines in livestock numbers in Scottish upland farms over several decades, temporary overstocking of individual holding areas and fields can cause soil poaching, mixing with faeces and contributing temporary high pollution source zones. There may be also be incidences of poor animal husbandry leading to pollution sources (for example failing to remove dead stock).
- Slurry has massive potential to cause pollution if spread on to frozen or saturated soils when runoff is likely to initiate rapid transport. Slurry can also be spread too near watercourses and

boreholes and can be applied in excess of crop requirements. However, best management practices for spreading are well developed in terms of application timing (closed periods exist in Nitrate Vulnerable Zones), amounts (in nutrient budgeting that is effective generally for N balances) and set back zones from waters.

- Poor nutrient management is a general issue and can involve using fertilisers beyond crop requirements, through to poor practice in siting manure heaps. Advice, online guidance and tools exist to aid nutrient planning on farms. This includes interactions with other soil factors like pH where fertiliser is used, but a better course of action where acidity is a problem would be liming followed by more effective fertiliser usage.
- Stock access to streams produces localised points of polluted water along tracks and access points, and access along a whole field edge can lead to widespread bank erosion. Fencing is a good but expensive control measure for this kind of pollution.
- Sheep dipping with chemicals which are toxic to both the operator and the environment brings a risk of pollution. Full immersion dipping is now less prevalent than the use of applicator-applied 'pour-on' treatments. However, there are highly polluting outcomes from siting of dippers and hard-standings too close to surface waters. Other previous issues such as chemical disposal now have effective regulation and guidance.
- Land improvement including drainage goes together with intensification of land use and may be secondary to other polluting factors such as excess use of fertilisers. Much land drainage is historical as it has not been subsidised since the 1980's, but poorly carried out maintenance of ditches (e.g. by dredging and dumping of sediments) can be polluting. However, land drainage can be beneficial in terms of reducing soil saturation which reduces the likelihood of surface runoff and associated soil loss. However, soluble pollutants in runoff, such as nitrates and some pesticides, can be exacerbated by enhanced drainage pathways.
- Herbicides have limited usage in upland farming. Spraying, most commonly grassland herbicide treatments, will usually be carried out by trained operators in the employ of contractors who abide by current codes and legislative requirements, to minimise pollution risk.

To reduce the risk of causing diffuse pollution it is also important to understand water flows around fields and yards farmyard (Environment Agency, 2007; Holden et al., 2017; see also section 2.2). In addition to the measures outlined above, appropriate stocking/grazing of the available natural resources , reduction in the use of chemical fertilisers and pesticides and efficient use of machinery are some of the measures required to help conserve water, reduce water contamination from upland farming and conserve habitats (Clark et al., 2019).

There has been little work done to test the potential transfer of diffuse pollution management methods as developed in lowland landscapes and soils to the specific situations of many UK upland farms. More research is also needed on controlling the movement of water flow from peat and organo-mineral soils that are commonly present in upland farmed areas (see the review on soil and carbon that is part of this series.

4.2. Wastewater treatment from domestic buildings

Domestic toilet water and greywater disposal on upland farms generally uses the basic septic tank system, where domestic wastewater is stored in the tank for physical treatment (sludge settlement) and chemical and biological treatment (breaking down organic matter by enteric bacteria). The best practice is for resulting effluent to be discharged to an effective soakaway soil system that is a vital second stage for breakdown of organic matter and nutrient retention in a soil bed. Then accumulated sludge can be pumped out of the tank for disposal at durations depending on tank size and usage (every few years generally). A septic tank system is the favoured option for its low technology, low energy, low cost and practicality. Many older and failing septic tank systems exist in rural areas and tank registration is non-mandatory until a house is sold. Tanks may be cracked, and around 15% discharge directly to watercourses, which makes this a significant source of water pollution in upland farming areas. For saturated soils a mounded, designed system is meant to be built on the surface from infiltrating soils but this is not done except for new tanks. Tertiary treatment systems (using a powered aerator) allow effluent discharges to watercourses but are uncommon and require electricity.

4.3. Wastewater treatment from farm buildings

Where the amounts of dirty water created in farm operations pose an environmental hazard then dirty water from farmyards should be treated to an appropriate standard depending on the usage or discharge route. The primary treatment is settlement in a tank or lagoon, then further treatment can involve a constructed wetland, reedbed, aeration and filtration units to produce a cleaner effluent that may be recovered and reused if it meets the legal requirements (GPP 4, 2017; Abusam et al., 2015; Oliveira et al., 2018) or alternatively used for subsurface irrigation on non-food land (e.g. forestry and biomass production), fodder crop land, and in limited amounts for food crops such as cereals and oilseed rape (where they are not directly consumed).

1. Wastewater treatment ponds: Wastewater ponds can improve water quality through natural processes such as exposing pathogens to the environment (UV from the sun) and allowing particles to settle in the sedimentation process. Wastewater is usually allowed to settle in a first pond, while the water is drawn from a second pond. Variability in the settlement time of particles and die-off time of pathogens with differing particle sizes, densities and concentrations in the runoff means that treatment can be difficult to predict.

