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Work Package 2

CHANNELISATION RECOVERY ASSESSMENT

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EXECUTIVE SUMMARY

1 Channelisation in Ireland

1.1 River flooding and unsatisfactory land drainage are problems of major significance in Ireland. Inadequate drainage has been cited as one of the major limiting factors in achieving maximum agricultural output from the land

1.2 The principal legislation relating to drainage in ROI was the Arterial Drainage Act 1945, and in NI was the Drainage Act 1947

1.3 Arterial drainage has generally involved the deepening and widening of river channels to increase their capacity to contain flood waters and to provide an outfall for drainage from agricultural lands

1.4 There is a statutory requirement for the relevant authorities in both parts of Ireland to maintain drained channels

1.5 Changes in EU policy with regard to agricultural production have reduced the demand for land drainage

1.6 The authorities responsible for drainage maintenance have adopted a revised approach with the development of working practices to minimise ecological disturbance

2 Effects of Channelisation on the River Environment

2.1 Undisturbed rivers are in a state of equilibrium with the surrounding environment and are characterised by a variety of morphological features, the range and type of which are determined by fluvial processes

2.2 Plants, invertebrates and fish are key features of the aquatic community with specific habitat requirements related to the natural diversity of the river environment

2.3 Channelisation results in major modifications to channel morphology through engineering works to produce a structurally simplified and hydraulically efficient channel

2.4 In the short term the entire ecology of the river environment is seriously disrupted and impaired

2.5 Key ecological impacts are a reduction in habitat diversity, increased sediment loads and changes in flow regime

2.6 In certain circumstances a drainage scheme can have some positive effects on fisheries

3 Studies on Impacts and Recovery

3.1 Many US studies have shown that channelisation can have serious biological impacts with severe reductions in fish abundance and diversity

3.2 Studies on Irish rivers have shown that drainage works are extremely disruptive to stream ecology in the short term, but that some channels can recover fully

3.3 Channel gradient is a key factor in the recovery process, in facilitating the erosion of coarse materials from the riverbanks and the distribution of bed materials, to re-establish a riffle-glide-pool sequence

3.4 Studies on British rivers have demonstrated that non-salmonid species with different habitat requirements can be seriously impacted by channel works in both the short term and the long term

3.5 Effects on aquatic flora can range from complete removal to changes in species composition and diversity associated with altered substrate and flow conditions, particularly in low gradient channels

3.6 Invertebrate abundance and diversity are typically reduced by drainage works due to direct removal, alterations in substrate composition, flow regime and sediment deposition

3.7 The Experimental Drainage Maintenance Programme has shown that it is feasible to adopt environmentally sensitive procedures in channel maintenance while meeting the objectives of restoring conveyance

3.8 A new Environmental River Enhancement Programme is being implemented by OPW and will focus on both capital river enhancement works in drained channels, and an enhanced drainage maintenance programme

4 Effectiveness of Physical Rehabilitation / Enhancement Works

4.1 River enhancement through physical rehabilitation works originated in the US during the 1930s. Rehabilitation projects have now been undertaken in many parts of Europe including Ireland

4.2 The physical effects of drainage in Irish salmonid rivers have led to:

- seriously reduced capacity of small streams to support 1+ and older fish
- reduced spawning opportunities
- reduced frequency of pools for adult fish

4.3 Monitoring of river rehabilitation projects in ROI has shown that channels which have been subject to arterial drainage schemes can be enhanced significantly

4.4 Enhancement of small spawning and nursery streams (basewidth <3m) is very effective in relation to increasing 1+ year-old trout carrying capacity

4.5 Enhancement programmes in larger channels (3m to 6m basewidth) is very effective in relation to 1+ year-old trout and also 1+ year-old salmon parr up to the springtime period of their second year

4.6 The enhancement of larger channels (>6m basewidth) is a successful process in relation to increasing standing crop of both 1+ year-old salmon and trout, and adult trout

4.7 Restoration of the natural morphological form in channels can also enhance salmonid spawning opportunities, increase fish food production in certain circumstances, and increase angling opportunities for trout and adult salmon

5 Timescales for Biological Recovery

Natural Recovery

5.1 Surveys have shown little recovery in morphology of many drained channels up to 60 years after drainage works

5.2 Natural biological recovery after channelisation is entirely dependent on morphological recovery

5.3 A variable period of morphological and biological adjustment takes place during which channel processes operate to recreate lost characteristics such as the riffle-glide-pool sequence

5.4 Ecological recovery is largely dependent on channel gradient and immediate subsoil characteristics, but documented timescales of recovery are highly variable

5.5 Higher gradient channels can recover significantly after 2-3 years with full recovery over a period of up to 7 years

5.6 The process of recovery can be inhibited or set back according to the extent and frequency of drainage maintenance operations

5.7 Lower gradient channels do not generate sufficient energy to scour materials from the riverbed and banks, and are the most seriously affected in the long term by drainage schemes

5.8 Lower gradient channels typically have a more frequent maintenance requirement (3 to 5 years) due to increased siltation and macrophyte growth

Enhanced Recovery

5.9 Although high gradient channels often have the potential to recover quickly, there can be imbalances in the riffle-glide-pool sequence or an impoverished riparian zone. Intervention in the form of restoration programmes is required to facilitate ecological recovery in these areas

5.10 The proximity of potential colonising species to enhanced areas is an important factor in the rate of colonisation

5.11 Benthic invertebrates can colonise enhanced sections rapidly and a stable invertebrate community can be anticipated 3-4 years after enhancement

5.12 Macrophyte recovery after physical enhancement works may be a gradual process lasting several years

5.13 Fish populations can recover significantly within a year of enhancement works, but optimum stocks may not be realised until 3-5 years after the works stage

6 Case Studies

6.1 Data are presented from the Ulster Blackwater and the River Maine to illustrate the impacts of channelisation works on selected features of river ecology and channel processes

6.2 Historical data indicates that there was a significant elevation in suspended solids and the level of sediment transport during the Blackwater Drainage Scheme

6.3 The macrophyte community of the Blackwater at a selected location appears to be undergoing a process of recovery in line with the changing physical characteristics of the channel. The marginal and bankside species were the first to recover, and the site is now dominated by a limited range of species, in contrast to the relatively species-rich assemblage observed on the un-drained R Finn.

6.4 The persistence of these impacts on the macrophyte community more than 15 years after completion of the drainage scheme indicates that ecological recovery in this area of the catchment may take many years.

6.5 A comparison of two tributaries of the R Maine would suggest that the impact of drainage on the lower reaches of the Braid appears to have persisted for more than 40 years in a relatively high gradient area.

6.6 Morphological recovery in this stretch of river appears to be an extremely slow process, possibly due to excess widening of the channel. This is reflected to some degree in the salmonid fish populations.

1 BACKGROUND

Morphology pressures have been identified across many EU member states as exerting significant pressures which might result in waterbodies failing to achieve their WFD status objectives. With regard to historical channelisation and dredging works, and ongoing maintenance dredging in Ireland's rivers, there is uncertainty as to the long term impacts of these activities on river morphology and ecology. The National Article 5 Characterisation report, completed in March 2005 in compliance with the EU Water Framework Directive, stated that this uncertainty would be investigated post initial characterisation.

The objectives of this assignment (Work Package 2) as part of the Freshwater Morphology Programmes of Measures and Standards (POMS) Study, are to use fish stock and other biological data to establish recovery rates of fish and other populations following channelisation works, and to establish the effectiveness of habitat enhancement measures.

The major part of this report takes the form of a literature review on the impacts of channelisation on river morphology and ecology, with an emphasis on the recovery of fish populations, but also considering recovery of the aquatic community in general, with particular reference to benthic macroinvertebrates and aquatic macrophytes. The report also includes worked examples from specific case studies to illustrate the impacts of channelisation works on selected features.

Specific aspects of the study were undertaken by the Central Fisheries Board, the results of which are included in summary form, and contribute significantly to the conclusions on the effectiveness of enhancement works and timescales for biological recovery.

2 INTRODUCTION

The term channelisation (or arterial drainage) encompasses a range of river channel engineering works employed to control floods, improve drainage, maintain navigation or restrain bank erosion (Brookes, 1989).

River channel works have most frequently been undertaken to improve land drainage and reduce the frequency of flooding of agricultural land. In both cases these objectives have been achieved through modification of two principal components of the fluvial system: channel capacity and the flow of water within the channel. This generally involves four main activities:

- Channel widening
- Channel straightening
- Channel deepening
- Removal of instream obstructions and bankside vegetation

In addition, when channel works have been carried out to give flood protection, the excavated materials have often been used to construct flood embankments for increased containment of flood waters.

Many drainage schemes in the US, and to some extent in Europe and Britain, have involved diversion of the river into a newly excavated and largely straight channel. In contrast, the major schemes carried out in Ireland since 1945, for the most part, followed the original course of the river and did not result in widespread straightening and realignment of rivers.

Although these procedures can be described collectively as “channelisation”, the term “arterial drainage” more accurately describes the approach which has generally been adopted in Ireland. This approach is often referred to in the US as “channel clearance” rather than “channelisation” (Kennedy *et al* 1983).

After arterial drainage there is a resumption of natural hydrological processes and a gradual move towards the re-creation of lost characteristics (Keller 1978). However, the implementation of a drainage scheme usually infers future channel management or maintenance operations. This may include renewed dredging, clearance of aquatic and bankside vegetation and other instream obstructions to reduce the roughness of the channel and improve conveyance. Indeed there are statutory obligations on the relevant authorities in both parts of Ireland to maintain drained channels. This is a highly significant factor in considering the impacts of drainage and ecological recovery as, if not carried out in a sensitive manner, maintenance works have been recognised as being potentially more disruptive to fish life than the original capital works (McGrath 1985), and can interfere with the process of natural recovery (Inland Fisheries Commission 1975; Brookes 1992).

3 CHANNELISATION IN IRELAND

- River flooding and unsatisfactory land drainage are problems of major significance in Ireland
- Inadequate drainage has been cited as one of the major limiting factors in achieving maximum agricultural output from the land
- The principal legislation relating to drainage in ROI was the Arterial Drainage Act 1945
- The principal legislation relating to drainage in NI was the Drainage Act 1947
- Arterial drainage has generally involved the deepening and widening of river channels to increase their capacity to contain flood waters and to provide an outfall for drainage from agricultural lands
- There is a statutory requirement for the relevant authorities in both parts of Ireland to maintain drained channels
- Changes in EU policy with regard to agricultural production have reduced the demand for land drainage
- The authorities responsible for drainage maintenance have adopted a revised approach with the development of working practices to minimise ecological disturbance

3.1 The need for land drainage

River flooding and unsatisfactory land drainage have long been recognised as problems of major significance in Ireland (Lynn 1980). These problems are not caused by exceptional rainfall, but by the topography of the country with mountainous areas around the coast and a flat central plain. Many rivers with their sources on the inland side of this mountainous rim flow towards the centre of the country, with low gradient floodplains and extensive areas of flat, low-lying ground (Harris *et al* 1984). Many of these rivers also follow circuitous, roundabout routes to the sea (Howard 1993).

This situation is compounded by large areas of soil, derived mainly from boulder clay and peat, which are of low permeability (Wilcock 1979). These soils are often waterlogged in their natural state, difficult to drain, and provide limited storage capacity at times of heavy rainfall. In addition, the problem of waterlogging is further aggravated by the rainfall pattern in Ireland, with 45% of the annual rainfall occurring over 6 months which coincide with the growing season (Howard 1993).

Agriculture is an important feature of the economy throughout the country and inadequate drainage has long been recognised as one of the major limiting factors in achieving maximum output from the land. The disadvantages of poorly drained land are numerous and have been outlined by Doherty (1980):

- poor trafficability
- late spring growth and shortened growing season
- prevalence of stock diseases
- poor response to fertilisers
- poor quality of pastures – tendency for rush infestation, problems at harvesting

3.2 History of Arterial Drainage

3.2.1 Early legislation

There is a long history of state involvement in land drainage in Ireland dating back to the Act of 1715 which was designed to encourage improvements in land drainage and navigation. Various amending acts were passed and problems of drainage and navigation remained an issue for the Irish Parliament until its dissolution by the Act of Union in 1800 (Howard 1993).

Further Acts of Parliament in relation to drainage were passed in 1831, 1842, 1863, 1924 and 1925, followed by the Owenmore Act 1926 and the Barrow Acts 1927 and 1933, facilitating schemes in those catchments. The most effective of these was the 1842 Act which led to several hundred improvement schemes being carried out in localised areas of river catchments. However, many of the schemes carried out under these various Acts fell into disrepair due to a lack of maintenance.

Agriculture has always been an important feature of the economy in both parts of Ireland, and major initiatives were introduced during the post-war period to raise production, with improved land drainage being seen as a key factor.

3.2.2 The Arterial Drainage Act 1945 (ROI)

The Arterial Drainage Act 1945 provided a new impetus in dealing with the problems of land drainage in ROI. The OPW was nominated as the body responsible for design, implementation and maintenance of arterial works, and there was a major shift in policy from small schemes to the drainage of entire catchments. Between 1948 and 1995 the OPW completed 34 arterial drainage schemes and 5 estuarine embankment schemes in ROI, amounting to some 11,505km of river channel and 730km of embankments, which benefits over 260,000 hectares of land (OPW 2007). The extent of these schemes is shown in Fig 1.

Several of the small-scale schemes carried out under previous legislation were later subsumed into Arterial Drainage Schemes implemented through the 1945 Act, but a significant number remain standalone as Drainage Districts with Local Authorities having statutory maintenance responsibility (OPW 2007).

The 1945 Act was amended in 1995 due to the incidence of serious localised flooding problems particularly in urban areas. The Arterial Drainage Amendment Act 1995 enables the OPW to carry out flood relief works in isolation of whole catchments, although downstream effects must be taken into consideration. The OPW is required to develop a Catchment Flood Risk Management Plan (CFRMP) for specific catchments, taking an overview of flood risks and management options.

Since 2003 a dedicated Environment Section has been in place within the Drainage Maintenance Service of OPW, and a framework has been established for the discussion of environmental issues with the primary statutory stakeholders (RFBs, CFB, NPWS).

