Riparian wetlands for enhancing the self-purification capacity of streams

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Abstract Best Management Practices (BMPs) are increasingly used to restore river water quality but design guidance is limited. An alternative approach to remediating diffuse pollution loads is to identify the most polluting high flows from pollutographs and hydrographs and spill these flows into riparian treatment wetlands for treatment before drainage back into the watercourse. The approach is demonstrated for two contrasting catchments in Scotland impacted by diffuse pollution. The Caw Burn receives industrial estate drainage with high suspended solids, hydrocarbons, BOD and ammoniacal-nitrogen concentrations. Applying the proposed design criteria demonstrated that the existing retrofit BMP system at the site is undersized (4950 m^2) compared to the required wetland area (11,800 m^2), but accommodating the additional area is likely to be expensive. The second case-study is Brighouse Bay where bathing waters are impacted by faecal indicator organisms derived primarily from livestock runoff. In this catchment the riparian wetland area required to retain runoff so that *E. coli* bacteria would die-off to concentrations below bathing water standards was estimated to be 3–6 ha (0.5–1% of catchment area). Further refinement and testing of the design approach is required, including consideration of other factors such as vegetation type, ownership and maintenance, to develop a more holistic approach to river restoration.

Keywords BMPs; design criteria; diffuse pollution; riparian wetland; Scotland

Introduction

The retrofitting of structural Best Management Practices (BMPs) to control diffuse pollution is an increasingly accepted priority area for remedial efforts to restore river quality (Campbell *et al.*, 2004). Many headwater or small tributary watercourses in urban areas and intensive farmland are already heavily modified, in terms of river engineering and hydrogeomorphology. Under the EU Water Framework Directive (WFD) (CEC, 2000) such watercourses may need restoration schemes which could provide opportunities to enhance self-purification capacity (D'Arcy *et al.*, 2007). Enhancement schemes for water quality improvements in the UK have been attempted, with initial efforts commonly characterised by the use of on-line, in-stream ponds and wetlands (Kay *et al.*, 2005a). Examples of this in southern England are the River Thame treatment lakes and the Bourne Stream ponds in Dorset. At the Caw Burn, Scotland, an offline pond/wetland was created to treat a proportion of storm flows (Heal *et al.*, 2005). Residence time for sedimentation is typically low and extremely brief at high flow conditions. More recent monitoring of diffuse source pollutants has shown that the greatest proportion of the load is carried at high flows and treatment of low flow is less important.

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Therefore, an alternative approach is needed. This paper explores the following proposal: spilling high flows into designed riparian treatment wetlands, which would seek to apply the treatment technology to the flow regime most significant for diffuse pollution, whilst allowing low flows to pass forward in the channel. Treatment would be by establishing conditions for settlement or filtration of suspended matter in the riparian wetland and for drainage back into the watercourse as the flow subsides. For many important diffuse source pollutants sedimentation is a primary treatment need, but the subsequent fate of the pollutants (e.g., oil and other hydrocarbons, and faecal indicator organisms (FIOs) and pathogens) in the treatment system is often a function of access to UV light or oxygen for degradation (D'Arcy *et al.*, 2007). Possible design criteria for this approach are discussed and explored with hypothetical worked examples for two contrasting Scottish watercourses impacted by diffuse pollution: the Caw Burn that receives drainage from an industrial estate and Brighouse Bay which is impacted by runoff from livestock farms.

Possible design criteria

Target diffuse pollution load

The target load for treatment needs to be identified from the watercourse's pollutograph and corresponding hydrograph: at what point should the spill onto the designed wetland margin be encouraged? For this exploratory paper estimates of high and modal flows have been used. The approach to treatment of the polluting load depends on the contaminants present. For example, in the Caw Burn, where contamination is mainly through suspended solids and associated pollutants (hydrocarbons), treatment would aim to allow settlement of pollutants and decay in the wetland area (possibly over a period of successive flood events, with some resuspension and loss back to the stream). Where FIOs are of concern, as in Brighouse Bay, treatment could be achieved by allowing sufficient retention time in a constructed riparian wetland for degradation or inactivation.