2. Filtration systems: Straining of effluent and the retention of pathogens, solid particles and metals using organic filters, slow sand filters, trench filter beds, reed bed and constructed wetlands. These systems produce good quality effluent for reuse for irrigation. The drawback of these systems is the requirement for regular management, regular washback of the filters and regular replacement.

4.4. On-farm use of materials of wastewater origin

Two sources of materials are considered here, namely: (a) the use (often considered disposal) of the wastewater and sludge created by containment of dirty water from the yards of larger upland farms; and (b) materials from the municipal wastewater treatment system brought onto farms for the purpose of supplementing fertilisers.

Sludge is generated during the containment of on-farm wastewater and is infrequently cleaned out from the treatment areas (maybe every 5-10 years, depending on source nature, storage volumes and flow rates). The handling of this material is like that of cattle slurry with application to land according to the Safe Sludge Matrix. Since it may be a relatively small volume compared with other available materials, like farmyard manure, the sludge is probably not a major component in farm nutrient planning; the main intention is disposal. After treatment that varies according to the level of infrastructure for containment present on the farm the liquid fractions can be applied to soils using similar techniques as cattle slurries. Using wastewater in irrigation is not a new concept and may contribute to reducing overall water wastage and conserve water supply (Novus Environmental, 2019), although as discussed earlier, this is unlikely to be of importance currently in upland farming. If untreated wastewater is used for irrigation the high content of pathogen and microorganisms (Matichenkov and Bocharnikova, 2016) means that specific best practice guidelines must be followed such as the Safe Sludge Matrix, to restrict use to certain crops and appropriate intervals after applications. There is limited data available on soil exposure to sewage effluent. More work is needed to validate the long-term effect of irrigation with sewage effluent on soil quality, microbial die-off, phosphorus mobility and accumulation in soil as well as the effect of sewage exposure on productivity of different crop species.

In some cases, municipal wastewater treatment sludge is available from a local source and treated to a sufficient level at the source (e.g. the Cambi-process generates a sterilised, accredited sludge cake) that becomes a viable option for fertiliser replacement. These types of sludge are rich in nutrients such as phosphorus, nitrogen, calcium, magnesium, sulphur and organic matter that can provide nourishment to plants, an enhancement to soil structure and increase soil ability to retain water through increasing soil organic matter (Bhadha et al., 2017). Composting of the sludge as a sanitizing step before applying to the soil is required to reduce the risk of contamination and safeguard public health. Composting is typically conducted on a large scale as municipal sludge, as opposed to the farm scale. Raw sludge application is not recommended in the UK, but in some countries applying raw sludge to agricultural land is practiced and is considered legal with crop restriction limitation (Clemett and Ensink, 2006). In Scotland, undigested sludge or septic tank sludge should not be applied on land used for food crops (PEPFAA Code and Safe Sludge matrix) and treated sludge must not be surface applied to grass for grazing.

Technology has been developed over the years to treat sludge (domestic and industrial wastes) to reduce pathogens, bacteria, heavy metals and odours as well as converting the waste into fertilizer (biosolids) with high nutrient content for plants growth. More research is needed to consider the biosolids suitability as a fertilizer, heavy metal removal, the safety of its use; for upland farm considerations of the upland soil context (e.g. soil type, leachability/acid conditions, background metal loadings, organic matter interactions etc) should be specifically considered.

One of the restrictions of using biosolids for agriculture is that farmers are required to demonstrate that they have taken steps to follow the Sludge use in agriculture regulations -1989 Great Britain and Northern Ireland 1990 (Farmers Weekly, 2020), including waste material testing and constraints of crop type and periods after application.

4.5. Summary of managing water pollution

- Water can be polluted by both point source and diffuse pollution.
- In the uplands, strong slopes and wet soils increase tendencies for surface runoff that can interact with pollution sources where present, both mobilising the pollution and carrying it distances to watercourses.
- Key diffuse pollution sources in fields include those to which fertiliser has been applied in excess of crop requirements, use of slurries in inappropriate amounts or weather, access of animals to watercourses for drinking and congregation points of livestock such as feeders. The ‘permanent’ vegetation cover of grassland limits soil erosion, but arable soils at the fringes of higher ground can be sources of soil loss.

- Point sources of pollution include farmyard drains, septic tank discharge and animal handling areas and tracks.
- Measures to slow and control the movement of flowing polluted water can be considered, such as: ponds to catch and retain runoff water and sediments; buffer strips to retain nutrients; and fencing watercourses to prevent animals fouling the water.
- Septic tanks are commonly used to treat domestic wastewater on upland farms but many are old and in poor condition.
- Some livestock farms will have systems for the containment and disposal to land of dirty yard water. This water is often considered a burden rather than a resource. Enormous storage is prohibitively costly but large volumes can accumulate during winter months such that spreading to land is required outside of periods of crop growth.
- Additional sludge materials may be brought onto farms from processing of municipal wastewaters. Where such materials have higher grade processing, they form a useful component of fertiliser replacement.
- There are established rules for the handling of sludges and slurries, their application to fields, and constraints on cropping following application.