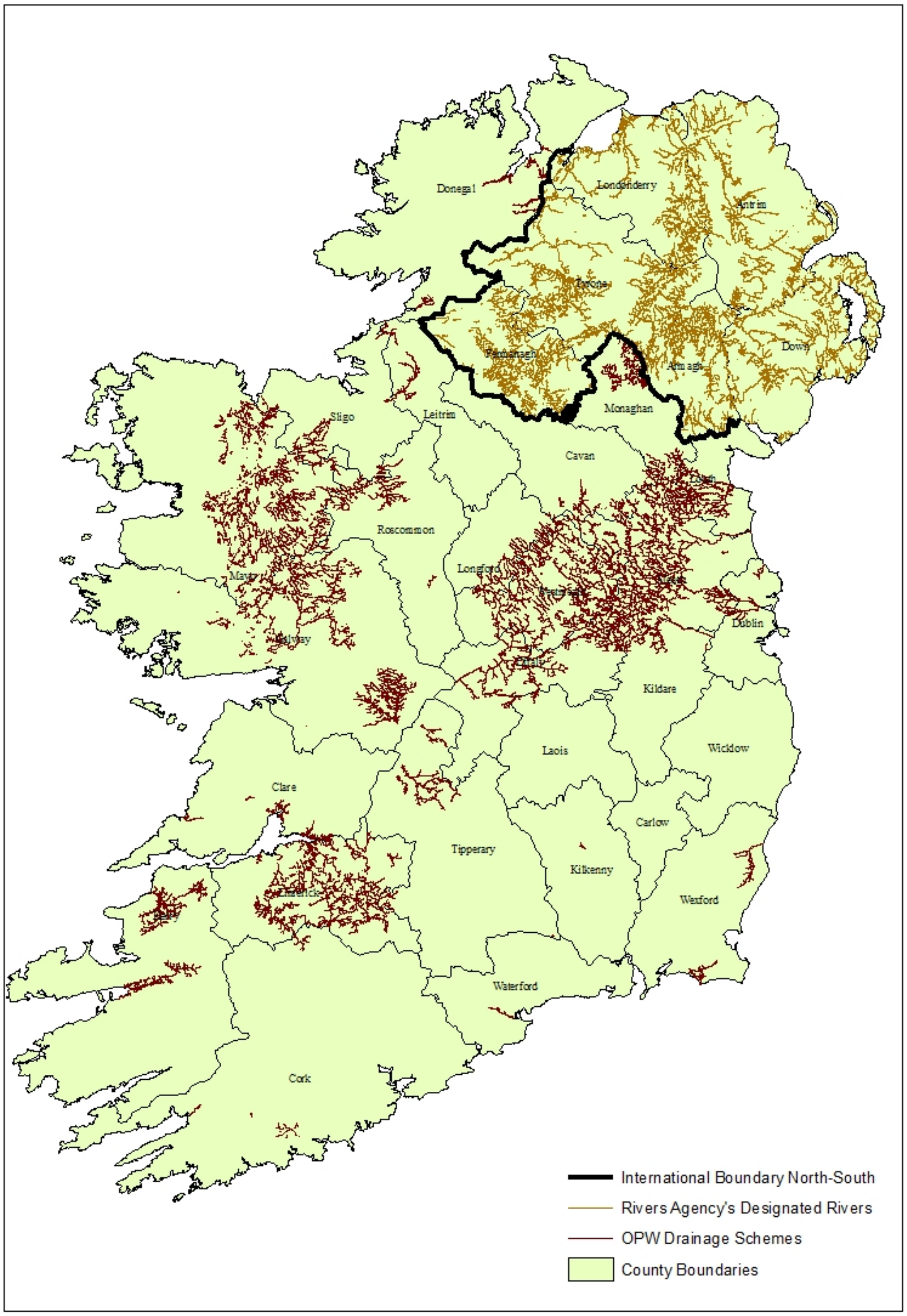

Figure 1 Location of arterial drainage schemes and embankment schemes in ROI and NI

3.2.3 The Drainage Act 1947 (NI)

In NI a significant pre-war development was the Drainage Act 1929 which led to drainage of the Lower Bann for control of the level of Lough Neagh. However the major legislative action relating to land drainage was the passing of the Drainage Act (NI) in 1947. By the late 70s "main" schemes involving 1,263 km of river had been completed or were in progress, with benefits to 38,366 hectares of land (Wilcock 1979). This was followed by a programme for "minor" rivers, implemented by the Drainage Act (NI) 1964, which scheduled a further 4,828 km of minor rivers for improvement. The location of drained channels is shown in Fig 1.

The Drainage (NI) Order 1973 is the legislative basis for carrying out watercourse maintenance work and flood defence schemes, while the Water (NI) Order 1999 requires the Department of Agriculture to have regard for environmental factors when carrying out functions under Drainage Legislation. More recently the Drainage (Environmental Impact Assessment) Regulations (NI) 2006 apply to all drainage and flood defence proposals and require an assessment of the environmental impact and public consultation on all drainage works and schemes.

3.3 Arterial Drainage Schemes

The engineering works entailed in arterial drainage schemes carried out since 1945 have been outlined by OPW (2007). Generally this involved the deepening and widening of the channel, with some localised straightening through the elimination of bends - in some cases a new channel section was excavated.

These procedures involved the excavation of all bed materials and vegetation, while bedrock may have required blasting. The channel was designed to increase its capacity to contain flood waters with a standardised profile (depth and width) and a more uniform longitudinal gradient, along with a cross section excavated to give a trapezoidal form with an even bed level.

Watercourses have been deepened by an average of 1 to 1½ metres (Howard 1993) to provide an outfall for drainage from agricultural lands. This has resulted in a lowering of the immediate water table by up to 1 metre, although this varies according to a number of factors including soil type, geology, topography, catchment hydrology and design criteria.

In relation to hydrological changes, drained channels have significantly more uniform flow velocities than natural channels, with more constant width/depth ratios, increased instream storage and reduced potential for flooding (OPW 2007). In addition, drainage schemes may increase peak flood flows by 40-60%, but floods tend to be shorter in duration (Howard 1993).

3.4 Arterial Drainage Maintenance

As noted above, there is a statutory requirement for the relevant authorities in both parts of Ireland to maintain drained channels. The criteria for maintenance works and the procedures involved are outlined by OPW (2007) – this document defines the purpose of arterial drainage maintenance as:

"to retain a scheme channel's design capacity to convey water in an effective manner."

In the years following a drainage scheme there is a tendency for the channel capacity to be progressively reduced due mainly to the transportation and deposition of bed materials, the accumulation of silt and the growth of vegetation. Restoring the channel to its original capacity is achieved by removal of deposited materials and dense growths of vegetation where necessary, with repairs to bank slippages and the removal of significant obstructions such as trees encroaching at low levels on the banks. In effect, these works consist mainly of the removal of silt and excessive weed growth using hydraulic excavators, while impinging trees may be completely removed or pruned to remove the lower branches.

Medium to high gradient channels generally require little maintenance, as opposed to channels of low gradient which are subject to rapid accumulation of silt and proliferation of vegetation. On average maintenance is required on a 4-6 year cycle, although channels with a prolific weed growth may require maintenance on an annual basis. In some cases where prolific plant growth is prevalent, weed-cutting boats are used to carry out maintenance works.

In low gradient channels requiring maintenance, the deposition of silt and the growth of vegetation may have caused the low flow level to rise by 50-300mm above the scheme design level. Maintenance works are therefore carried out to restore both low-flow and flood-flow water levels to original scheme design levels.

3.5 Environmental considerations

The drive towards increased agricultural production throughout Ireland was enhanced in 1973 when the UK and Ireland joined the EEC (EU), which at this time encouraged the intensification of farming. However, subsequent shifts in EU policy have been directed towards the reduction of product surpluses with incentives for farmers to take land out of production through set-aside schemes. The role of land drainage and maintenance works has been questioned along with their economic viability set against the impacts on natural habitats and species of the river channel and floodplain (Penning-Rowsell & Chatterton 1984; Morris 1989). On the other hand a study commissioned by OPW indicated that the maintenance programme in Ireland produced a cost-benefit ratio of 1:14 in 1998 representing a high return on investment (Anon, 1999).

This shift in policy has coincided with a growing public awareness that environmental issues are a key component for human quality-of-life, and this has included a new appreciation of the value of rivers as an environmental asset worthy of protection (Downs & Gregory 2004). In the current climate it therefore seems highly unlikely that any new drainage schemes will be undertaken in Ireland with the aim of increasing agricultural output. Future channel works are likely to focus on maintenance of existing drainage schemes and flood relief initiatives.

These changes have also engendered a greater widespread awareness of environmental issues in the authorities with responsibility for drainage maintenance. This has resulted in a revised approach to channel maintenance with the adoption of measures to ensure consistent standards of environmentally-sensitive maintenance (Exton & Crompton 1990), and the development of computer models to include conservation interests in maintenance programmes (Fitzsimons & Pimperton 1990). A number of practical manuals have been published on techniques for river management, integrating the requirements of drainage maintenance with wildlife and other river interests e.g. Newbold *et al* 1989; Ward *et al* 1994.

Accordingly both the OPW and the Rivers Agency have developed specific working practices to minimise ecological disturbance with clear guidelines for staff responsible for carrying out of maintenance works (Rivers Agency 1999a, 1999b; OPW 2007).

4 EFFECTS OF CHANNELISATION ON THE RIVER ENVIRONMENT

- Undisturbed rivers are in a state of equilibrium with the surrounding environment and are characterised by a variety of morphological features
- The range and type of morphological features are determined by fluvial processes
- Plants, invertebrates and fish are key features of the aquatic community with specific habitat requirements related to the natural diversity of the river environment
- Channelisation results in major modifications to channel morphology through engineering works to produce a structurally simplified and hydraulically efficient channel
- In the short term the entire ecology of the river environment is seriously disrupted and impaired
- Key ecological impacts are a reduction in habitat diversity, increased sediment loads and changes in flow regime
- In certain circumstances a drainage scheme can have some positive effects on fisheries

The environmental impacts of river channel works associated with land drainage improvement have been recognised for many years and have been widely documented in both the scientific and the grey literature. These impacts have been reviewed by Swales (1982a) who noted that, although the effects of channelisation have been well documented, the evidence is largely based on studies from outside of these islands, mostly in North America.

However, although the impacts on aquatic communities in Irish rivers may not have been measured to the same degree, it is now generally accepted that the physical changes brought about by drainage works have had a major effects on the biology of our rivers. This was clearly recognised by Reynolds (1998) who stated that:

"The greatest challenge to freshwaters in Ireland over the last 200 years has come from arterial drainage which has significantly altered the natural regimes of many rivers."

The engineering works associated with drainage schemes bring about a series of changes in river morphology and fluvial processes which in turn impact on the full range of organisms occupying the river environment.

4.1 Natural River Morphology and the Aquatic Community

Rivers in their natural state are essentially open hydraulic systems in equilibrium (Nunnally 1978), providing a rich variety of habitats for wildlife.

4.1.1 Fluvial processes and natural habitats

Relatively undisturbed rivers are dynamic by nature but also stable, gradually adapting their course and flow patterns as they progress from source to sea. Such rivers are also in a state of equilibrium with the surrounding environment and are characterised by a variety of morphological features such as a meandering channel, the riffle-pool-glide sequence and a stable vegetated riparian zone. Although these features are vital components of the river system and its associated ecology, they may not be conducive to efficient land drainage.

The range and type of morphological features are determined by fluvial processes – as the river flows downstream energy is dissipated through the transportation and re-arrangement of materials in the river channel and its floodplain (Gordon *et al* 1992). Materials eroded from the riverbed, banks and floodplain are deposited as the underlying slope of the channel declines and the river loses energy. These processes give rise to a diverse and stable range of habitats which support different forms of aquatic and terrestrial life within the river channel and the riparian zone.

4.1.2 Aquatic and marginal vegetation

Most aquatic macrophytes require a relatively stable substrate, and different assemblages of plants occupy different substrate types. In a natural undisturbed river system the plant community performs a range of important functions (Caffrey 1990; Ward *et al* 1994). Submerged plants introduce habitat diversity in many lowland channels which would otherwise be somewhat uniform, and improve the physical heterogeneity of the channel by increasing the variation in flow conditions. They provide shelter and a source of food for many aquatic invertebrates and fish species, while invertebrates and coarse fish also use plants as an egg-laying substrate. Emergent plant species such as reeds also provide emergence routes for several aquatic invertebrate species, and it is well established that vegetated river channels in general support richer and more diverse animal communities (Marshall & Westlake 1978).

Marginal and bankside plants play an important role in binding bank soil materials to provide stability and prevent erosion, while in-channel plants assist in stabilising the river substrate through the binding of loose bed materials. Bankside plants also provide shelter and food for many terrestrial invertebrates, birds and small mammals.

Submerged aquatic plants have an influence on chemical water quality through the processes of respiration and photosynthesis – in daylight CO_2 is consumed and oxygen is released through photosynthesis while, in low light intensity and darkness, oxygen is consumed and CO_2 is released through respiration.

4.1.3 Benthic macroinvertebrates

Aquatic invertebrates are a key feature of a healthy river and play an important role in the ecology of the river environment by providing a major source of food for both fish and insectivorous birds. They are also an important factor in the recycling of nutrients within the aquatic environment, through their consumption of dead organic matter and other living plant and animal materials. In addition burrowing animals redistribute nutrients from the sediment while filtering organisms remove particles from the water column. Certain invertebrates are also sensitive to pollution and are regularly used as a means of assessing river water quality.

Invertebrate assemblages are associated with particular types of river and many species have very specific environmental requirements. Throughout the course of a river a wide range of conditions and micro-habitats is available, and this is reflected in the diversity of invertebrate communities. Different species have evolved to exploit a range of habitats and precise distribution is often determined by local variations in current speed and substrate characteristics. Low gradient channels tend to contain much more diverse and complex invertebrate communities due to the broader range of micro-habitats available in comparison to upland high gradient channels (O'Grady 2006).

4.1.4 Fish

Fish populations are present in unpolluted rivers and provide a source of food for piscivorous fish as well as some birds and mammals. Fish are sensitive to pollution and can be used as indicators of water quality – abundant fish stocks suggesting a healthy aquatic environment as a whole, since their position in the food chain means that they are dependant on other forms of aquatic life in order to thrive. Methods for the classification of waterbodies on the basis of fish stocks are currently being developed in connection with the Water Framework Directive.

Apart from their ecological value, fish are highly significant in terms of their recreational value for angling. Fish stocks have therefore been recognised as an important natural resource with significant economic value, especially through the development of specialist tourism centred on angling (Whelan & Marsh 1988; Scottish Executive 2004; PwC 2007).