Flow requirements for protection of vegetation

Filtration through standing vegetation could be an important treatment process in riparian wetlands. Horner *et al.*, (1994) have reported that flow velocities greater than $0.9\,\mathrm{ft\,s^{-1}}$ ($0.27\,\mathrm{m\,s^{-1}}$) will knock over most grass and herbage and reduce settling of finer particles. Therefore in a riparian wetland the flow velocity (V) should not exceed $0.27\,\mathrm{m\,s^{-1}}$. From this the minimum width (W) of the riparian area can be estimated if the target flow (Q) and water depth (D) are known (equations 1–3):

$$Q = V \times A \tag{1}$$

$$A = W \times D \tag{2}$$

Rearranging equation 2 in equation 1 and rearranging for $W \Rightarrow W = \dfrac{Q}{V \times D}$ (3)

Settling velocities

The riparian wetland needs to be sized to allow sufficient time for settlement of suspended pollutants. The shallower the flooded area, the shorter the time required for sedimentation. For the target wetland flow and width (determined from equation 3) the settlement time can be used to determine wetland length. Particle behaviour is subject to various factors. For example, even if a well engineered riparian wetland could be established, turbulent flow is more likely than laminar flow, with consequent poorer sedimentation and increased likelihood of resuspension. This is less of an issue in a parallel oxbow pool system than in a riparian flood marsh, especially if flow distribution baffles are provided. Particle shape and aggregation also affect settlement time. Stokes' law estimates the falling velocity of particles that are assumed to be individual and spherical. Estimating the settlement time of aggregates and irregular particles is more complex, but generally fall velocity increases, and therefore settlement time decreases, for aggregates (Table 1).

Habitat

A mosaic of habitats provides the greatest biodiversity benefits and also opportunities for species to survive shock pollution events (SEPA, 2000). Such a mosaic could be included in the design of riparian areas in a number of ways: as a gradient across the width of the area from the low flow channel; as a deep pool within a flood plain, replicating the habitat of an oxbow feature; or as irregularities in the distribution of areas of higher ground which would replicate natural irregularities in the deposition of heavy material in extreme events, but increase the likelihood of turbulent flow and its negative effects on sediment behaviour. Compliance with the target velocity through the riparian wetland and a maximum inundation depth close to the low flow channel of 0.3 m, grading to zero at the terrestrial edge, should allow establishment of semi-natural vegetation. Good ecological condition could be compromised by structures such as access routes to facilitate sediment removal or an overflow spillway in the river channel. In Scotland these structures would probably require licensing by the Scottish Environment Protection Agency (SEPA).

Method summary

From the above design considerations the possible dimensions of a riparian treatment wetland of width (W), length (L) and area ($A = W \times L$) can be estimated. Where the depth of inundation (D) does not exceed 0.3 m and the width and depth of the channel are considerably smaller at low flows compared to high flow conditions, W can be calculated by substituting these values in equation 3:

$$W = \frac{Q}{0.3 \times 0.27} \tag{4}$$

Q is the flow at which treatment of diffuse pollution will be most effective and is ideally identified from storm hydrographs and pollutographs for the specific watercourse. To estimate the length (L, m) of the riparian wetland that would be required for sedimentation (ignoring possible filtration processes in the vegetation), the settlement time (T) first has to be estimated from equations 5 and 6, assuming a settlement velocity (V_s, m s^{-1}) (values can be taken from Table 1) and that D is 0.3 m.

$$V_s = \frac{D}{T} \tag{5}$$

Rearranging equation 5 for T and substituting for $D \Rightarrow T = \dfrac{0.3}{V_s}$ (6)

Table 1 Comparison of settling velocities of individual particles (Stokes' settling velocity) and aggregates (after Mehta *et al.* (1989) and Novotny and Olem (1994))

Original particle diameter (μm)	Stokes' settling velocity (m s^{-1})	Aggregate settling velocity (m s^{-1})	Aggregate diameter (μm)
20 (fine sand/silt boundary)	2.4×10^{-4}	2.7×10^{-4}	88
2 (clay/silt boundary)	2.4×10^{-6}	1.7×10^{-4}	56
0.2 (clay)	2.4×10^{-8}	1.1×10^{-4}	34

From the calculated T and knowing that the maximum allowable flow velocity (V) of water in the riparian wetland is $0.27\,\mathrm{m\,s^{-1}}$, the wetland length can be estimated from equations 7 and 8:

$$V = \frac{L}{T} \tag{7}$$

Rearranging equation 7 for L and substituting for $V \Rightarrow L = 0.27 \times T$ (8)