5. How might runoff and water availability change under predicted climate change?

5.1. Water availability and drought conditions

Extreme weather events bring additional stresses for water management, which can be magnified in the uplands relative to lowlands (Soulsby et al., 2016). In a generally water-rich region such as Scotland, there is usually sufficient water to meet human needs and industry such as farming. However, climate variability, or extra water demands from farm expansion or new domestic residences can mean that during prolonged dry periods, water levels in reservoirs and boreholes drop and water resources become depleted in upland UK (Environmental Agency, UK, 2007; SEPA, 2020). Thus, conserving upland water resources and adapting water management on the large land areas capturing rainfall (especially those of upland farms), plus recirculation and water storage are all critical to protect the UK's and Scotland's vital natural water resources (Environment Agency, UK, 2008; SEPA, 2020). There are not many studies focused on quantifying the predicted impacts of climate change on water quality, as opposed to quantity, in upland areas.

The UK is considered a water sufficient country, with long-term average annual rainfall (2001-2019) for the whole UK and for Scotland of 1,429 mm and 1,567 mm, respectively (Met Office, 2020; Statista, 2020). Uplands have generally wetter conditions than lowlands and form the headwaters on which lower parts of catchments rely for water resources (including buffering against extreme low flow effects). Some of the slow to deplete water sources in the uplands (late snowmelt, or deep ground water) is important to mitigating extreme low river levels and associated ecological damage down catchments. In recognition of water scarcity events in Scotland, the Scottish Environmental Protection Agency (SEPA) has developed a water scarcity index of cumulative rainfall and average flow, to allow better planning and response to prolonged dry spells for agricultural water usage and abstractions from rivers (SEPA, 2020). The index utilises different time periods (30 days, 90 days and 180 days indices) to pick up any short-term rainfall and flow patterns as well as long term anomalies to assist with the early warning of water scarcity (Table 3). This helps SEPA to implement water saving measures such as reviewing existing authorised abstraction volumes, staggering abstractions within the catchment, temporarily suspending abstraction, switching to alternative sources, and perhaps compensating flows from dams.

Table 3: Water scarcity indices in Scotland, developed by SEPA to better manage water sources, (SEPA, 2020).

Indices	Purpose
30 days rainfall and flow	Managing abstractions from rivers including agricultural abstractions
90 days rainfall and flow	Early warning of possible water shortages and to assess supplies with shortage
180 days rainfall and flow	To assess cumulative impacts of longer-term events

5.2. Management against extreme hydrological conditions

Flooding due to heavy rainfall in the UK has increased in frequency in recent years during both summer and winter. For recent examples, flash flooding and landslides occurred in Scotland after intense storms in August 2020, and storm Ciara in February 2020 brought prolonged heavy rain and flooding to much of England and Scotland. The likelihood that heavy rain is transported down catchments and may cause flooding is intimately associated with land management practices that increase the rates of runoff being generated. Generally, water storage capacity is reduced and runoff rates exacerbated as soils are drained and compacted more and 'roughness' (trees and scrub vegetation) and field boundaries are removed (Holden et al., 2017; Marshall et al., 2009).

The specific action of soil wetness and drainage on flooding is complicated. Drainage, ditching, dredging and straightening of watercourses is part of the overall 'fast runoff response' attributed to landscapes that are improved for agriculture. However, field drains and ditches can also reduce soil saturation and thus trade lower surface runoff for faster pathways of deeper drain waters or channel water in open ditches. Keeping livestock outside during winter weather can lead to animal trampling and soil compaction that increases soil bulk density and reduces soil porosity, both of which lead to decreases in water infiltration rates, promoting more overland flow (Mcdowell et al., 2003; Cournane et al., 2010). However, a prevalent current livestock farming practice is for farmers to house cattle over winter, which reduces this problem (Forbes, 2019).

Reducing soil erosion and runoff has benefits for water quality and helps to reduce localised and nuisance flooding which can cause damage to roads, houses and farmlands. The threat of flooding may be reduced through implementing measures such as temporary water storage areas on agricultural lands in the uplands. This measure may also provide ecological benefits through reduced sediment runoff, soil carbon loss, and loading of nutrients to surface waters (Manale, 2000).

5.2. Wider climate implications for water and management

Well managed soils will help the uplands to adapt to the predicted hotter, drier summers and warmer or wetter winters. Implementing buffer strips containing natural vegetation such as trees and shrubs will become increasingly important to protect watercourses during wetter winters. Farm buildings may require increasing in area to accommodate stock indoors for increasing duration in wetter periods. Excess rainwater may require to be collected and kept clean for a wide range of uses during drought periods (Natural England, 2010).

Conserving usable water on the farm can be maximised when water conservation measures are accompanied by separation of clean and dirty water (SRDP, 2020). For example, clean water that is used in hosing down farmyards produces more dirty water. Therefore, where practical removing solid material before hosing can reduce the volume of dirty water, which can be collected and stored. Collecting clean rainwater and storing it for hosing down could save water, money and energy. A pressure washer instead of a regular hose can limit water volumes used. Roofing the slurry store could prevent contact with rainwater, reducing the amount of effluent produced and reducing greenhouse gases emissions. Field midden positions should be circulated and located away from watercourses, wells, springs and boreholes. Keeping livestock drinking troughs clean and leak free also reduces water losses (SRDP, 2020).