The habitat requirements of fish are highly specific and vary between species and with age. Upland high gradient channels are occupied almost entirely by salmonids, and often only trout. As the river emerges into its floodplain the fish stock tends to be more abundant and varied due to the wider range of micro-habitats available, with large numbers of 0+ salmonids present in riffle areas (O'Grady 2006). Glide areas are dominated by 1 and 2 year-old salmonids with larger trout occupying lateral scour pools on meander bends. These deeper meandering channels may also be occupied by a range of non-salmonid species due to the wider availability and more diverse range of habitat types (O'Grady 2006).

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The principal impacts of channelisation are on channel morphology and channel processes – alterations in these features induce potentially far-reaching impacts on the ecology of a river, affecting all life forms. The impacts on channel morphology, channel processes and river ecology are summarised in Figure 2.

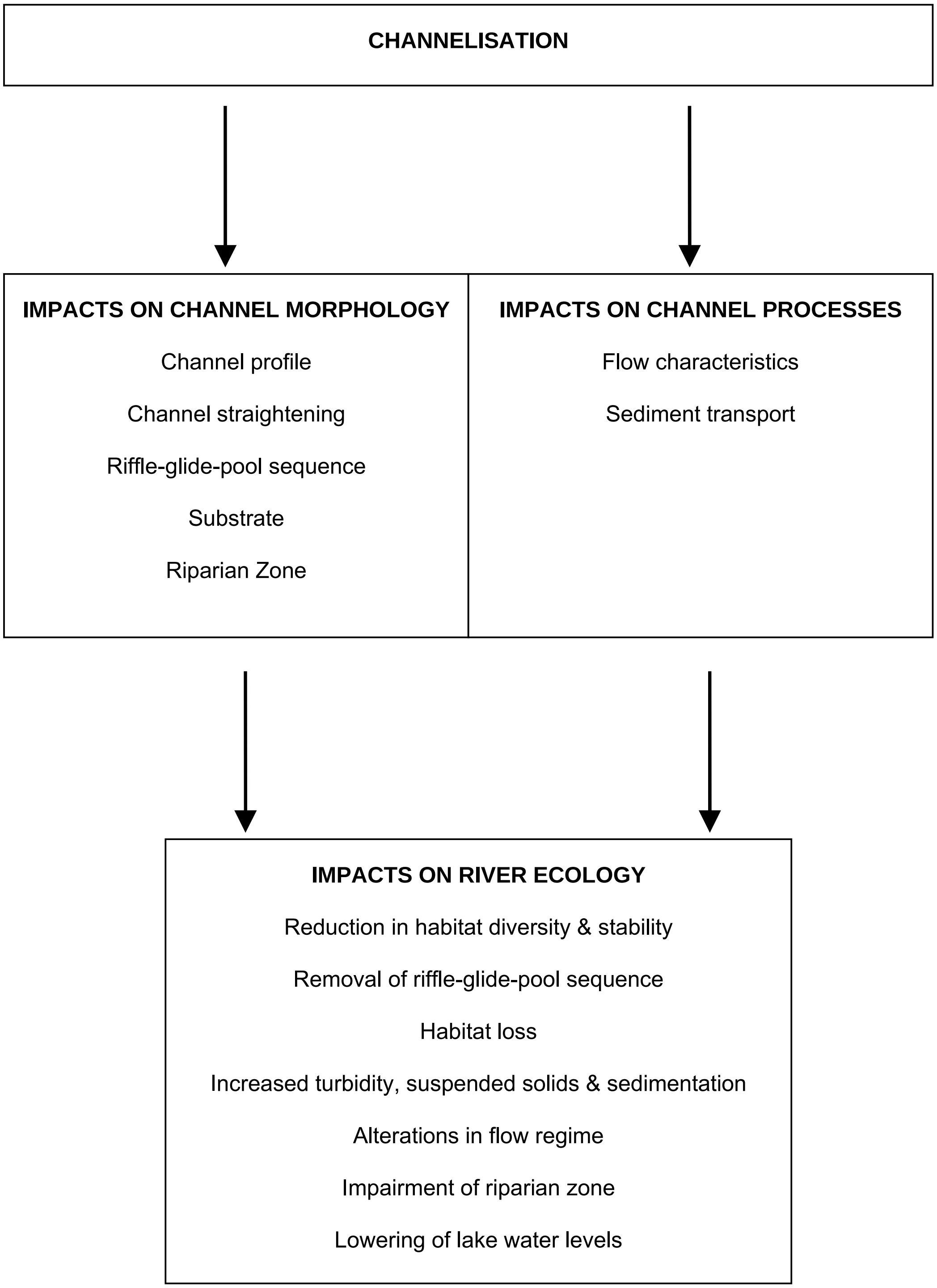

Figure 2 Impacts of channelisation on channel morphology, channel processes and river ecology

4.2 Impacts of Channelisation on Channel Morphology

Arterial drainage schemes designed to improve land drainage and reduce the incidence of flooding have resulted in major modifications to channel morphology through engineering works to deepen and widen the channel. This results in a structurally simplified and hydraulically efficient channel, designed for the rapid clearance of water from the floodplain (Brookes 1985; Wilcock & Essery 1991a; Hodgson & O'Hara 1994). The direct environmental effects of channelisation are mainly physical and affect channel geometry, streamflow and suspended sediment loads (Wilcock & Essery 1991b).

It is generally accepted that the entire ecology of the river environment is seriously disrupted and impaired immediately after a new drainage scheme (O'Grady 1990; Ward *et al* 1994). However this study is primarily concerned with longer term impacts and recovery rates from drainage activities, including both new schemes and maintenance programmes.

The adverse effects of channelisation on river ecology have been reviewed by Swales (1982a) and McCarthy (1985), while O'Grady (1990) has outlined the leading impacts on Irish salmonid rivers. The following discussion draws largely on these reviews.

4.2.1 Channel profile

The cross-sectional profile of an undisturbed river channel shows marked variations over relatively short sections, associated with such natural features as meanders and the inherent riffle-pool-glide sequence. In this situation a state of equilibrium pertains in which channel width and depth have adjusted according to a wide range of frequently occurring discharges. In contrast, arterial drainage schemes are designed to increase channel capacity and this is achieved through deepening and widening of the channel, with a uniform trapezoidal cross-section and banks of 2:1 slopes. The longitudinal profile of the channel is also altered through deepening and regrading of the riverbed to create a more uniform gradient.

4.2.2 Channel straightening

It is recognised that channel straightening has not been employed in Ireland to the same extent as in the US, but it has been carried out to varying degrees, from the removal of meanders to the cutting of a new channel over a significant distance e.g. a 5.23 km section of the R Maine, Co Antrim was reduced in length by 23% during the 1970s (Wilcock & Essery 1991a).

River meandering is a fundamental fluvial process and is of major importance in maintaining the energy balance within a river system (Leopold & Langbein 1966). When a channel is straightened the course of the river is shortened for the same drop in height resulting in an increase in gradient and stream velocity.

4.2.3 Riffle-glide-pool sequence

The riffle-glide-pool sequence is a system of bedforms associated with the minimisation of energy expenditure while permitting sediment transport (Ward *et al* 1994). These features occur as a natural sequence in those areas of a river channel where gradient and substrate conditions are suitable (Keller 1978). Riffles and pools generally occur at intervals of 5 to 7 river widths regardless of the form of the river or its geographical location, suggesting that their formation is a fundamental fluvial process in rivers (Keller 1978).

During river engineering works the combined effects of channel straightening, widening and deepening eliminate the riffle-glide -pool sequence, thereby disrupting the natural energy balance of the fluvial system (Keller 1978).

4.2.4 Substrate

River engineering works to deepen and widen the channel clearly have an immediate impact on the characteristics of the river substrate. The extent of this impact depends on the natural composition of the riverbed and the underlying materials, together with the amount of material removed. In its natural state the form of the riverbed is in equilibrium with channel hydrology and particle size is relatively stable (Morisawa 1968).

Drainage schemes are designed to contain flood waters within the channel and this inevitably results in a reduced capacity for connectivity with the floodplain. A consequence of this new regime is a higher degree of entrapment of sediments within the channel, some of which would formerly have deposited on surrounding lands during flood events (O’Grady 1990; King 1996). This factor in combination with changes in flow characteristics may impact on the size composition of the substrate with a greater degree of settlement of fine sediments and infiltration of coarser bed materials.

4.2.5 Riparian Zone

Channel works have obvious implications for the riparian zone with the loss of natural bank profiles and marginal habitats. Riverbanks tend to be cleared of natural vegetation to gain access to carry out the initial works scheme and to permit access for future maintenance works.

Removal of vegetative cover from the riparian zone also increases the tendency for erosion and in-stream sedimentation (Keller 1976; Karr & Schlosser 1978; Nunnally 1978). The newly formed or modified banks tend to be steeper than previously due to deepening of the channel and the construction of standard 2:1 slopes in the formation of a trapezoidal channel. This profile can be very unstable and subject to damage through erosion and also through poaching by livestock (O’Grady 2006).

Ecological recovery of rivers depends on the erosion of gravel and rubble materials from the banks to form riffles but sand and marl materials are a poor medium for macroinvertebrates and therefore less beneficial (O’Grady 1990).

4.3 Impacts of Channelisation on Channel Processes

4.3.1 Flow Characteristics

Changes in river flow characteristics are brought about through realignment and re-sectioning of the channel which increase gradient and reduce channel roughness. It is generally believed that these changes lead to an increase in the extremes of discharge, with reduced flow during times of low discharge and increased flow during times of high discharge (Swales 1982a).

Howard (1993) reports that Irish drainage schemes may have increased peak flood flows by 40-60% while Campbell *et al* (1972) observed that steam straightening in the US resulted in increases of more than 100% in peak discharges. Higher post drainage peak flows can give rise to greater velocities which may cause erosion on some watercourses with steep gradients (Howard 1993).

On the River Maine, Co Antrim drainage works in the upper section of river increased channel slope by 30% and hydraulic radius by 69%, while channel roughness was reduced by 50% (Wilcock & Essery 1991a); this resulted in an increase in flow velocity by a factor of between 2 and 4, with the largest relative increases being associated with the more extreme flows (Wilcock & Essery 1991b).

Although the popular view is that low flows are reduced post-drainage, analysis of dry weather flows in Ireland would suggest that low flows are actually slightly augmented (Howard 1993; Wilcock & Essery 1991a).

In low gradient Irish rivers where drainage works have widened the channel, reduced flow velocities have contributed to an increased deposition of silt (O'Grady 1990; King 1996).

4.3.2 Sediment Transport

River channel works lead to an increase in suspended solids (SS) as unconsolidated bed and channel wall sediments are washed out by the action of the river (Wilcock & Essery 1991a). During and after drainage works on the Trimblestown River, SS concentrations of 945-1889 ppm were recorded by McCarthy (1983). On the R Maine mean SS increased from 7.9 mg/l pre-drainage to 116.7 mg/l in the immediate post drainage phase while the maximum level increased from 151 mg/l to 1210 mg/l (Wilcock & Essery 1991a).

A recent sediment monitoring programme was carried out on the River Bush, Co Antrim to examine the links between catchment sediment erosion and downstream sediment delivery (Evans *et al* 2006); drainage maintenance work was found to contribute 60% of the annual suspended sediment and 30% of the annual bed sediment load.

4.4 Impacts of Channelisation on River Ecology

The changes in river morphology and fluvial processes brought about through arterial drainage can have potentially far-reaching impacts on river biology, affecting all forms of life dependent on the river environment.

4.4.1 Reduction in Habitat Diversity and Stability

The diversity in river morphology and sedimentology which characterises an undisturbed, meandering river provides a range of habitats which enhances biological richness and diversity within relatively small areas (Wilcock & Essery 1991b). This natural diversity of the river channel is exhibited in the form of a meandering channel with a riffle-glide-pool sequence, a stable substrate of coarse materials, with instream cover and bankside vegetation.

Clearly habitat diversity is severely disrupted after drainage works and this has profound effects on fish and other aquatic organisms which exploit a range of habitats in the river environment. In particular, fish community structure, diversity and resilience to disturbance appears to be related to habitat complexity (Gorman & Karr 1978; Pearson *et al* 1992).

Habitats with a high level of spatial heterogeneity tend to have an inherent buffering capacity which confers a degree of environmental stability (Swales 1982a). Drainage works invariably decrease habitat diversity and the stability of the environment, resulting in reduced species diversity and stability of the aquatic community (Swales 1982a).

4.4.2 Removal of riffle-glide-pool sequence

The riffle-glide-pool pattern is a natural characteristic of undisturbed rivers and provides a variety of features which are fundamental to the maintenance of a balanced aquatic community (Hynes 1970). Riffles are shallow, turbulent, fast-flowing and highly-oxygenated areas with high substrate diversity – they have a key role as nursery areas for juvenile salmonids and also as the most productive areas for invertebrates (Swales 1982a).

Glides are deeper areas of the channel with a slower, more uniform flow than adjacent riffle areas. The productivity of glide areas depends on depth and substrate materials - shallower glides (< 0.7m depth) and coarse substrate having a greater capacity for invertebrate and salmonid fish production (O’Grady 1990).

Pools are well-defined deeper areas (>1m depth) which are relatively slow-flowing and often incorporate back-eddies and a complex flow regime (O’Grady 1990). These areas provide refuge for the larger fish and, in a salmonid river, are generally occupied by the largest trout along with adult salmon.

Elimination of the riffle-glide-pool sequence through drainage works to form a more uniform channel disrupts the aquatic community which depends on this natural pattern. Many drained Irish lowland river reaches are characterised by long, deep and slow-moving deep glides/pools (>300m long) – these areas tend to be very unproductive in fishery terms, in contrast to discrete pools located in a riffle-glide-pool sequence (O’Grady 1990).

4.4.3 Habitat loss

Removal of the riffle-glide-pool sequence and the consequent reduction in habitat diversity and stability clearly amount to an overall loss in quantity of habitat as an immediate effect of channelisation. This may be further compounded through straightening of the channel which, by eliminating bends and meanders, results in a shorter albeit wider channel length. The riffle-glide-pool pattern will re-establish where gradient and substrate conditions are suitable, but river straightening permanently reduces the overall length of channel and the effective wetted area of river available to the aquatic community.

4.4.4 Increased turbidity, suspended solids and sedimentation

Drainage works generally lead to increased turbidity and high levels of suspended solids which can have impacts on survival and abundance in the aquatic community (Alabaster 1972; Cordone & Kelly 1961; Edwards 1969).