Caw Burn case study

Background

The Caw Burn, in central Scotland (55°51′N, 3°30′W), has a long history of diffuse pollution, principally from hydrocarbons, detergents, BOD and ammoniacal-nitrogen, arising from surface runoff from a separately sewered industrial estate which was constructed over the burn's headwaters from the 1960s. To reduce the pollution load to the burn, in 1996 a retrofit BMP, comprising an off-line settlement pond and overland flow zone/wetland, was constructed where the burn emerges from a culvert beneath the industrial estate. The system was designed to treat low flows and the first pollution flush during storm events by diverting a maximum of $0.425\,\mathrm{m^3\,s^{-1}}$ flow from the burn. The system was designed pre-national guidance, with a limited budget and sized according to land availability. In 2004, the BMP performance was assessed and structural and maintenance improvements identified that are likely to improve water quality to at least class B (fair) (Heal *et al.*, 2005). Although a 2 km reach of the burn downstream improved from class D (seriously polluted) to class C (poor) after BMP construction, the system is considerably undersized compared with current guidance (CIRIA, 2000). The main priority for remedial work is increasing the BMP storage volume and hydraulic retention time by increasing the riparian area for treatment. The design criteria discussed above were applied to estimate the riparian area required to improve treatment of diffuse pollution in the Caw Burn.

Flow regime

Since no flow data are available for the Caw Burn, the modified rational method was used to estimate peak flow (Q_p) for rainfall events of different intensity (Table 2). From the estimates of peak flow and velocity (V_p) and using the channel width (W_c, m) of the burn at the culvert of 3.6 m (and ignoring the effects of sediment bars in the culvert), the water height in the channel was calculated for the different rainfall events (Table 2) using equation 3 rearranged for H.

Riparian wetland dimensions

Hence, if a wetland is to be designed for treating flows at the Caw Burn associated with heavy rain, then, at a stage height of 0.74 m and greater, the flow should be able to spill out of the channel onto the riparian land. The current treatment system was designed to

Table 2 Estimates of peak flow, peak velocity and channel water height for the Caw Burn

Rainfall event	Rainfall intensity (mm hour^{-1})	Peak flow (Q_p, m^3 s^{-1})	Estimated peak velocity[a] (V_p, m s^{-1})	Water height in channel (W_c, m)
Light/steady rain	2	1.00	0.50	0.56
Heavy rain[b]	4	2.00	0.75	0.74
Significant storm[c]	12	6.00	1.50	1.10

[a] From field observation; [b] Defined as 4 mm hour^{-1} or greater by the UK Meteorological Office;
[c] 60 minute storm of 5-year return period (M5-60 storm) for the Edinburgh area

take a maximum flow of 0.425 $m^3 s^{-1}$ and therefore appears to be insufficient to treat pollution during heavy rain conditions. The dimensions of the riparian area required to treat the Caw Burn flow during heavy rain, without flattening of vegetation and allowing settlement of suspended matter, were calculated from the design considerations discussed above. Substituting the peak flow value during heavy rain of 2.0 $m^3 s^{-1}$ in equation 3 (assuming adjacent riparian land will flood to a depth of 0.3 m), the width of the riparian area required is 25 m. To calculate the length required for sedimentation (ignoring possible filtration processes in the vegetation), first the settlement time (T) was estimated to be 29.4 minutes from equation 6, assuming a settlement velocity of 1.7×10^{-4} m s^{-1} (intermediate value for aggregates from Table 1). Substituting the value of T in equation 8, the wetland length was estimated to be 476 m, giving a total wetland area required of 11,800 m^2 (to 3 significant figures). This is more than double the total area of the existing Caw Burn BMP (4950 m^2) and, although there is some additional land potentially available on the other side of the burn, the area (~1500 m^2) is insufficient to accommodate the additional wetland area required. An alternative, but expensive, means of creating additional riparian area for treatment would be to daylight the culvert upstream. The volume of the wetland required is 3540 m^3 (11,800 m^2 area × 0.3 m depth), slightly smaller than the total design volume of the existing system (3790 m^3). However some of the design volume of the existing system has been lost through sedimentation (estimated to account for 150 m^3 in the settlement pond) and biomass accumulation in the overland flow zone.