Weather conditions can influence water usage and activities on the farms. Unpredictable weather, wetter summers, frequent storms events and episodes of heatwaves and droughts interfere with farming activities in different ways. For example, wet weather hinders farmers in the uplands in timely cutting of hay and silage that impacts via longer, later sward use and reduced crop quality and usability. Although drier and warmer weather can produce favourable conditions for early harvesting and aids establishment of winter crops, prolonged heatwaves and soil water deficit with low levels of rainfall hinders plant growth, which means that less vegetation is available for livestock feed (DEFRA, 2017). In summary, many aspects of farming practices are affected now by shifting seasonal patterns in climate and water yield/availability. If trajectories of climate change intensify this may require new strategies to adapt to future climate-driven water extremes and consequences for potential detrimental outcomes such as water shortage, flooding, pollution or altered GHG emissions.

5.3. Summary

- In Scotland's uplands, there is usually sufficient annual rainfall to supply water for farming needs. However, shifts in the timing and intensity of individual rainstorms and periods of drought interfere with farming activities and alter environmental impacts of farming.
- Conserving upland water resources and adapting water management practices, capturing rainfall and water storage are critical to protect water resources. Such management in headwaters in the uplands is locally influential as well as impacting land and water down-river.
- Flooding risk, locally and in the neighbouring lowlands, has increased due to a general reduction of water storage areas, soil degradation and speeding of runoff response rates through soils, drainage and landscapes of the uplands. Natural flood management to promote water storage is particularly beneficial in the uplands where disproportionately more rainfall generates more runoff.
- In dry periods farm operations can be halted or delayed and crop quality affected. As with flooding, the uplands are a key zone in which natural processes (e.g. runoff vs aquifer recharge and snowmelt) and their management can alter the down-river impacts of low flows on habitats and water availability.

6. What options for change in/integration of water management systems do farmers have?

If climate variability continues to affect patterns in rainfall, then increasingly farm water management must include adaptation (altering farm operations to respond to the consequences of climate extremes) and mitigation (in turn reversing some energy/C-negative aspects of water management and guarding against worsening under future stress). Some of the possible actions are explored below.

6.1. Harvesting rainwater

Rainwater harvesting (RWH) is a way to engineer improved storage of rainwater in numerous discrete, localised ways (as opposed to one large reservoir in a landscape). The harvested water then is an alternative source that may alleviate water demand pressure and contribute to a sustainable future for the UK water resources and management. A rainwater harvesting catchment could be a roof of a building connected to a storage tank, or a collection pond at the top of the field, a trench or a clay or synthetic lined reservoir that stores rainwater on the farm. On an upland farm, rainwater can be collected at the top of the field where it does not require a pump and can be used for livestock drinking and irrigation facilitated by gravity. RWH can reduce the dependence on water supply from rivers and groundwater sources (Environment Agency, UK, 2009). Not only does RWH practice play a role in water security but also, it may reduce the risks of flooding (primarily surface water flooding): as the water storage tank is filled with rainwater, the excess water overflows into a soakaway, reducing the burden on storm drains (Domènech and Sauri, 2011). It is more economical (depending on the amount of water that can be used and the lifespan of the equipment) to use the harvested rainwater (AHDB, 2016; Ndeketeya and Dundu, 2018) for cleaning farmyards and buildings and reusing the resulting greywater for irrigation.

To install a rainwater harvesting system, consideration should be paid to the quantity and frequency of local rainfall, the size and the material of the rainwater catchment area (which in most cases is the roof of a building) as well as the storage and distribution system (AHDB, 2016). The area of rainwater catchment controls the amount of rainwater collected. The use of building roofs as rainwater collecting areas is preferred since roof runoff is considered cleaner than other surfaces such as trenches and draining gutters (Melidis et al., 2007). The storage tank can be buried under the ground or stored above the ground, with water holding capacity selected to be proportional to the farm water use and requirement as well as the annual rainfall and area of the rainwater collection catchment. A RWH system can be a simple system or a more complex and costly system with high energy consumption and carbon footprint (AHDB, 2016); the decision depends on the intended use of the stored water. A first flush diverter and filter system would be installed to ensure that cleaner water enters the storage tank, that is fit for animal consumption. An additional disinfectant process may be required such as chlorine addition or UV treatment to reduce bacterial accumulation during storage time, depending on the intended water use. RWH can have an impact on overall farm energy use and carbon emissions if the stored water is pumped to where it is needed around the farm (Environment Agency, UK, 2009). Therefore, the location of the RWH system should be considered in relation to the farm requirements.

An example is a dairy farm in Wiltshire that installed a RWH system to provide a supply of drinking water for 300 cattle. In this system, rainwater is collected from 2000 m^2 of barn roof via screening filters into a 50,000-litre underground storage tank. The water demand is fed through fine sediment filters and a UV disinfection unit before being pumped to 8 drinking troughs. A saving of over 2,400 m^3 of water was made from this system in the first 3 years and a reduction in peak times of runoff from the surrounding land was observed (Rainharvesting System, 2018). Energy and installation costs are not given but the system requires a primary and booster electrical pump. In their case the motivation was saving of the alternative water source of mains water and the storage necessary due to being in a relatively low rainfall area (750 mm annually).