Increased turbidity reduces light penetration and photosynthesis, which limits the production of attached algae and rooted vegetation. This in turn limits the production of invertebrates and fish as consumer species. High levels of suspended solids can also interfere with fish respiration and can affect normal patterns of movement and migration within a river.

The settlement of sediments on the substrate can smother invertebrates and fish eggs, while the infiltration of coarse sediments (gravel and cobble) with fines can have longer term implications for the productivity of both groups. The characteristics of the riverbed are critical for fish spawning (Fluskey 1989), and the tolerance of salmon eggs to sedimentation has been examined on the River Bush by O'Connor & Andrew (1998) who found that alevin survival was closely related to the level of fines with impacts detectable at a level of 10% fines.

4.4.5 Alterations in flow regime

The flow regime of a river is a key characteristic in regulating the distribution and abundance of invertebrates and fish (Fraser 1972; Hynes 1970) – any alterations in flow following drainage works therefore have the potential to impact on the aquatic community.

The increase in peak flow rate following a drainage scheme has been outlined under Channel Processes (Section 4.3) – this leads to flood periods of shorter duration but with a higher peak and shorter run-off time, since the same volume of water is being conveyed through the channel over a reduced time interval. The upstream migration of salmonids occurs during higher than average flows, and generally when the flood is running down (Alabaster 1970). Elson (1975) has suggested that an increased rate of run-off resulting from drainage schemes on tributaries of the River Foyle has reduced the period over which returning salmon can move upstream.

4.4.6 Impairment of riparian zone

The clearance of bankside vegetation in the form of shrubs and trees removes the shading effect on the channel provided by overhanging and bankside growths, a significant factor in providing camouflage for fish (O'Grady 1990), and in controlling water temperature by protecting the river from direct sunlight (Swales 1982a). Trees are particularly effective in this respect and also provide a food source for aquatic invertebrates through leaf-fall into the channel (O'Grady 2006). The shading effect in controlling water temperatures may become an increasingly significant factor as the impacts of climate change intensify.

At the other extreme, excessive growths of bankside vegetation can exclude light from the channel with negative impacts on the production of aquatic communities. Shading in this way can exclude herbaceous plants, which have an important role in maintaining bank stability, leading to bank erosion and channel widening. Excessive growths of trees over significant lengths of river, known as "tunnelling", is widespread in Ireland and has been shown to be a significant factor in reducing salmonid production (O'Grady 1993). Tunnelling can be an indirect impact of drainage schemes and is a common feature of many drained channels in Ireland on which a monoculture of alders has developed to produce a heavy shading effect (O'Grady 2006).

4.4.7 Lowering of lake water levels

When a drainage scheme involves the lowering of a lake's water level there can be significant ecological impacts and there are 2 examples from Ireland (O'Grady 1990). Through drainage of the Boyle River the level of Lough Gara was lowered with summer depth reducing to <1.5m. This resulted disturbance of bed materials through wave action with increased turbidity preventing a stable floral regime from becoming established – this had a knock-on effect through the aquatic community and the trout stock collapsed.

After the lowering of Lough Conn, as part of the Moy drainage scheme, the condition and quality of adult fish was noted to be poor for several years. This was due to a reduced food supply in the new shallow zones, which took 10 years to fully recolonise with plants and invertebrates.

4.5 Positive effects on fisheries

In certain circumstances a drainage scheme can have some positive effects on fisheries, and there are a number of examples of this occurring in Ireland.

4.5.1 Exposure of shallow areas

On River Bonet (Co Leitrim) the removal of a series of shallow areas and rock ledges, to reduce flooding and improve drainage, inadvertently led to the exposure of new shallow areas which significantly extended the area of productive salmonid channel (O'Grady, *et al* 1993). Similarly on the River Boyne, a 32km length of channel became a major salmonid nursery and quality trout angling area after drainage which included high point removal, in the form of 10 stone weirs, and de-silting of the channel (O'Grady 1991a).

4.5.2 Exposure of glacial gravels

During the Moy drainage scheme in the 1960s dredging works in the Bunree sub-catchment resulted in the exposure of glacial gravels, previously overlain with boulder clay and peat, leading to the formation of new spawning areas on the river (Toner *et al* 1965). A similar long term potential benefit on the River Maine was suggested by Wilcock and Essery (1991b) - the authors noted that the newly excavated channel in the upper section of river intersected glacial gravels which now make hydraulic contact with the river channel along a much greater length of river than prior to channelisation, where previous gravel exposures in the bed and sides of the channel were limited.

4.5.3 Thinning of bankside vegetation

The removal or thinning of excessive bankside vegetation can also have positive results on fisheries and the aquatic community in general (O'Grady 1990, 2006). Extensive lengths of channel, particularly in the sub-catchments of major Irish rivers, are enclosed with heavy growths of bank vegetation to a level at which the river is enclosed in a tunnel with little light penetration from outside. "Tunnelling" results in a lack of adequate light reaching the riverbed which restricts algal and macrophyte production, and in turn reduces the potential production of invertebrates and fish. Research has shown that the potential production of salmonids is significantly reduced by tunnelling (O'Grady 1993).

5 STUDIES ON IMPACTS AND RECOVERY

- Many US studies have shown that channelisation can have serious biological impacts with severe reductions in fish abundance and diversity
- Studies on Irish rivers have shown that drainage works are extremely disruptive to stream ecology in the short term, but that some channels can recover fully
- Channel gradient is a key factor in the recovery process, in facilitating the erosion of coarse materials from the riverbanks and the distribution of bed materials, to re-establish a riffle-glide-pool sequence
- Studies on British rivers have demonstrated that non-salmonid species with different habitat requirements can be seriously impacted by channel works in both the short term and the long term
- Effects on aquatic flora can range from complete removal to changes in species composition and diversity associated with altered substrate and flow conditions, particularly in low gradient channels
- Invertebrate abundance and diversity are typically reduced by drainage works due to direct removal, alterations in substrate composition, flow regime and sediment deposition
- The Experimental Drainage Maintenance Programme has shown that it is feasible to adopt environmentally sensitive procedures in channel maintenance while meeting the objectives of restoring conveyance
- A new Environmental River Enhancement Programme is being implemented by OPW and will focus on both capital river enhancement works in drained channels, and an enhanced drainage maintenance programme

Although channelisation was carried out widely in the developed world during the 20th century, the associated environmental impacts first received serious attention in the US in the 1970s (Emerson, 1971; Keller, 1975), with a series of major reports to the US government between 1970 and 1973 (Gregory, 1985). One of these reports considered the impacts of 42 channelisation schemes in 18 states and found that over 3,000km of stream had been severely affected (Little 1973). This has led to in a significant volume of literature on the environmental impacts of channelisation, particularly in relation to fisheries as opposed to other biological consequences (Brookes 1989).

However in Britain and Ireland, while river channel works have long been considered extremely damaging to fisheries (Mann 1988; O'Grady 1990), the scientific evidence to support this is actually quite limited, as there is a lack of fish stock data from most rivers in their pre-drainage form. However a small number of studies have been carried out on Irish salmonid rivers and British non-salmonid rivers.

5.1 Impacts on US rivers

The extreme nature of channelisation schemes in the US with extensive channel straightening and major reductions in river length have already been noted in Section 4.2.2. Most quantitative investigations have involved post-channelisation comparisons of modified and un-modified rivers or river sections (Wilkinson 1973), and many of these studies have recorded serious biological impacts with severe reductions in both fish and invertebrate abundance and diversity.

For example Congdon (1971) found that of the 1,842 miles (2,966km) of major streams in Missouri, 55% had been channelised, and the biomass of all fish species was reduced by more than 80% in channelised reaches relative to un-channelised areas. Similarly, Golden & Twilley (1976) found that mean fish biomass was 61% lower in channelised sections of Big Muddy Creek (Kentucky), while the number of species was reduced by 11%. In another study Peters & Alvord (1964) found that in 13 Montana rivers, one third of the 768 miles (1,237km) of river examined had been altered by channelisation, and that natural stretches contained over 5 times as many trout and nearly 10 times as many whitefish as modified sections.

On the other hand, less severe impacts have been noted in some cases. For example, a study of 6 Pennsylvania streams by Duvel *et al* (1976) recorded no long-term deleterious effects on water quality, attached algae, benthic fauna, or forage fish populations, although trout were found to be greater in numbers and weight in natural stream reaches than in channelised reaches.

5.2 Investigations on Irish salmonid rivers

Studies on the impact of drainage schemes on Irish rivers have been carried out by Toner *et al* (1965); Vickers (1969); McCarthy (1977) & (1983); Kennedy *et al* (1983). The sites sampled by Toner *et al* (1965) in the Moy catchment, and by McCarthy (1977 & 1983) in the Boyne catchment, were re-visited some years later by O'Grady & King (1992) and by O’Grady (1991b).

5.2.1 Moy catchment (Bunree River)

The first study of the effects of arterial drainage anywhere in these islands using pre and post works survey data was carried our by Toner *et al* (1965). The Bunree is an important salmon spawning tributary of the R Moy and was scheduled for drainage in 1960 – a single experimental site was selected from one tributary along with a control site from a separate tributary not to be drained. Prior to machine works the authors collected information on riverbed topography, physical and chemical features, invertebrate fauna and fish stocks. Sampling was carried out on 2 occasions prior to dredging in 1960 and continued at regular intervals through to 1962.

Toner *et al* found that the drainage works resulted in major short term changes to the ecology and physical characteristics of the experimental site with almost complete disappearance of flora and fauna accompanied by 30% reduction in juvenile salmonid numbers. Recovery of invertebrate fauna was slow but by September 1962 was considered satisfactory. The density of juvenile salmonids had returned close to pre-dredging levels over the same time period suggesting significant recovery after 2 years.

Areas of the Bunree catchment consist of glacial drift overlain with boulder clay and peat - the authors noted that at many locations, dredging resulted in exposure of glacial gravels which led to the formation of new spawning areas on the river.

In 1990 the sites sampled by Toner *et al* (1965) were re-surveyed by O'Grady & King (1992) with the addition of 3 extra sites to confirm that the original control and experimental sites were representative of their respective sub-catchments. This supplementary study indicated complete recovery of the stream to pre-drainage conditions in terms of its capacity to support salmonids. (Sampling of the additional sites also confirmed that the level of recovery demonstrated by Toner *et al* on the experimental stretch was typical of this stream and not exceptional).

The authors considered that this recovery had been largely facilitated by the relatively steep channel gradient and the erosion of glacial drift material from the riverbed and banks, which was exposed during the dredging works. Fencing of the riverbanks after drainage was also a key factor in facilitating regeneration of the riparian zone. In addition, a narrowing of the channel base-width had resulted in a deeper, faster flowing and more erosive channel devoid of significant silt deposits. The authors note that prior to drainage the river consisted of a sinuous channel of relatively broad base-width, with the low flow discharge confined to a narrow portion of the full base-width. In sections of relatively low gradient the pre-drainage channel was subject to braiding and consequently low fish carrying capacity. A greater salmonid fry carrying capacity in the drained sections over the summer period is now evident and is considered by the authors to be the result of these physical changes, with a narrower channel and deeper water bringing areas into production which formerly would not have supported juvenile salmonids.

Whilst this study has shown a satisfactory and perhaps enhanced recovery in this system, there were clearly a number of factors which aided the situation significantly. Moreover, it would appear that this was a “one-off” scheme without subsequent maintenance operations which would have resulted in renewed disruption to the physical characteristics and ecology of the stream (O'Grady *pers comm*).

5.2.2 Lough Erne catchment

During a survey of Lough Erne tributaries in 1968, a total of 17 sites were sampled across 6 tributary systems (Vickers 1969). No pre-drainage fish data was available for comparison but it was apparent that the standing crop of juvenile salmonids was significantly reduced in dredged sections of river compared to undredged sections. Standing crop was reviewed against the time interval since drainage and the author suggested that this indicated a recovery period of up to 10 years.

5.2.3 Foyle catchment (Camowen River)

Kennedy *et al* (1983) carried out a survey on the Camowen over an 11-year period (1968-78) at 5 sites, 4 of which were dredged 3 years after the start of the survey while one site remained as an undredged control area. After dredging salmonid densities were reduced but this was followed by a progressive downstream recovery, with fry densities taking up to 6 years to improve at the most downstream site while older fish recovered more rapidly. This pattern of recovery was related to a progressive consolidation of the substratum and the erosion of rock bank protection materials into the channel to act as current deflectors and to provide additional cover for fish. It was also recognised that fish recolonised the area from the undredged section upstream of the limits of this scheme.

An additional change was noted in population structure in response to altered water depth, with deepened sites containing larger numbers of older fish than prior to drainage, and shallower areas containing larger numbers of fry.

5.2.4 Boyne catchment (Trimblestown River)

The Trimblestown is one of the major tributaries of the Boyne and was drained in 1972 as part of a catchment-wide scheme. The impacts of the scheme on river ecology were examined by McCarthy (1977 & 1983) and subsequently by O'Grady (1991b).

In his initial paper McCarthy (1977) reported on the effects of drainage on the aquatic flora and benthic macroinvertebrates. A site was sampled annually from 1968 to 1974, with the exception of 1971, and dredging was carried out early in 1972. Prior to drainage the study section was characterised by an extensive bank cover of trees and marginal aquatic plants, undercut banks and an instream flora and fauna typical of an undisturbed Irish limestone stream.

Immediately after drainage both flora and invertebrate fauna were seriously depleted, but had recovered rapidly in both numbers and biomass a year after completion of the works, although biomass remained below pre-drainage levels. Major floristic changes were a dramatic increase in filamentous algae and an increase in the area colonised by emergent plants, as a result of increased silt deposition on the riverbed.

The second paper in this series (McCarthy 1983) reported on the impact on fish stocks as determined from pre and post drainage electrofishing surveys of the Trimblestown R. After 2 years the fish fauna had changed from predominantly salmonid (brown trout and juvenile salmon), to small coarse fish species (mainly stone loach and minnow).

The same section of river was again surveyed in 1989 by O'Grady (1991b) who examined the nature of the riverbed, instream and bank flora, and fish stocks. This study suggested a general recovery in stream ecology 17 years after drainage works with most channel characteristics having returned to their pre-drainage condition including substrate type, channel width and flow rates.

The floral regime had returned to that recorded by McCarthy in the pre-drainage period, with the same species recorded as abundant, while the silt-tolerant species were no longer present. In addition fish stocks had recovered completely both in terms of numbers and species composition, with trout and salmon being predominant.