Brighouse Bay case study

Background

Brighouse Bay is an identified coastal bathing water in southwest Scotland (54°48′N, 4°7′W), and is subject to the requirements of the 1976 EU Bathing Water Directive (CEC, 1976). There are no direct inputs of human sewage to the Bay but it does receive drainage from an agricultural area used for livestock farming and this is thought to be the principal cause of poor bathing water compliance with microbiological standards. The site has been used for research in which a series of remedial measures have been applied to one catchment (the Brighouse Burn) and compared with a control catchment as reported in Kay *et al.*, (2007). As part of these investigations a spatial survey of bathing water quality around the beach was undertaken during two time periods on 19 August 2004 following a storm event on 18–19 August and the results for *E. coli* are shown in Table 3. It is clear from these data that the beach is affected by high flow events and that *E. coli* concentrations exceed current and proposed standards for bathing waters.

Table 3 *E. coli* concentrations (100 ml^{-1}) in Brighouse Bay during the passage of the high flow event, 19 August 2004 (source: Kay *et al.*, 2007)

Sampling location	Sampling period 1 (13.00–15.00 GMT)	Sampling period 2 (15.30–16.50 GMT)
100 m west of stream input	1091	3273
50 m west of stream input	1909	5364
Adjacent to stream input	8182	11,818
Stream water prior to input	70,000	70,000
50 m east of stream input	3273	2541
100 m east of stream input	1400	10,727
150 m east of stream input	200	4072

Design of wetlands to treat FIOs at Brighouse Bay

Treatment could be attempted by storage of high flow event waters in a flood retention wetland as used for other UK bathing waters (Kay *et al.*, 2005b). UV light is bactericidal and retention wetlands reduce FIO concentrations through sedimentation and die-off. Marine decay rates, expressed in terms of the time for 90% of the FIOs to disappear (T_{90}) were reported in Kay *et al.*, (2005c) who observed very low rates of enterococci die-off in highly turbid UK estuarine water. T_{90} values for irradiated tanks of sea water ranged from <10 hours for low turbidity sea waters to >80 hours for more turbid waters. Decay rates for coliform organisms would be slightly more rapid and a range of 5–80 hours is envisaged. The total discharge volume of the Brighouse Burn during the August 2004 event was 6548 m^3 discharged over an 18 hour period. For compliance with 100 *E. coli* 100 ml^{-1} and with a 2004 bathing season geometric mean event concentration of 26,800, three T_{90} cycles would be needed, i.e. 15–240 hours retention (ignoring diurnal T_{90} variability). It should be noted that T_{90} is highly variable and likely to increase under overcast conditions when the received dose of UV radiation would be much lower than under direct sunlight.

If a flow diversion structure could be built to route all high flow water to a retention wetland, then the wetland volume would be determined by the storm volume and the number of storms requiring storage. For single storm storage perhaps 10,000 m^3 would be needed or a wetland area of 3 ha, assuming a mean water depth of 0.33 m. If it were intended to route all flows through the retention wetland then a much larger volume would be required because the volume of baseflow for the retention period (both before and after the storm) must be added to the constructed volume. The baseflow discharge in the stream was 0.014 $m^3\,s^{-1}$ which for a 15 hour retention period would produce 756 m^3 and for 240 hours would produce 12,096 m^3. Thus, for a through-flow system the required size would be 7304–18,644 m^3 depending on the assumed T_{90} value. These figures represent the minimum requirements and it would be prudent to construct baffles in any free water areas to prevent preferential flow of polluted waters, particularly if the design was to take the baseflow component following input of high flows. The wetland treatment option would therefore involve a significant land take of ~3–6 ha (i.e. approximately 0.5–1% of the 647 ha catchment area) but could produce a stream discharge to sea within bathing water quality standards.

Discussion

The results presented for the two case studies above give approximate dimensions of the riparian wetland areas that might be required to treat contaminants within specific catchments. More generally it would be useful for initial options appraisal exercises to have a rough index, perhaps through a "wetland area:modal flow ratio", for the amount of land take that may be associated with riparian wetland creation. This index would be a prerequisite for then commissioning catchment and site specific design of appropriate systems.