6.2. Using renewable energy to reduce carbon emissions in water management

Modern technologies used in agricultural systems (lights, heaters, sensors and computers) can require considerable electrical power inputs which can limit their use in upland farms. Electricity supply may not be readily available on all parts of smaller farms and those in off-grid situations, as is common in the uplands, in which case fossil fuels are often used to drive water pumps and generators. Reducing fossil fuel use on remote farms can be achieved through better incorporation of alternative renewable energy into water management infrastructure, thereby contributing towards conserving water and energy and carbon emission reduction. Examples include solar photovoltaic cells, wind turbines, and hydropower that can all be used as localised supplies of power. In contrast, bigger renewable energy systems such as anaerobic digestion, biofuel, sewage gas are generally restricted to bigger lowland farms.

Solar power operated pumps in grazing fields (Figure 4) can be used to pump water from a nearby stream to fill livestock water troughs, for example, removing the need for cabling from the farm's other energy sources (e.g. national grid) (SRUC, 2017). Rainwater harvesting systems can also be operated by solar power pumps to transfer water to the point of use. Another low energy option for water management is a hydraulic ram pump, which has no moving parts, and is fed by a header tank which is a source of potential energy. A proportion of the water which flows through the pump is lifted to a higher-level storage cistern, while the greater proportion of the water is released through a waste valve into the natural environment. Maintenance costs are low and no electrical power supply is required.

Figure 4: Illustrates solar power operating pump to provide water to livestock away from water margins, taken from SRUC, 2017.

6.3. Conserving water resources and increasing water use efficiency: key points

It is necessary to conserve water supply and to reduce water footprint on a farm by adopting and observing a strict water management system (AHDB, 2016). The following points highlight some of the options and reasons for conserving water resources.

- Reducing overall water use must be considered. Many upland farms use spring or river water (AHDB, 2016), but during droughts, mains water is used if available. If using mains water, water losses should be prevented by identifying and repairing any leaks, which can be identified through the loss of pressure or water meter readings.
- Using alternatives, such as harvested rainwater, instead of more highly treated potable water for livestock drinking water and for cleaning farm buildings could reduce water footprint and overall farm costs (SEPA, 2020).
- Maintaining good soil condition that leads to increased infiltration, uptake of nutrients and reduction of runoff risk can increase crop yield for grazing and increase the efficiency of rainwater use.
- Increasing grazing efficiency and reducing time-to-slaughter by adopting a paddock-based, or rotational, grazing system to increase the quality of the forage grazed, leading to higher growth rates, can lead to an overall reduction in water footprint per kg of meat (AHDB, 2016).
- Providing animals with shade (e.g. planting trees) in hot weather can reduce drinking water requirements.
- Reducing the use of water for cleaning pens can be achieved by brushing out pens prior to washing.
- Growing livestock feed-crops with better water-use efficiency to reduce water use per unit of feed (AHDB, 2016). This also includes using improved crop varieties that require less water and/or are tolerant to drought (fodder beet, stubble turnips and chicory) and/or recover quickly after a drought. This may have the additional benefit of reducing detrimental impacts of climate change on crop yields.
- In regions with severe and repeated droughts, it is helpful to use livestock such as sheep that have adapted to hot and dry climates, such as crossbreeds that are used in water scarce areas of America and Australia.
- Timing infrequent applications of treated wastewater to soils to coincide with times of drought and low soil moisture.
- Undertaking training or meetings with advisors to explore mechanisms for more active farmer participation in water management can result in significant water savings (e.g. using climate data or sensors as part of decision support).
- Good farming practices, such as appropriate stocking levels to reduce poaching and soil compaction, are essential; additional measures are needed to avoid soil erosion and runoff of sediment and other pollutants into water (Natural England, 2010).
- A shift in the focus of upland farming from grazing livestock for meat production to grazing livestock to improve environmental benefits is considered desirable and is under consideration particularly in relation to the design of UK farm payment systems into the future (Clark et al., 2019).

7. Water management at Glensaugh

7.1. Background context of Glensaugh

Glensaugh is an upland livestock farm extending over 1000 hectares astride the Highland Boundary Fault on the edge of the Grampian Highlands with an altitudinal range of 160-450 m above sea level with an annual rainfall of 1040 mm. The farmed landscape covers hill ground comprising peaty and organo-mineral soils supporting moorland and rough grassland vegetation to the north of the Highland Boundary Fault. To the south of the Fault dominantly mineral soils support improved grassland and a limited extent of arable ground around the farm, then rough grassland extend up hill. The farm area sits in the headwaters of the North Esk Catchment (~750 km^2). The farm has been a site for water research for several decades as part of the Environmental Change Network (www.ecn/sites/glensaugh) originally motivated by the sensitivity of the upland vegetation, soils and freshwaters to acidifying atmospheric deposition. This research has shown some change in water quality associated with longer-term processes in dissolved organic matter, sulphate and pH.