O'Grady (1991b) suggests that the re-establishment of the pre-drainage fishery status was probably due to a number of factors including:

- retention of stone and gravel materials in the channel after drainage
- scouring of further stone and gravel materials from the riverbanks
- fencing of banks post drainage facilitating the regeneration of a productive bankside ecology

A relatively high gradient of this channel was also a significant factor in recovery of this channel (O'Grady, *pers comm*).

O'Grady (1991b) notes that it is difficult to draw definitive conclusions on the rate of recovery due to the 15 year time-lapse between the 2 field studies, 1974 to 1989. However he comments that in general the recovery of drained channels in the Boyne catchment was relatively rapid, possibly in the order of 5 to 7 years.

5.2.5 The significance of channel gradient

The studies outlined above would suggest that, although the immediate effects of drainage works are extremely disruptive to stream ecology, natural recovery can take place over a period of up to 7 years (Kennedy *et al* 1983; O'Grady 1991b; O'Grady & King 1992), and that enhanced fisheries potential is sometimes possible, as in the case of the Bunree (Toner *et al* 1965).

However, recovery in all cases described was brought about by a combination of physical factors, most importantly a relatively steep channel gradient which has facilitated the erosion of coarse materials from the riverbanks and the distribution of bed materials to re-establish a riffle-glide-pool sequence. Other significant factors identified were the inherent bank subsoil and substrate characteristics, the lack of further disturbance, and the fencing of riverbanks, but the key physical feature was channel gradient. Indeed O'Grady (1990 & 2006) has drawn a distinction between high gradient channels (slope > 0.15%) and low gradient channels (slope < 0.10%), in terms of their potential for natural recovery.

The major drainage schemes, north and south, have taken place in the post-war period between 1950 and 1990. In ROI channel gradients in the main channels and first order tributaries of rivers drained during this era are generally within the range 0.05% to 0.3% (O'Grady & Curtin 1993). Clearly a significant proportion of each of these catchments must fall below the low gradient threshold (slope < 0.10%), and these have been the most seriously affected in the long term by arterial drainage (O'Grady 1990). The example studies outlined above must therefore be regarded as being untypical of the majority of drained channels in Ireland as a geographical area, and should not be quoted as reflecting the likely period of recovery in a wider sense.

Drainage scheme design in low gradient reaches usually involves significant deepening and widening of the channel which increases the containment of flood waters within the modified channel and reduces contact between the river and its natural floodplain. Under this modified regime the river's silt load tends to be contained within the channel, with increased in-channel deposition of sediments usually leading to lush growths of macrophytes, which in turn accelerate silt deposition. This sequence of events rapidly reduces the hydraulic capacity of the channel, and maintenance works may be required on a 3 to 5 year basis (O'Grady 1990), with renewed potential for disruption of stream ecology.

5.3 Investigations on British non-salmonid rivers

In mainland Britain extensive land drainage and channelisation has been carried out since the 1940s when increased government grants became available (Swales 1981). By the 1980s the extent of major or capital schemes in England and Wales totalled 8,500 km of channel with a further 35,500 km of channel maintenance (Brookes *et al* 1983).

The impacts of river drainage works on fisheries have long been an issue in Britain and concerns were expressed at a conference held on the subject by the Salmon and Trout Association (Brayshaw 1960; Crocker 1960; Stuart 1960). A later conference, “Conservation and Land Drainage” further highlighted the problems involved (Water Space Amenity Commission 1975). However, despite awareness of the environmental issues, particularly in relation to fisheries, there were no studies on impacts initiated until a research project was funded by Severn-Trent Water Authority (Swales 1980).

All of the investigations on British rivers have focused on waters dominated by non-salmonid fish species; this is not surprising as salmonids have been absent from many river systems in England due to anthropogenic interference in the form of river regulation, channelisation and pollution. Although many drained catchments in Ireland are important salmonid fisheries, several are of equal standing as coarse fish waters (e.g. the Lung-Breedoge and the Inny main stem), and it is important to recognise that the impacts of drainage works are not confined to salmonids.

The first “before and after” drainage study was carried out by Swales (1982b) in the River Soar, a lowland tributary of the River Trent - reductions of 70% and 76% in fish density and biomass were recorded in a 3 month period after drainage, with larger fish more severely affected. There was an indication of some recovery in fish numbers within this period and, in the author‘s view, a lack of instream cover was the major factor implicated in the decline of fish stocks.

An additional long term study on the River Soar was undertaken by Cowx *et al* (1986) and was designed to complement the before and after study completed by Swales (1982b). Fish populations were monitored over an 8 year period in two adjacent sections of the river, one of which was subject to channel works while the other remained in its natural state. After drainage there was a marked absence of fish from the dredged section which persisted for almost 5 years before any significant recolonisation. This decline in the drained section was accompanied by an increase in fish density and biomass in the natural stretch, suggesting that fish had been displaced by the channel works. The loss of instream cover and the removal of the riffle-pool pattern were believed to be the main factors responsible.

In a further study Swales (1988) examined the effects of long term drainage maintenance on fish stocks in the River Perry, a small lowland tributary of the River Severn. Fish abundance and diversity were lower in areas which had been drained more than 80 years previously than in nearby unmodified areas. Habitat diversity at the channelised sites was found to be low compared with a partially channelised site and an unmodified site where natural features such as the riffle-pool pattern were more apparent. The author concluded that long term river maintenance and management works may delay the morphological and biological recovery of lowland channels.

A later study carried out on slow-flowing lowland tributaries of the River Thames (Spillett *et al* 1985), found that there was no indication of recovery 6 years after initial channel works in one river, and concluded that this was mainly due to long term disruption of the riffle-pool ratio. In another tributary, maintenance dredging resulted in reductions of 31%-64% in cyprinid biomass with good indications of recovery after 3 years.

Fish community structure and habitat preferences were examined by Punchard *et al* (2000) in natural and channelised areas of the R Wensum catchment, a system dominated by small fish species (minnow, stickleback, bullhead), but with significant numbers of trout. It was found that differences in physical habitat structure were responsible for observed differences in fish community structure, abundance and biomass. A riffle-pool structure and the presence of a wooded riparian zone contributing woody debris to the channel were identified as key features, promoting a higher density and biomass of fish in the natural, unmodified area.

Pilcher *et al* (2004) compared fish assemblages in adjacent natural and channelised stretches of the rivers Lea and Stort, two tributaries of the River Thames. Both rivers were channelised for navigation during the 18th and 19th centuries, but side-loops and original meanders were left intact, with the flow regime designed to allow flow by overspill weirs from the canal through these remnants of the original river channel. The remnant side-loops are relatively narrow pool and riffle systems with diverse instream macrophyte assemblages and bankside plant communities. It was found that the natural stretches had significantly higher fish density, biomass and species diversity than the channelised stretches, and this was attributed to reduced habitat heterogeneity within the navigation channel.

5.4 Impacts on aquatic flora and invertebrate fauna

The immediate impact of drainage schemes is direct removal of the flora and fauna through engineering operations involving excavations to deepen the channel. In the long term the impacts on aquatic flora are potentially more persistent than on macroinvertebrates, as whole plant communities and substrates are removed while invertebrates are more mobile and can re-colonise through drift from upstream areas (Hale *pers comm*). Some specific examples of the impacts of drainage on aquatic flora and invertebrate fauna have already been outlined in Section 5.2 (Toner *et al* 1965; McCarthy 1977; O'Grady 1991b; O'Grady & King 1992).

5.4.1 Aquatic flora

Significant, long term changes in species composition, abundance and diversity of aquatic plant communities in rivers rarely occur in the absence of artificial interference (Bayley *et al* 1978, in Caffrey 1990). However, disturbance of the natural form through river engineering works (or other factors) can result in a serious distortion of plant community structure – if the vegetation is not entirely removed by machine works, in-channel conditions may be altered in favour of mono-specific or low species diversity regimes (Caffrey 1990).

The widening of low gradient river channels during drainage scheme works has rendered many channels incapable of self-cleansing (King 1996b) – siltation within the river channel facilitates the development of various macrophyte species leading to further siltation. In this situation major lush growths of a limited range of species are commonly observed, often featuring *Sparganium* or water celery species (O'Grady 1990; King & Wightman 2006). Similarly, in moderately fast-flowing channels, *Ranunculus penicillatus* (Stream water crowfoot) has established dense stands covering large areas (Caffrey 1990).

This process of sediment accretion and macrophyte proliferation can impede the free flow of water and reduce the efficiency of land drainage, resulting in a requirement for intermittent maintenance in the form of machine works to remove excessive dense vegetation and sediment deposits. Periodic maintenance requirements therefore result in further disruptions to the plant community. It has been noted that standard OPW maintenance works pre-2001 frequently resulted in severe impacts on aquatic macrophytes, particularly in cases where the vegetation was a major component of, or contributor to, the maintenance requirement (King 2001). Growths of *Scirpus* (Bulrush) and *Sparganium* (Bur-reed) both contribute to the accumulation of sediment, and were noted to be a principal target during OPW maintenance works in specific channels. Maintenance in water celery channels frequently resulted in complete removal of the carpet of cover, while the strategy of "topping" lateral silt depositions led to complete loss of the cover of tall marginal vegetation (King 2001).

Water level changes brought about by drainage schemes may cause successional changes in plant communities, with the loss of aquatic and wetland species, and replacement by common terrestrial species (Ward *et al* 1994).

The removal of bankside shade through drainage schemes or maintenance works has also been shown to impact on macrophyte growth. Caffrey (1990) observed that light sensitive species, such as *Ranunculus penicillatus,* established dense stands only a few growing seasons after the removal of shade.

5.4.2 Invertebrate fauna

Arterial drainage works alter the complex in-channel habitat structure which supports the invertebrate community, producing a more uniform channel with a significant decrease in invertebrate abundance and diversity (Ward *et al* 1994). Altered flow regimes may also affect invertebrate species and their habitats through a change in the pattern and rate of sedimentation which affects the nature and composition of bed materials (Ward *et al* 1994). In addition, a reduction in water level may have serious impacts on invertebrate communities both within the channel and along the river margins (Ward *et al* 1994).

Drainage of the Camowen River, Co Tyrone, resulted in a decrease in abundance and diversity of the invertebrate community, and this was linked with a reduction in habitat diversity due to changes in substrate composition, current velocity and water depth (Kennedy 1980).

Morris *et al* (1968) found that channelisation of the Missouri River reduced both the size and variety of aquatic habitat by destroying key productive areas, although the standing crop of invertebrates was similar in channelised and un-channelised reaches; however, it was also found that the standing crop of drift organisms in the channelised section was only 12% of that in the unaltered river.

Invertebrate communities in drained rivers may also be more susceptible to depletion during flood conditions. In a low gradient Japanese stream Negishi *et al* (2002) found that a spate had a greater effect on invertebrate assemblages in a channelised area, and this was attributed to a low availability of flow refugia such as backwaters and inundated habitats.

Drainage maintenance operations involving dredging to remove excessive weed growth and silt can also remove significant numbers of invertebrates from a watercourse (Ward *et al* 1994). Some species may be able to move back to the river channel if the spoil is deposited in close proximity, but this is contrary to current recommended practice which encourages deposition of spoil on the bankfull (OPW Environmental Drainage Maintenance Guidance Notes). Weed-cutting exercises in particular can cause an increase in invertebrate drift (Pearson & Jones 1978) which may result in a decline in fish growth rates or even starvation (Garner *et al* 1996).

Aldridge (2000) has suggested that maintenance dredging has significant impacts on the distribution and abundance of unionid mussel populations. The freshwater pearl mussel *Margaritifera margaritifera* is listed under Annexe II of the Habitats Directive but is now virtually extinct in England and Wales. Although this species has a relatively widespread distribution in Ireland, the last recruitment in some rivers may have been during the 1960s or

70s (Moorkens 1999). Arterial drainage is believed to one of the main causes for the decline of pearl mussel in Ireland (Moorkens 1999).

Similarly the white-clawed crayfish, *Austropotamobius pallipes*, also listed under Annexe II of the Habitats Directive, is believed to be particularly vulnerable. This species has disappeared from many Irish rivers and this has probably been due habitat alteration caused by arterial drainage and urban growth (Reynolds 1979).

However it is worth noting that both pearl mussel and crayfish are still present on a range of drained channels in Ireland and OPW, as part of an ongoing research programme, are conducting Ecological Impact Assessments for a range of Annex II species which will assist in mitigation of the environmental impacts of drainage maintenance activities Gilligan, *pers comm*; OPW, 2007).

5.5 The Experimental Drainage Maintenance Programme

5.5.1 The need for Arterial Drainage Maintenance

The low probability that any new drainage schemes will be undertaken in Ireland has been noted in Section 3. However there is a need to maintain existing schemes to ensure the free flow of water in rivers and to provide an adequate outlet for land drainage, as required under legislation. Maintenance works, by their very nature, imply some degree of disturbance of the river channel and/or the riparian zone, and therefore have the potential for disruption of river ecology at some level on an intermittent basis according to the frequency of the maintenance requirement.

5.5.2 EDM Programme

During the 1990s the OPW embarked on an Experimental Drainage Maintenance (EDM) programme, funded by the OPW and carried out in partnership with the CFB. The programme was initiated in 1990 as a pilot project in the OPW Drainage Maintenance East Region and expanded in 1997 as a national programme of study to include all 3 regions - East, West and South West (King 2001).

The EDM programme has been conducted in 3 phases:

- 1990-95 – pilot project
- 1997-01 – national programme
- 2002-06 – national programme

5.5.3 EDM 1990-2001

Full details of the programme are outlined by King (2001) - the aims during the initial phases were:

- To examine the environmental impacts of current OPW maintenance practice
- To examine the feasibility of alternative, more environmentally-sensitive, maintenance practices
- To monitor the rate of return or regression of channels following maintenance

Within this framework the OPW identified a range of specific factors for study which, individually or in combination, lead to a requirement for channel maintenance e.g:

- excessive in-channel growth of tall emergent vegetation
- bank erosion
- lateral siltation

A series of monitoring exercises was carried out over the period 1990-2001 on a number of channels to examine the effects of standard maintenance and experimental maintenance strategies. The study was successful in identifying the impacts of standard maintenance practices on fish stocks and aquatic flora, and in assessing the feasibility of alternative (experimental) maintenance strategies.