The approach discussed above is extremely simplistic and many other engineering, ecological and maintenance factors need to be considered in the design of riparian treatment wetlands. At some sites the treatment area could simply be an area of land through which the watercourse passes and that floods gradually as flows rise. However the configuration at other sites might require some engineering to cause overflow from the channel into the wetland. Appropriate and sustainable engineering structures and practices would therefore need to be devised which have minimal impact on site biodiversity. More specifically, engineering and geomorphological expertise is required to address questions such as: can meanders be designed which effectively pass forward flows and also cause overflow to the treatment area at the optimum point on the pollutograph?

Should an overflow area, perhaps by analogy with an oxbow lake, receive the high flows from a single low point in the river bank and the treatment area be designed as a parallel flow alongside the river but behind the river bank, with excess flows returning *via* another cut in the bank downstream? The overflow area created would need to be vegetated to maximise pollutant removal and degradation. Care would be required in locating the exit point for high flows from the river, since a poorly located point would probably be subject to frequent damage at high flows and have higher maintenance requirements.

There is considerable debate about whether riparian wetlands should be designed to hold a permanent pool of water. A permanent pool in at least some of the area is desirable for many reasons (minimising preferential flows and erosion, pollution treatment, increased biodiversity), but has the disadvantage of attracting large waterfowl colonies. If there is a permanent pool of water, how deep should it be at normal (pre-spill) flow conditions? The role of trees and vegetation management are also topics of debate with regards to treatment wetlands. Degradation by sunlight is an important treatment process for some contaminants (e.g. FIOs) but it is not known to what extent this process is impeded by wetland aspect or shading by trees and buildings. Can trees be planted in the riparian area and what effects might they have on flows and self-purification processes? The advantages of trees are that their roots would help bind sediment together and the litter input would form a carbon source for microbial degradation of pollutants. However vegetation management is likely to be an important maintenance consideration and might require large efforts to arrest vegetation succession. NGOs with experience of wetland management (e.g. the Royal Society for Protection of Birds) might be able to contribute to design guidance in this area.

Another maintenance requirement for riparian treatment wetlands is likely to be sediment removal. If sediment removal is anticipated within the design lifetime of the wetland then the design should include appropriate provision for access. A sedimentation pool close to an initial overflow point from the channel could be incorporated to collect heavier sediments that may be the bulk of deposited material and thereby reduce the maintenance needs of the entire wetland. Such a pool would also provide some means of controlling pollutant spills. Sedimentation rates expected in riparian wetlands in Scotland are $0.4-1.9\,\mathrm{cm\,y^{-1}}$ based on measurements in the Caw Burn settlement pond (Heal *et al.*, 2005) and SUDS ponds draining residential urban catchments in central Scotland (Heal *et al.*, 2006). If the higher rate of sedimentation occurs in wetlands of maximum water depth 0.3 m, then sediment removal will be required in the absence of other sediment control methods to prevent the system from clogging and becoming ineffective within 15 years. The principal costs associated with sediment removal are excavation and disposal of the sediment removed. These costs will vary considerably depending on ease of access to the wetland and the physical and chemical composition of the excavated sediment. Relatively clean sediments could probably be disposed of by spreading along the margins of the wetland area for dewatering and incorporation into the soil whereas contaminated sediments might require costly disposal to landfill. Related to maintenance is the question of ownership of riparian wetland treatment areas. In an urban stream context, ownership would probably be a matter for the local authority, whereas for farm ditches or small tributary streams affecting bathing waters, ownership by the farm/farmers would be most appropriate. In order to comply with Scottish legislation that implements the WFD licensing of riparian wetland treatment areas by SEPA would probably be necessary.

Conclusions

The design criteria presented here for approximate sizing of riparian treatment wetlands have been demonstrated to be readily applicable to catchments with different diffuse pollution problems. Although the approach is simplistic it could form the basis for initial assessment of the wetland area required using minimal information. Such methods are needed to meet the increasing requirement for river restoration, e.g. under the WFD of rivers that are heavily modified and/or impacted by diffuse pollution. Further refinement and testing of the design approach is required, including consideration of other factors such as vegetation type, ownership and maintenance. Riparian wetlands have been the focus here but other actions can also enhance self-purification in watercourses, for example: aeration associated with riffles and the daylighting of streams formerly contained within culverts; UV light penetration also associated with taking watercourses out of culverts; and preventing un-natural numbers of waterfowl using riparian wetlands and on-line pools and adjacent grassland, especially in urban areas. The development of a more holistic approach to river restoration requires a rationale for including all these considerations.

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