Water Supply

Glensaugh is supplied by both mains (source Loch Lee) and a private spring, from which ~ 10 m^3 of water daily is pumped by a ram pump to a cistern c. 40m above the source. Well water is provided to livestock and is also consumed at Glensaugh Lodge. The private supply was installed in 1945 and repaired and reinstated in stages between 2002 and 2010.

Wastewater

Contaminated run-off from paved yards is collected in a lagoon within the steading complex. It is pumped from there to nearby fields where it is spread using a "rain gun". The process is beneficial during periods of soil moisture deficit. It is sometimes necessary to spread wastewater during winter months to prevent over-topping of the lagoon, but this is avoided if possible. There are no time restrictions ('closed periods') on the spreading of wastewater. The farm spreads this material as a matter of disposal with some useful benefits to supplement nutrient returns to fields. The sludge from settlement in the lagoon is manually removed about every ten years (requiring two days work). This is done during a soil moisture deficit period and the nutrient-rich material is spread on grazing land during its rest period.

Septic Tanks

A variety of non-centralised domestic wastewater systems are in use: (i) Cottages 10 and 11 and the Animal House are served by a packaged tertiary treatment system using an electrically powered aerator to reduce the effluent's biological oxygen demand (Klargester system). This higher level of treatment then allows the discharge into the field drainage system in Drive field (under consent from SEPA). However, these systems have been criticised for allowing P-rich effluents to enter watercourses. (ii) Glensaugh Lodge is served by a conventional septic tank which discharges to a land drain, and eventually on to a bracken-covered bank. No effluent reaches the burn. (iii) Cottages 4, 5, 6 and 6A are served by individual tanks, some of which have structural or soakaway problems. These are subject to a proposal to put in a combined system to serve these properties. The discharge would be to porous ground.

Environmental management of river corridors

Various water margins around the farm have been fenced off from animal access as part of riparian woodland planting schemes. Primarily this was to allow the trees to establish as part of the woodland benefits for the watercourse environment. However, a secondary benefit has been exclusion of grazing animals from marshy bottomland which tended to harbour *Fasciola hepatica* (liver fluke) and the exclusion has promoted a more sustainable usage of veterinary products in animal management.

Other water management infrastructure

The farm's spring water source does not require to be supplemented by collected rainwater. High rainfall periods present a problem through disposal of wastewater and the potential contamination of run-off to watercourses. The productivity of Glensaugh is good relative to many uplands during drier than average seasons when excess wetness does not hamper the land operations and crops and animals perform best. There is no present need for pumps and wider water infrastructure to be powered by remote or localised renewable sources such as solar-powered water pumps.

7.2. Summary of recommendations for Glensaugh

The issues and measures adopted for upland farm water management as reviewed by the current report were assembled and analysed against the current and future needs of the Glensaugh farm system. The main purpose was to identify the state of implementation of measures that were deemed as suitable at Glensaugh, then to highlight opportunities for additional management. The remit of this was not to look at the widest range of possible actions that may be needed against possibly uncertain futures (influenced by markets, technology change or climate) years ahead, but to focus on priorities over the next few years. This synthesis is given as Table 4.

From this, a set of future high priority and a set of medium priority management actions have emerged:

High priority actions:

- Improvements in degraded domestic septic tanks not recently already replaced.
- Developing further manure management including wider pre-treatments/handling before spreading (e.g. composting).

Medium priority actions:

- Provision of improved structures for the areas where winter feeders are sited for sheep (such as pads and areas where dirty runoff is diverted away from watercourses).
- Areas related to woodland expansion, namely: assessing any further improvements in winter shelter (mainly tree wind breaks) that can be incorporated as part of the overall increase in woodland on the farm. Associated again with strategies to increase woodland, examining any further role of the developing woodland as runoff interception zones to trap sediment and nutrients between fields and watercourses. Further to animal shelter and edge-of-field runoff control provided by woodland, increasing the woodland planting in riparian zones for overall improvements to the river corridor habitat and functions, with the noted side benefit of reducing incidence of liver fluke in livestock (thereby lowering veterinary chemical usage).
- Increasing the extent of water storage from the current spring source.
- Considering additional supplementing of chemical fertilisers with less-polluting soil amendments, subject to concerns about pollution such as micro-plastics that may be brought into the landscape with imported materials (e.g. shredded wrappers in food source derived fertiliser alternatives).

Table 4: Summary of the water management intervention options analysed for Glensaugh. This synthesis addresses a range of measures from the current review, their interactions with environmental and farming factors (shaded boxes), suitability to Glensaugh farm, stages of implementation and potential for additional management. A system of High (H), Medium (M) and Low (L) is used with a 'traffic light' notation indicating high (green colour) and medium (orange) priorities for near- future actions.