This phase of the study concluded that it would be feasible for the OPW to incorporate environmentally sensitive maintenance procedures as normal working practice in channel maintenance while meeting the objectives of restoring conveyance. It was suggested that this approach be adopted by OPW with the development of agreed maintenance strategies, in the form of a manual, indicating the range of environmentally sensitive options available in different situations and how these should be applied.

In addition it was suggested that a training and education programme be developed for OPW staff to incorporate this environmental approach, and that ecological and engineering studies should be continued with regard to specific topics in the EDM programme.

5.5.4 EDM 2002-07

The CFB recommendations from the previous study period were adopted for the next phase of the EDM programme, summarised by King & Wightman (2006), which focused largely on the implementation of the new environmental protocols and the development of a training programme for OPW maintenance staff.

The training programme involved presentations to maintenance staff at centres throughout the country followed by a series of site visits to machine crews during maintenance works. Training concentrated on 10 alterations to previous working practices in the formulation of an environmentally sensitive approach to drainage maintenance - this was condensed onto a single sheet of Guidance Notes for OPW maintenance staff. This has led to a formalisation of the existing process of walkover surveys on a proportion of channels involving OPW, CFB and RFB staff, with written agreement on maintenance requirements and agreed procedures to be carried out in each channel section.

Scientific studies continued during this phase of the EDM programme and included investigations on:

- Annexe II (Habitats Directive) species – crayfish and lamprey
- Coarse fish – previous EDM work had concentrated on salmonids but maintenance works also have the potential to impact on coarse fish species

- Tree management – trees are viewed as an important feature of the riparian zone but can hinder conveyance
- Water celery – an important component of fisheries channels but can hinder conveyance

5.5.5 Environmental River Enhancement Programme 2008-12

Following on from the EDM programme the OPW has embarked on a new Environmental River Enhancement Programme to cover the period 2008-12. The new programme has been outlined by Gilligan (2007) and is focused on 2 central objectives:

Capital river enhancement programme

A 5-year programme of salmonid enhancement works on sub-catchments of drainage scheme channels with optimum enhancement potential. The programme will target 50km of channel annually throughout the 3 arterial drainage maintenance regions, and will facilitate the measurement and understanding of hydromorphological changes arising from enhancement works on representative reaches.

Enhanced drainage maintenance programme

A yearly programme of enhanced maintenance as part of the OPW's annual maintenance programme - this enhancement programme will also target 50km of channel annually throughout the 3 arterial drainage maintenance regions.

During this new 5-year programme the OPW will also develop and deliver a revised environmental training programme for maintenance staff and will carry out audits on the level of compliance with the existing 10 step Guidance Notes and new criteria as developed through the revised training schedule.

6 EFFECTIVENESS OF PHYSICAL REHABILITATION / ENHANCEMENT WORKS

- River enhancement through physical rehabilitation works originated in the US during the 1930s. Rehabilitation projects have now been undertaken in many parts of Europe including Ireland
- The physical effects of drainage in Irish salmonid rivers have led to:
    - seriously reduced capacity of small streams to support 1+ and older fish
    - reduced spawning opportunities
    - reduced frequency of pools for adult fish
- Monitoring of river rehabilitation projects in ROI has shown that channels which have been subject to arterial drainage schemes can be enhanced significantly
- Enhancement of small spawning and nursery streams (basewidth <3m) is very effective in relation to increasing 1+ year-old trout carrying capacity
- Enhancement programmes in larger channels (3m to 6m basewidth) is very effective in relation to 1+ year-old trout and also 1+ year-old salmon parr up to the springtime period of their second year
- The enhancement of larger channels (>6m basewidth) is a successful process in relation to increasing standing crop of both 1+ year-old salmon and trout, and adult trout
- Restoration of the natural morphological form in channels can also enhance salmonid spawning opportunities, increase fish food production in certain circumstances, and increase angling opportunities for trout and adult salmon

6.1 Background

River enhancement through physical rehabilitation works originated in the US during the 1930s, with the initiation of restoration projects on trout streams which had been degraded through various anthropogenic activities. The methods were developed quickly and a series of evaluation studies demonstrated improved stream morphology and habitat conditions with positive impacts both fish and invertebrate communities (Hubbs *et al* 1932; Burghduff 1934; Tarzwell 1937; Shetter *et al* 1946). Over the years enhancement works extended to cover Pacific and Atlantic salmon, and a considerable volume of useful literature has been published on the subject including Saunders & Smith (1962); White & Brynildson (1967); Hunt (1976 & 1988); Finnigan *et al* (1980).

River rehabilitation projects have now been undertaken in many parts of Europe with several studies on salmonid dominated rivers (e.g. Brittain *et al* 1993; Jungwirth *et al* 1995; Linløkken

1997). Numerous restoration projects have been undertaken in Denmark since 1983 when revision of the Watercourse Act provided for an ecological approach to maintenance practices and made special provisions for stream rehabilitation activities (Iverson *et al* 1993). Up to this point farming priorities requiring land drainage had led to the physical modification of more than 90% of the 35,000km of natural streams (Iverson *et al* 1993). Large and small-scale schemes have also been carried out widely in both Britain and Ireland over the last 25 years, and have been reviewed respectively by Holmes (1998) and O'Grady (2002).

In ROI a major EU funded programme of restoration of salmonid rivers was undertaken under the National Development Plan 1994-99 through the Tourism Angling Measure (TAM). This scheme, aimed at improving the angling resource, was executed through the Central Fisheries Board (CFB) with the assistance of the Office of Public Works (OPW), both of whom have funded research and development works in this field since the 1980s. In NI a similar angling development initiative has been funded under successive rounds of the EU Programme for Peace and Reconciliation – initially the Salmonid Enhancement Programme (SEP) 1995-99, and followed by the Water Based Tourism measure 2000-04.

A large proportion of the funding on both sides of the border was directed at restoration of salmon and trout habitats in river reaches throughout Ireland, many of which had been degraded as a direct result of arterial drainage works carried out since the 1950s.

6.2 Problems and solutions

The impacts of arterial drainage on channel morphology and river ecology have been reviewed in Section 4. O'Grady (2006) states that the physical effects of drainage in salmonid rivers lead to:

- **uniformity of channel with significantly reduced ecological diversity**
- **reduced spawning opportunities**
- **seriously reduced capacity of small streams to support 1+ and older fish**
- **reduced frequency of pools for adult fish**

In addition the riparian zone is often removed and may not have recovered due to a lack of fencing to exclude livestock. In many locations this has led to serious damage to banks through grazing and trampling by farm livestock. Tunnelling can also be a problem in many drained rivers when the banks have been cleared of their original vegetation and have re-grown with a monoculture of alders which can seriously reduce the penetration of light to the channel.

O'Grady (2006) explains that it is necessary to identify the imbalances in a stretch of river as a basis for drawing up an enhancement plan which may include a range of procedures that have proved successful in Irish rivers. Most of the techniques employed to address these imbalances, problems and deficiencies have been developed in North America, and some have been adapted to suit Irish conditions. Many of these procedures have been used successfully in the restoration of drained channels and have recently been outlined in detail by O'Grady (2006). The specific problems associated with arterial drainage are summarised in Table 1 along with potential rehabilitation measures as described by O'Grady (2006).

Zone	Problem	Potential rehabilitation measures
Instream	Excessive basewidth Imbalance in riffle-glide-pool sequence	Construction of 2-stage channels, deflectors, bank stabilisation
	Substrate deficiency	Addition of gravel, rubble mats, and random boulders
	Absence of sinuosity	Excavation of thalweg
	Lack of pools	Excavation of lateral scour pools Construction of timber/stone weirs
Riparian zone	Absence or impairment of riparian zone	Fencing programme Planting programme
	Bank damage, instability or erosion	Stabilisation/revetment measures - log/christmas tree - log/rock - standard rip/rap
	Tunnelling	Thinning/pruning of trees

Table 1 Summary of problems associated with arterial drainage and potential rehabilitation measures (compiled from O'Grady (2006).

6.3 Evidence for the effectiveness of enhancement works

Up until relatively recently a general criticism of enhancement works in Britain has been that such schemes were often opportunistic and lacked proper scientific evaluation (Mann & Winfield 1992). The first such study in Britain or Ireland was carried out by Swales & O'Hara (1983) who recorded increases in fish abundance and biomass following the installation of low dams, deflectors and artificial cover structures in a lowland cyprinid river. However, although river rehabilitation schemes are now widespread in Britain, Pretty *et al* (2003) have again highlighted the lack of systematic assessments of the ecological effects, particularly on target organisms such as fish. Moreover, in focusing on the impact of individual instream structures both Pretty *et al* (2003) and Stewart *et al* (2006) found only weak positive responses among fish populations. This contrasts with the approach in Ireland which has generally been on a larger scale, often incorporating a range of measures tailored to address the deficiencies of a particular channel reach, and with generally more demonstrable positive outcomes.

6.3.1 Drainage rehabilitation in ROI

In ROI a considerable volume of research has been carried out on the effectiveness of enhancement measures, particularly in relation to the rehabilitation of rivers impacted by arterial drainage schemes. Monitoring programmes have been established on all of the major catchments where enhancement schemes have been implemented, and the impacts of several of these enhancement schemes have been reported prior to commencement of the Freshwater Morphology Study including:

River Boyne	O'Grady, King & Curtin (1991) O'Grady (1991a) Lynch & Murray (1992) Lynch (1994)
Rye River (Liffey Catchment)	Kelly (1996) Kelly & Bracken (1998) McCreesh (2000)
Lough Corrib catchment	Gargan *et al* (2002)
Lough Ennell Sub-Catchments	O'Grady, Delanty & Igoe (2002)

The principal findings of these schemes have also been reported by O'Grady & O'Leary (2007), as outlined in the following section. In general the monitoring of these river rehabilitation projects has shown that channels which have been subject to arterial drainage schemes can be enhanced significantly. An exception has been the Rye River in the Liffey catchment - although the physical structures installed were found to remain intact and self-maintaining, the anticipated increases in salmonid production were not realised due to water quality problems (McCreesh 2000).

6.3.2 CFB Recovery Datasets

As part of the Channelisation Recovery Assessment the Central Fisheries Board was engaged to provide additional data on the impacts of arterial drainage and the effectiveness of enhancement measures through the various schemes completed. This information has been combined with the data from the above catchments in a single report as the major data input to this assessment (O'Grady & O'Leary 2007). An outline of each scheme, enhancement measures applied, and the leading outcomes as detailed by O'Grady & O'Leary are summarised in Table 2a & 2b.

Catchment	Study areas	Enhancement measures	Principal results	Additional observations
L Ennell catchment	8 tributary streams 2 - 4m basewidth 0.09 -1.7% gradient	• Basewidth reduction • Sinuosity introduced • Timber/stone weirs • Log/rock bank reconstruction • Fencing	Significant increase in 1+ trout nos 46.4% decrease in 0+ trout biomass 889% increase in 1+ trout nos	100% increase in CPUE for adult trout in L Ennell
L Sheelin catchment	**7 smaller streams** 0.05 -1m basewidth 0.1 - 0.7% gradient	• Basewidth reduction • Sinuosity introduced • Timber/stone weirs • Log/rock bank reconstruction • Fencing • Vortex weirs • Rubble mats	No significant differences in fish nos detected	Increase noted in lake trout (not necessarily due to works)
	5 larger streams 2-4m basewidth 0.09 - 1.7% gradient Upper Inny 2.7%		Significant increase in 1+ trout nos	
L Arrow catchment	**5 tributary streams** 1 – 3.5m basewidth 0.024 - 1.47% gradient	• Basewidth reduction • Sinuosity introduced • Stone weirs • Log/rock bank reconstruction • Fencing	Significant increase in 0+ trout Significant increase in 1+ trout	Increase noted in lake trout (not necessarily due to works)
R Moy catchment	**< 3m basewidth** 23 stream reaches (0.17 - 1.33% gradient)	• Fencing • Timber/stone weirs • Log/rock & log/xmas tree bank revetment • Spawning gravels added • Random boulders added	Significant increase in 1+ trout nos No significant increase in 1+ salmon nos (except in 2 streams where salmon are normally dominant	
	3 - 6m basewidth 3 tributary streams (0.61 – 2.8% gradient) 10 tributary streams (0.12 – 1.58% gradient)	• Rip rap & log/xmas tree bank revetment • Fencing • Tree planting • Random boulders added	Some areas: Significant increase in 1+ trout nos Some areas: Significant increase in 1+ salmon nos	
	> 6m basewidth 2 rivers	• Basewidth reduction • Excavation of thalweg • Rubble mats • Excavation of pools • Random boulders added • Fencing • Tree planting	No significant changes in fish nos (all categories)	Failure attributed to poor water quality in both rivers post works

Table 2a Summary of CFB data on effectiveness of salmonid enhancement programmes (compiled from O'Grady & O'Leary 2007)

Catchment	Study areas	Enhancement measures	Principal results	Additional observations
L Corrib catchment	**8 tributary streams** 20 stream reaches	• Timber/stone weirs • Vortex stone weirs • Rubble mats • Stone deflectors • Restoration of thalweg • Log/rock bank reconstruction • Fencing	Significant increase in 1+ salmon nos Significant increase in 1+ trout nos	
L Carra & L Mask catchments	**27 stream reaches**	• Excavation of thalweg • Timber/stone weirs • Stone bank revetment • Fencing • Tree planting	Significant increase in 1+ trout nos	Increase in CPUE for adult trout in L Carra following works – probably due to programme
R Moy catchment	**Owengarve River** (9 - 11m basewidth)	• 2 stage channel construction • Vortex stone weirs • Random boulders added	Significant increase in 1+ salmon nos Significant increase in 1+ trout and adult trout nos	
R Boyne	**Main channel** (13 - 17m basewidth)	• Rubble mat construction in uniform glide areas	Significant increase in 1+ salmon nos Significant increase in 1+ trout and adult trout nos	3 years post works – many larger adult present
R Liffey catchment	**R Rye**	• De-silting • Stone weirs & deflectors • Stone bank revetment • Tossing of gravel beds • Fencing • Tree planting	Unsuccessful in enhancing juvenile salmon Unsuccessful in enhancing juvenile or adult trout	Failure attributed to poor water quality in both rivers post works
R Bonet catchment	**Shanvaus R**	• Timber revetment of eroding banks • Fencing • No instream works	Substantial increase in salmon spawning redd count	
Moy	**Tobergall stream**	• Timber revetment of eroding banks • Fencing • No instream works	Substantial increase in salmon spawning redd count	
L Corrib catchment	**Currerevagh stream**	• Vortex stone weirs	Substantial increase in salmon and trout spawning redd count	

Table 2b Summary of CFB data on effectiveness of salmonid enhancement programmes (compiled from O'Grady & O'Leary 2007)

O'Grady and O'Leary (2007) concluded that these datasets indicate that arterial drainage and any other activities which alter the natural morphology of river channels are likely to impact negatively on salmonid stocks. In addition, with regard to the effects of stream enhancement, the authors note that analysis of the datasets has highlighted a number of definite trends as summarised in their report:

- Enhancement of small (basewidth <3m) spawning and nursery streams is very effective in relation to increasing their 1+ year-old trout carrying capacity. Data indicate that salmon rarely utilise these channels for spawning or nursery purposes.
- Enhancement programmes in larger (3m to 6m basewidth) channels are also very effective in relation to trout stocks. They are also beneficial to 1+ year-old salmon parr up to the springtime period of their second year. Data suggest that, subsequently, 1+ year-old salmon, in the summer of their second year, migrate downstream from these reaches into bigger channels.
- Analysis suggests that in enhanced streams, where either juvenile salmon or trout were the dominant species present pre-works, the same species remains dominant in the post-works phase.
- The enhancement of larger channels (>6m basewidth) is a successful process in relation to increasing standing crops of both 1+ year-old salmon and trout and adult trout.
- Poor water quality (Q3-4 for salmon parr and Q3 for trout) can negate the positive effects of stream enhancement.
- Data suggest that the enhancement of very small sub-catchments (≤4.28km2) is relatively ineffective probably because of low Q values (volume discharges) in summertime.
- Restoration of the natural morphological form in channels can also enhance salmonid spawning opportunities, increase fish food production in certain circumstances and increase angling opportunities for trout and adult salmon.

A recent study by Stewart *et al* (2006) to assess the effectiveness of in-stream structures on salmonid abundance does not provide such conclusive evidence of the positive impacts of enhancement schemes. This review examined the results of a range of assessments from Europe and North America, 38 of which provided quantitative data for inclusion in a meta-analysis; results from the Corrib system as documented by Gargan *et al* (2002) were included in the analysis. The meta-analysis failed to demonstrate an ecologically significant impact of engineered instream structures on salmonid populations, although it was noted that they may provide preferential habitat at higher river discharges. However the authors stressed that there were high levels of heterogeneity between studies, many of which were of inadequate duration and assessed habitat preference rather than long term population change; in addition many studies were restricted to habitat units rather than river reaches or watersheds. Clearly the CFB datasets, most of which were unavailable to Stewart *et al*, were not limited with regard to any of these factors as detailed in the methodology outlined by O'Grady & O'Leary (2007):

- a high proportion of control reaches was selected
- control and experimental sites were all electrofished prior to implementation of enhancement works
- each control and experimental site was selected to include at least one riffle-glide-pool sequence
- control and experimental sites were re-fished annually at the same time of year as pre-implementation
- due to different electrofishing protocols at different sites, only data using the first electrofishing numbers was used for purposes of comparison by estimates of minimum density
- the data was analysed in discrete batches based on watershed/catchment and channel basewidth

6.4 Drainage rehabilitation in N Ireland

The River Blackwater was the last major drainage scheme undertaken in NI and a series of mitigating measures were incorporated to minimise the impacts on fisheries, including the construction of several fish passes and numerous fish weirs and groynes (Johnston *et al* 1994). Towards the end of the scheme it was felt that the river would not be restored to its former potential without additional enhancement, leading to the selection of a further 350 sites for remedial works with the objective of restoring fishery habitat to at least its pre-scheme value (Johnston *et al* 1994). The works at each site generally took the form of a "habitat unit" comprising a pool, a spawning area and a nursery area, but the subsequent monitoring exercise revealed only low densities of salmon fry measured against a control site on an undrained tributary – it was concluded that the resultant habitat at both drained and enhanced sites was insufficient for juvenile salmon (Fisher *et al* 1995).

Since the Blackwater scheme, habitat enhancement works have been carried out on many rivers mainly by angling clubs, under successive rounds of the EU Programme for Peace and Reconciliation 1995-99 and 2000-04. A number of individual projects within these programmes would have featured the restoration of drained reaches and, although this initiative is considered to have had positive results, there has been a lack of monitoring to support this view.

The River Bush, historically regarded as a prime salmon river, was subjected to a major arterial drainage scheme in the 1950s. An experiment in habitat reconstruction carried out by the Department of Agriculture during drainage maintenance in the 1990s, highlighted significant problems related to the stability of introduced gravel and stone, and siltation of downstream areas due to the restoration works (Crozier *et al* 1996). However the authors noted that the addition of stone did produce positive results in terms of habitat enhancement and the establishment of more balanced populations of salmon and trout.

Subsequently a 4-year experimental habitat enhancement programme on the Bush was implemented by the Department of Agriculture in 1997 (Turner *et al* 2001). The aim of this study was to incorporate habitat improvement features into the existing flow regime and to enhance natural features, such as riffles and pools. Works were carried out at 6 experimental sites in 1997 with pre-works assessment of physical features and fish stocks, and post-works monitoring up to 2000. Similar problems were encountered during this study with newly imported gravels showing a high degree of instability on some sites and a tendency to accumulate fines over 2-3 years. Water depth was found to be critical factor in refurbishment of nursery areas in that fry could compete successfully with older age classes if the restored habitat was too deep. No clear benefits were evident as the authors found that natural fluctuations in the recruitment of juvenile salmon and trout could exceed the potential changes in juvenile densities resulting from habitat changes (Turner *et al* 2001). However the study did highlight the need for further research in relation to engineering design to improve stability, and on the sources of gravel and sediment in streams together with the transport processes involved.

A recent salmon habitat enhancement initiative in 2005/06 has yielded some very positive results in terms of increasing salmon parr carrying capacity at previously drained sites in the River Maine catchment (Kennedy *pers comm*).

6.5 Effectiveness of enhancement works on flora and fauna

Although river restoration projects are now widespread in western Europe, few have been systematically evaluated on ecological criteria (Harrison *et al* 2004). In cases where restoration projects have been evaluated the results have generally indicated a very positive impact on stream biota including macrophyte and invertebrate communities e.g. Biggs *et al* (1998); Friberg *et al* (1998); Gørtz (1998); Laasonen *et al* (1998).

Harper *et al* (1998) concluded that riffle reinstatement in lowland rivers of low energy will produce desirable geomorphological and ecological changes if the riffles are correctly spaced and shallow (<30cm) under low flow conditions. The significance of using restoration structures to increase substrate heterogeneity and leaf litter retention has been highlighted by Laasonen *et al* (1998), as these factors are likely to enhance the formation of detritivore-dominated macroinvertebrate assemblages.

In Ireland, prior to embarking on a large scale post-drainage enhancement programme on the River Boyne, 2 pilot projects were undertaken to examine the effectiveness of physical instream works (O'Grady, King & Curtin 1991) – fish data from this project has been included in the current CFB analysis reported at 6.3.2 and by O'Grady & O'Leary (2007). Experimental limestone rubble structures were placed on the riverbed in pre-determined spatial patterns at deep and shallow glide areas, with experimental and control sites sampled prior to and post installation. Prior to works a very poor invertebrate fauna existed at all sites, but rapid colonisation of the new structures was evident within 6-12 months, with a slower build-up in faunal density over the next 2 years to give a significant range of invertebrate species (Lynch & Murray 1992; O'Grady, King & Curtin 1991).

Macrophyte colonisation at the Boyne experimental sites varied according to the physical configuration of the rubble structures (O'Grady, King & Curtin 1991). Rubble mat areas exhibited an initial dominance of filamentous algae, with a lack of macrophytes probably due to an absence of finer materials in the gaps between the stones and boulders forming the experimental structures. In the area of V-shaped rubble structures floral cover was reduced with the new flow regime favouring selected species. Nevertheless the addition of the rubble materials in both formats was viewed as creating new habitat for plant colonisation and the results suggested that this process was still in the early stages (O'Grady, King & Curtin 1991).

7 TIMESCALES FOR BIOLOGICAL RECOVERY

Natural Recovery

- Surveys have shown little recovery in morphology of many drained channels up to 60 years after drainage works
- Natural biological recovery after channelisation is entirely dependent on morphological recovery
- A variable period of morphological and biological adjustment takes place during which channel processes operate to recreate lost characteristics such as the riffle-glide-pool sequence
- Ecological recovery is largely dependent on channel gradient and immediate subsoil characteristics, but documented timescales of recovery are highly variable
- Higher gradient channels can recover significantly after 2-3 years with full recovery over a period of up to 7 years
- The process of recovery can be inhibited or set back according to the extent and frequency of drainage maintenance operations
- Lower gradient channels do not generate sufficient energy to scour materials from the riverbed and banks, and are the most seriously affected in the long term by drainage schemes
- Lower gradient channels typically have a more frequent maintenance requirement (3 to 5 years) due to increased siltation and macrophyte growth

Enhanced Recovery

- Although high gradient channels often have the potential to recover quickly, there can be imbalances in the riffle-glide-pool sequence, or an impoverished riparian zone. Intervention in the form of restoration programmes is required to facilitate ecological recovery in these areas
- The proximity of potential colonising species to enhanced areas is an important factor in the rate of colonisation
- Benthic invertebrates can colonise enhanced sections rapidly and a stable invertebrate community can be anticipated 3-4 years after enhancement
- Macrophyte recovery after physical enhancement works may be a gradual process lasting several years
- Fish populations can recover significantly within a year of enhancement works, but optimum stocks may not be realised until 3-5 years after the works stage

Although channelisation can produce major changes in channel morphology and hydrology, rivers have considerable powers of natural recovery (Swales 1989). However, natural morphological and biological adjustment, towards a new equilibrium or the pre-drainage condition, is conditional on removal or cessation of the original disturbance (Swales 1989).

The ability of rivers to recover ecologically is largely dependent on channel gradient and immediate subsoil characteristics, but documented timescales of recovery are highly variable. The observation that physical enhancement works in drained Irish catchments have been shown to produce positive results in terms of improved aquatic communities demonstrates:

- that full recovery had not taken place prior to enhancement works
- that the recovery process can be rapidly accelerated through enhancement works

These conclusions assume that the enhanced condition of the river is not superior to the pre-drained condition in terms of ecological diversity.

7.1 Natural Recovery

Since the biological recovery of rivers affected by channelisation is entirely dependent on their morphological recovery, natural river features such as pools and riffles must become established before complete recovery of the aquatic community can occur (Swales 1982a).

7.1.1 Channel Morphology and Ecology

It is clear that the river environment is seriously disrupted in the immediate aftermath of a drainage scheme (O'Grady 1990; Ward *et al* 1994). Thereafter, once ecological disturbance of the channel has ceased at the completion of drainage works, a variable period of morphological and biological adjustment takes place during which channel processes come into operation again and begin to recreate lost characteristics such as the riffle-glide-pool pattern and point bar deposition (Swales 1989). These processes of recovery can however, be inhibited or set back according to the extent of maintenance operations which, if carried out a on a regular basis, may disrupt recovery to a degree that a morphologically stable riffle-glide-pool sequence will never become properly re-established (Keller 1976).

O'Grady & Curtin (1993) have observed that, in channels of gradient between 0.16% and 0.4%, natural recovery of channel morphology is evident, but not complete, in shallow gravel/stony bed sections 2 years after works with the re-formation of a limited thalweg and a riffle-glide-pool sequence. Although high gradient channels often have the potential to recover quickly, there can be imbalances in the riffle-glide-pool sequence, with 1 or 2 habitat types being dominant to the detriment of the fishery (O'Grady 1990). An impoverished riparian zone due to a lack of fencing to exclude livestock following drainage may also limit recovery of the fishery. Intervention in the form of enhancement programmes is required in these areas to restore fish stocks to pre-drainage levels.

There appears to be little information available on timescales for morphological recovery in rivers subjected to arterial drainage, but there is a large volume of information from the US on the recovery of aquatic organisms, particularly with regard to fish stocks. As the recovery of aquatic communities is dependent on morphological characteristics, these studies provide an indication of the timescales for morphological recovery (Swales 1989).

7.1.2 Benthic Invertebrates

Invertebrates can recolonise an area from 4 sources – downstream by drift, upstream by migration, migration from within the substrate, and from aerial sources e.g. egg deposition (Williams & Hynes 1976). These authors showed that, in a denuded section of a Canadian stream, downstream drift was the main source contributing over 40% of the new colonisers while 28% came from aerial sources.

Benthic invertebrates are often the first to recover, depending on the return of stable substrate conditions (Swales 1989). McCarthy (1977) noted a rapid recovery within a year of dredging on the Trimblestown River, while Pearson & Jones (1978) observed that most species were recovering within a 5 month period after drainage of an English chalk stream. Similarly, Barton & Winger (1973) found that invertebrate abundance, diversity and biomass in channelised reaches of the Weber River, Utah were similar to those in unchannelised reaches 6 months after dredging works. In contrast to these findings, Arner *et al* (1976) observed that benthic communities in a Mississippi river had not recovered after 52 years.

Recovery of invertebrates depends mainly on the stabilisation of the riverbed, particularly in gravel-bed streams where the benthos is dependent on stable, large-sized materials in the form of cobble and boulder. Recolonisation of drained reaches also appears to be aided by the proximity of upstream populations and their ability to disperse downstream into suitable habitats (Lynch & Murray 1992).

7.1.3 Aquatic Macrophytes

Recovery rates of aquatic macrophytes also reflects the stabilisation of substrate conditions and the flora can recover within a year, but there may be changes in species composition and diversity associated with altered substrate conditions (McCarthy 1977). This latter effect may be more pronounced and persistent in low gradient channels which have been excessively widened and are liable to deposition of sediments along the margins. In such cases there has often been a major increase in macrophyte biomass and a shift form diverse plant communities to communities dominated by 1 or 2 opportunistic species (Caffrey 1991). This in turn results in an increased risk of flooding and a requirement for regular maintenance which re-introduces a variable element of disturbance to the channel.

On the Trimblestown River, O'Grady (1991b) noted a return to the pre-drainage floral regime after 17 years, suggesting that full recovery of macrophyte communities will take place in higher gradient channels, but may be a somewhat longer process in comparison to benthic invertebrates. In contrast, low gradient channels are unlikely to recover naturally due to radical alteration of the flow regime and substrate conditions, and also due to regular disturbance in the form of maintenance works to restore channel capacity.