Issue main group	Possible actions and measures	Overall suitability for Glensaugh (H,M,L)	Water supply resilience	Pollution source reduction	Nutrient efficiency	Runoff management	Wastewater management	Reducing energy usage for	Soil carbon or GHG	Wider habitat benefits	Current implem-entation (H, M, L)	Specific issues with implementation (e.g. why adopted or not)	Priorities for additional interventions (H,M, L)
Livestock manage-ment	Managing livestock access to, or crossing of, watercourses.	L									L	Not an aspect with issues. Open hill land is naturally watered by many small springs and streams where access in low intensity and less likely to lead to contamination or bank erosion. Intensively managed grass fields are almost all trough watered with no stream access. In general riparian woodland is increasingly limiting bank access.	L
	Provide alternative drinking arrangements, for example, using pasture pumps away from water margins.	M									H	Most fields are already trough watered, fed by the spring system and storage tank.	L
	Good siting of supplementary feeders away from waters	H									M	There's a shortage of suitable winter feeding areas for sheep that do not have proximity to water courses or Loch Saugh. A concrete pad for managing feeding areas leads to congregation at that point and runoff despite the concrete managing soil	M

												poaching. Better to move winter feeding areas away from Loch Saugh.	
	Re-house livestock indoors in wet seasons.	H									H	Already done for cattle and some deer and sheep. Limited scope for further extension as demands don't require it.	L
	Appropriate stocking and grazing practices, including paddock and rotational grass that improves grass quality and growth rates	H									H	The principle of graze, feed, rest of grassland is becoming well established. Over-grazing is effectively managed as this would harm the ability of the plant community to regenerate. Instead, hard, short grazing and resting rotations are used.	L
	Providing animals with shade in hot weather to reduce drinking water requirements or outdoor shelter in winter to reduce feed requirements.	L									M	Winter shelter is more important than summer shade. All animals like summer shade when the weather is hot. Woodland expansion helps to provide wind breaks for shelter.	M
	Using breeding or stock replacement or altered seasonal stock management to introduce resilience in livestock for water stress, such as crossing with animals from world areas with drought issues.	L									M	Sheep breeds at Glensaugh cope well with the dry periods of the Scottish climate. Sheep management (stocking, weaning etc) changes annually according to climate.	L
Crop and soil managem ent	Undertaking *in-field* soil erosion mitigation including cover crops,	M									L	Farm fields are exclusively grassland already (no arable) and so additional in-field erosion measures are not required.	L

	permanent crops on vulnerable slopes												
	Undertaking *edge of field* pollution mitigation such as stablishing a buffer zone between crops and watercourses	L									M	Exclusively grassland fields already, which limits erosion sources. Additionally, we have planted trees on slopes between managed grassland and watercourses to trap silt and nutrients.	M
	Supplementing natural rainfall with crop irrigation during periods of soil moisture deficit	L									L	Large irrigation is not viable and very infrequently necessary. The rain gun/ wastewater system is used - dry periods are favoured for this, but system storage potential is the main issue.	L
	Using improved crop varieties that require less water or are tolerant to drought to reduce the impact of climate change on crop yields.	L									L	Drought is still not the norm at Glensaugh. Occasional use of grass seed mixes tolerant to low soil moisture – this could be scaled up if climate change warrants this in future.	L
Good overall environm ental condition	Steps to making or retaining water holding features aligned with Natural Flood Management in the landscape such as water ponding areas, natural channel forms and complex topography	M									L	In this complex topography and upland area many of these features are present anyway.	L
	Protection and enhancement of river corridors habitats and functions for water protection	H									H	Riparian planting noted elsewhere in this table, plus benefits for liver fluke from animal exclusion from wet valley bottoms. Many opportunities already carried out but several remain.	L-M

	Appropriate use of moorland management including restoring artificially-drained or eroding peatland and managing muir burn	H									L	There is limited artificially drained peatland that would require water table restoration. There are eroded peatlands on the NE side of Thorter Hill with opportunity to act to stablise and reduce erosion risk. Muirburn can create localised fast run-off scenarios, this is managed by burning cross-slope and mixing burning with rough heather.	L
Water manage-ment in farm infra-structure	Ensuring appropriate siting of gates and farm tracks so polluted runoff is not channelled towards water courses.	M									L	Hill tracks are allowed to grass over to reduce erosion. Otherwise track runoff is not an issue. Gates have been widened to reduce erosion pinch-points. Rotation grazing manages gate access frequency.	L
	Reducing the use of water for cleaning pens by brushing out pens prior to washing.	L									H	This is already being done.	L
	Minimising volumes of dirty water produced, via separation of clean- (rain) and dirty- water.	H									H	Roof-collected rainwater is already separately channelled to watercourses.	L
	Increasing storage capacity of private water supplies	H									M	The 25 m^3 water cistern (spring-fed) is an important asset. It would be useful to locate another tank at the eastern end of the farm and tackle some leakage in existing tank/pipes.	M
	Maintaining clean water-handling infrastructure including effective roof guttering, covered hardstanding and drains or other water collection.	H									H	Already being done. Clean roof rainwater is collected into a separate drainage system.	L

	Using rainwater harvesting system for livestock drinking water and for cleaning farm buildings.	L									L	Not required due to existing use of spring water with a low energy (passive) pump system delivering adequate supply to farm buildings	L
	Diverting the dirty water to a containment area for treatment and re-use.	H									H	Improvements have been carried out decades ago, including building the containment area that receives all yard runoff and diverting clean water away from the containment system.	L
	Higher levels of treatment of contained waters including installing reedbeds to treat farmyard runoff.	L									M	There was once a reed bed, which was inadequate due to the volume and level of contamination. The lagoon replaced this in 1995. Current treatment is the re-application to soils of the materials for resource reuse.	L
	Protecting oil and fuel storage tanks from accidental spillage to waters.	H									H	Already fully in place.	L
	Storing farm chemicals (pesticides and fertilizers) in secure stores located away from watercourses and drains.	H									H	Already fully in place.	L
Handling of wastes in relation to water and pollution	Effective system of domestic waste disposal to ensure reduction of risks to surface and ground waters	M									H L	A range of septic tanks are in use already, including enhanced treatment with surface water discharge (High current implementation level; column to the left). Older individual dysfunctional tanks are now due for replacement (Low current implementation). Hence overall High priority.	H
	Appropriate storage for slurries	H									NA	Slurry is not produced.	L

	Following best practice in application of slurries, for example incorporation after spreading	H									NA	As above.	L
	Appropriate storage of manure before spreading, including siting of heaps in fields and yards.	H									H	Manure is stored in a bunker in the steading. Runoff from the bunker is collected in the wastewater lagoon for spreading.	L
	Following best practice in application of manures, including composting and pre-treatment of manure before spreading.	H									M	Manure management is developing but more could be done. Storage area for manure allows separation by types and some type-specific management (composting).	H
	Incorporating existing on-farm supply of organic fertiliser use in nutrient budgeting	M									H	Done effectively already.	L
	Options to supplement chemical fertiliser use with wider recycled materials from off-farm sources are considered.	L									L/M	Could do more in this area but there are concerns with importing pollution such as plastics with outsourced amendments. At one time cambi cake (recycled sewage) was spread, but nutrient benefits have trade-offs with pollution and this is not done currently (considered more suited to arable fertiliser replacement). A main concern is not to take materials potentially contaminated with micro plastic.	M

8. Conclusions and options to take forward

Private water supplies and abstractions from streams are dominant supplies to UK upland farms. Sources in good environmental condition promote healthy water resources that maximise water's many uses and minimise energy and resource investment. Consideration should be given to measures that reduce the risk of fast runoff in the farmed landscape and the risk of clean water mixing with dirty water. During periods of drought there may be pressures on water supply sources.

Water on upland farms is dominantly used for livestock drinking rather than crop irrigation. With secondary uses such as washing down livestock buildings and yards, sanitizing animal areas and slurry thinning and spraying. Disruption to water flow and supply on livestock farms due to droughts can be costly and detrimental to the running of the farm. Animal feed production from crops relies on consistent rainfall during the growing season. In Scotland's uplands, there is usually sufficient annual rainfall to supply water for farming needs. However, extended periods of soil saturation and drought can both damage crops. There is no real need to irrigate field crops presently in the uplands. Water may be perceived as currently plentiful (rather too much at times) and hence there are real and perceived barriers to uptake of innovation in some water efficiency measures that may be required under future altered climate, amongst upland farmers. Shifts in the timing and intensity of individual rainstorms and periods of drought interfere with farming activities and environmental impacts of farming. Water management in headwaters in the uplands is locally influential as well as impacting on land and water down-river. Flood risk, water quality for habitat and public health are factors that unite the uplands with the downstream waterbodies in rivers and the coasts.

Water can be polluted by both point source and diffuse pollution and, considering the likelihood of fast runoff in the uplands, any pollution present can be carried readily to surface waters. Diffuse pollution sources include fields to which fertilisers have been applied beyond crop requirements, use of slurries in inappropriate weather, access of animals to watercourses for drinking, and congregation points of livestock. The 'permanent' vegetation cover of grassland limits soil erosion but climate change may increase the potential for arable crops at higher altitude and sloping ground may become more utilised, such that wider control measures may be required in future. Point sources of pollution include farmyard drains, septic tank discharge, animal handling areas and tracks. Measures to slow and control the movement of flowing polluted water can be considered, such as ponds to catch and retain runoff water and sediments, buffer strips to retain nutrients, and fencing watercourses to prevent animals fouling the water. These collectively have benefits for diffuse pollution, flood and runoff mitigation, and for habitat enhancement. Some larger livestock farms will have containment for dirty yard waters and it is vital that this is contained and kept separate from clean water that is effectively managed by covered areas and rainwater diversion to gutters and drains. Best practices for handling of manures, sludges and slurries are well-developed and should be followed. Steps should be taken to ensure septic tank systems are kept in good condition.

Farming practices are identified that benefit and others disadvantage water resources, habitats, water usage, embedded energy in water-related resources (e.g. wastewaters) and required energy/chemicals in water treatment. Many key management aspects are already established at Glensaugh and some are deemed unsuitable. Overall, the practices being carried out at Glensaugh are thorough in many respects and wise caution is in place regarding practices such as bringing out-sourced amendments onto the farm in case of pollution (e.g. from micro-plastics). Potential actions have been identified as medium or high priority through a simple tabular approach, informing future management decisions. The approach taken here can usefully be applied to any farm system to help identify areas where changes can most usefully be made to improve water management.

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