7.1.4 Fish stocks

Natural rates of recovery of fish populations as reported from channelisation studies in the US are highly variable and, in many cases, it appears that fish communities will never recover fully without some form of intervention in the form of physical rehabilitation. Bayless & Smith (1964) found that fish populations in channelised reaches of North Carolina streams had not recovered after 40 years, while Arner (1975) noted little recovery after 43 years in the Luxapilia River, Mississippi. Similarly, Golden & Twilley (1976) found that full recovery in a channelised stream in Kentucky had not occurred after 33 years. On the other hand, Tarplee *et al* (1971) observed full recovery of fish in North Carolina streams after 15 years, provided there were no further alterations.

It has been noted previously that there is a lack of scientific information on the impacts of drainage on fish stocks in Britain and Ireland due mainly to absence of pre-drainage data (Section 5). The example studies from Ireland previously outlined (Toner *et al* 1965; McCarthy 1977 & 1983; Kennedy *et al* 1983; O’Grady 1991b; and O'Grady & King 1992), suggest that full recovery may take place over variable periods of up to 7 years, while Vickers (1969) suggested that impacts persisted for up to 10 years. However these examples are not typical of the majority of Irish catchments in which significant lengths of channel fall into the low gradient category (slope < 0.10%), and these have been the most seriously affected in the long term by arterial drainage (O’Grady 1990). Low gradient channels in this range do not generate sufficient energy to scour materials from the riverbed and banks, resulting in a deficiency in coarse substrates and a lack of habitat diversity in the form of the riffle-glide-pool sequence (O’Grady 2006).

Studies on British rivers have suggested considerable variability in timescales of natural recovery of coarse fish populations. Cowx *et al* (1986) recorded an absence of cyprinid fish from a dredged section which persisted for almost 5 years before any significant recolonisation, while Spillett *et al* (1985) found good indications of recovery in biomass 3 years after maintenance dredging. On the other hand Swales (1988) noted that fish abundance and diversity were lower in areas which had been drained more than 80 years previously than in nearby unmodified areas.

Drainage maintenance operations can interfere with or inhibit the recovery of fish stocks. King (2001) reports that standard OPW maintenance works pre-2001 consistently resulted in a shift in fish population structure, with an increase in the proportion of smaller fish of younger age, and a decrease in the numbers of older, larger fish in the population. In many cases the fish population structure returned to pre-maintenance levels within 3 years whereas, in cases of more extreme maintenance works, fish population density and structure remained severely impacted after 4 years (King 2001).

Surveys have shown little recovery in morphology of many drained channels up to 60 years after drainage works, with persistent negative impacts on fish stocks, and there is evidence to suggest that most channels might never recover without intervention in the form of enhancement programmes (O'Grady 2006).

7.2 Recovery following enhancement schemes

7.2.1 Aquatic Macrophytes

There appears to be little information available on recovery rates of aquatic macrophytes following river restoration/enhancement works. However it is clear that macrophyte recovery, or alterations in species composition and diversity, will be related to changes in substrate conditions and localised flow regimes, along with the proximity of other macrophyte communities. Following drainage of the Trimblestown River, although rapid recovery of macrophytes was observed, changes species composition and diversity were due to altered substrate conditions (McCarthy 1977). It follows that river enhancement schemes, by their very nature, involve changes in substrate conditions and localised flow characteristics due to many of the methods deployed e.g. rubble mats, 2-stage channels, deflectors, bank stabilisation, and that these factors will therefore determine the macrophyte assembly which colonises the any new area of habitat.

In the post-drainage enhancement programme on the River Boyne (see Section 6.4), it was concluded that the process of macrophyte colonisation at the experimental sites was still in the early stages at the end of the 3-year period of study (O'Grady *et al* 1991). In contrast, Laasonen *et al* (1998) noted that mosses in restored Finnish streams had recovered well within 3 years of restoration works.

In general, it would appear that macrophyte recovery after physical enhancement works may be gradual process lasting several years while substrate conditions mature and plant assemblages typical of newly-created habitats become established.

7.2.2 Benthic Invertebrates

Benthic invertebrates can colonise enhanced sections rapidly due to their mobility and shorter generation period in comparison to fish (Swales 1989). Even in the case of more extreme restoration works involving the creation of new meanders in the River Gelså (Denmark), the macroinvertebrate community recovered in 1-2 years, with increased diversity and density reflecting the creation of hew habitat areas (Friberg *et al* (1998). In this river a peak in abundance was noted shortly thereafter, with stabilisation of the invertebrate community observed 3-4 years after restoration (Friberg *et al* (1998).

During the River Bonet drainage scheme rock cutting changed the habitat at various locations from bedrock to rocky riffles, increasing the area of habitat for invertebrates and fish (Lynch 1994). These areas were rapidly colonised and the author recorded 44 taxa at one site within 1 year of the works.

In the Boyne enhancement experiment (see Section 6.4), a very poor invertebrate fauna existed prior to enhancement at all sites, but rapid colonisation of the new structures was evident within 6-12 months, with a slower build-up in faunal density over the next 2 years to give a significant range of invertebrate species (Lynch & Murray 1992; O'Grady *et al* 1991). The presence of potential colonising species within the system was highlighted as an important factor impacting on the rate of colonisation (Lynch & Murray 1992).

It seems clear that river enhancement works should lead to an initial rapid colonisation of new habitats by invertebrates, provided there is a pool of potential colonisers in reasonable proximity to the area of works. A stable invertebrate community can then be anticipated 3-4 years after enhancement, with a slow increase in species diversity due to the immigration of species with low dispersal abilities (Milner 1996).

7.2.3 Fish stocks

The benefits of enhancement programmes in salmonid rivers are described in O'Grady (2006), and the recovery rates of fish stocks have recently been outlined by O'Grady & O'Leary (2007). It is clear that the benefits of such programmes are, in most cases, evident only 1 year after the completion of physical works, but that optimum stocks of salmonids may not be realised in enhanced areas until 3-5 years after the works stage (O'Grady *et al* 1991; O'Grady *et al* 1993).

The success of physical enhancement works can be inhibited by poor water quality as demonstrated through the enhancement initiative on the Rye River (McCreesh 2000). Physical isolation has also been suggested as a factor which could limit the success of enhancement measures and recovery rates, as the response to restoration works will depend on proximity to a source of potential colonisers (Pretty *et al* 2003). Dispersal is clearly the means by which fish colonise new areas unless some form of stock enhancement or stock transfer has been practiced. Poor results through physical isolation are more likely to be a problem in the case of small-scale enhancement projects in extended reaches of river with degraded habitat (Pretty *et al* 2003).

8 OVERVIEW OF EXISTING LITERATURE

This section comments briefly on the significance and limitations of the existing literature on the impacts of channelisation, recovery rates, and river restoration programmes.

It has been noted that there is a lack of pre-drainage data on fish populations and on the aquatic community in general - the same can be said for river morphology and habitat features. There has therefore been an absence of robust reference points against which to measure the impacts of channelisation works and the subsequent recovery process. Many studies on channelisation have compared drained with un-drained rivers, or drained sections with un-drained sections within the same catchment. That is not to say that these studies have failed to produce useful data; indeed, a great number of the investigations on channelisation have been carried out in this way.

The strongest and most expansive information on the impacts of channelisation and recovery rates comes from the US. However White (1973), in commenting on the results of such studies stated that:

> ***some of the effects on habitat as well as the disappearance of the fishery are so obvious and final that many observers must feel close study superfluous.***

Clearly the way channelisation was approached in the early days was very insensitive to the environment and there seems to have been a level of frustration among biologists as to the level of destruction and the obvious impact on habitats.

The first before-and-after studies on the impacts of channelisation in the British Isles were carried out in Ireland with the three investigations on the Bunree (Toner *et al* 1965), the Camowen (Kennedy *et al* 1983) and the Trimblestown (McCarthy 1977, 1983), and follow-up studies by O’Grady (1991b) and O'Grady & King (1992). These landmark studies provided much useful information on the potential for rivers to recover both morphologically and ecologically. However, all three rivers were of relatively high gradient and therefore had considerable potential for natural recovery, and it is in some ways regrettable that similar studies were not initiated in other channel types where the potential for recovery may have been much lower. For example, it is now clear that low gradient sections of rivers have considerably lower potential for recovery due to the lack of hydraulic energy in the modified channel which is insufficient to erode coarse materials from the riverbed and banks. Bed and bank subsoil conditions are also important as a source of these materials. Moreover, in some cases excavation has entirely removed the coarse substrates forming the riverbed, and exposed dense, hard layers of boulder clay which have persisted for many years to the overall detriment of the aquatic community.

As a result of the above studies there has been a misconception in some circles that most rivers will recover from a drainage scheme within 5-10 years, but it is clear that this is not the case, and that many channels have shown little recovery in morphology 60 years after drainage (O’Grady 2006). Recovery is therefore an extremely variable process which is dependent on the natural morphological and fluvial properties of the river, and also on the extent and severity of the proposed engineering works.

Much of the research carried out on the impacts of drainage has traditionally focused on trout and salmon, and this is the case in Ireland where all of the major drainage scheme catchments are dominated by salmonids (O'Grady & Curtin 1993). However Punchard *et al* (2003) have commented that several of the generally common and widely distributed species have been relatively poorly studied, even though they may be relatively important in functional or conservation terms. It is noted that in Ireland the CFB and the OPW have addressed these issues through the EDM Programme with studies on coarse fish and Annexe II species (lamprey and crayfish) in drainage scheme channels.

With regard to the application of physical restoration works and their potential to facilitate recovery of fish stocks and stream biota in general, a frequent criticism has been that such schemes were opportunistic and lacked proper scientific evaluation (Mann & Winfield 1992; Pretty *et al* 2003). This can not be said of the enhancement works carried out in Ireland, many of which have been subject to robust and thorough monitoring and have generally demonstrated the very positive effects of such programmes.

9 CASE STUDIES

9.1 Overview

The impacts of channelisation have been outlined in Section 4 of this review. The objective of this section is to establish worked examples or case studies which illustrate the impacts of channelisation works on selected features of river ecology and channel processes. Rivers selected for this exercise are the Ulster Blackwater (Co Tyrone/Armagh/Monaghan) and the River Maine (Co Antrim), which were subject to the last two major drainage schemes in N Ireland. Both rivers are major tributaries of Lough Neagh, the largest lake in Ireland, which discharges to the River Bann at its northern end (Figure 3).

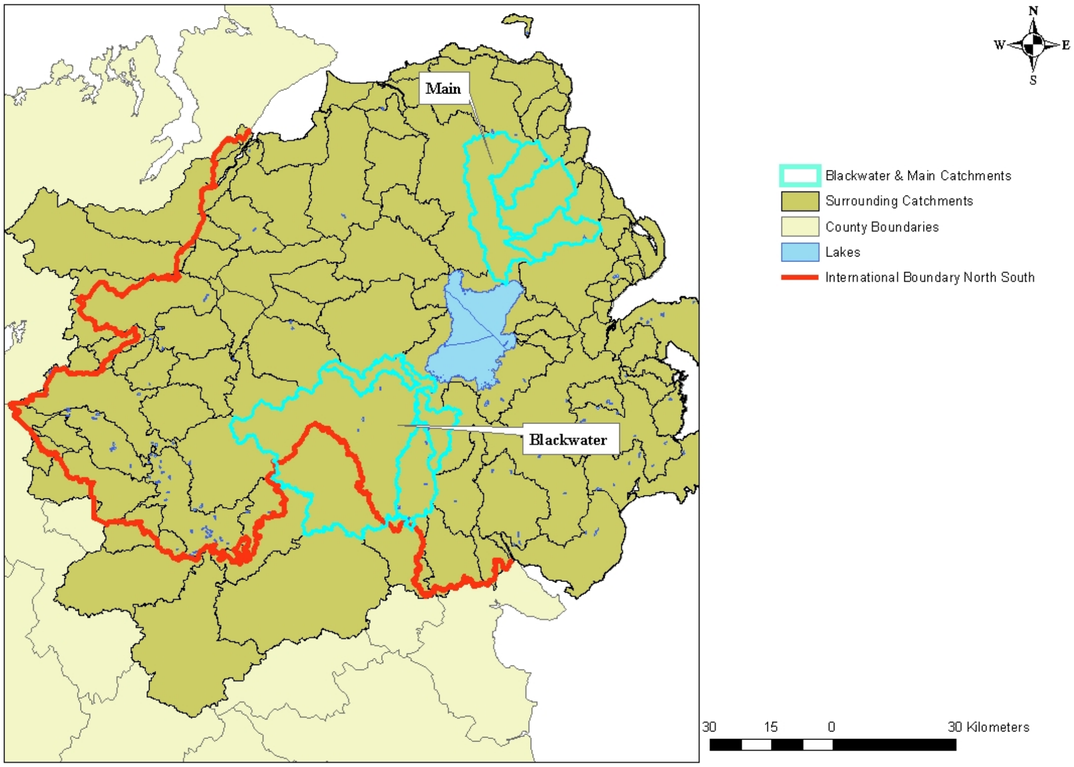

Figure 3 Location of Blackwater and Maine catchments

Through the Lower Bann Scheme, carried out in the 1930s, the water level of the lough was lowered, and sluices were installed at 3 points to regulate flow so that the level could be maintained at 16.3m OD (Wilcock 1979). This drainage scheme also increased the capacity of the River Bann by nearly 30% and facilitated the drainage of agricultural land surrounding the lough.

In 1952 the control level was reduced to 15.7m OD, and a further reduction 1959 means that the level of the lough can now be regulated between 15.24m and 15.39m OD (Wilcock 1979; Donnelly 1986). This most recent lowering of the lough facilitated Phase 1 of the Blackwater Drainage in the 1960s on the lower section of the river adjacent to the lough.

9.2 River Blackwater

The Blackwater is approximately 85 km in length and discharges to the south western corner of Lough Neagh from a catchment extending over an area of 1490 km². It is a cross-border catchment with a significant stretch in the middle reaches of the river forming the county boundary between counties Tyrone and Monaghan. The main Blackwater is joined in its middle reach by the Monaghan Blackwater which drains the numerous lakes around Monaghan town. It is an area of high annual rainfall, averaging 1030mm, and the agricultural land is mainly grassland pasture. The fish fauna of the Blackwater is dominated by salmonids in the middle and upper reaches, with abundant cyprinids in the lower reaches.

9.2.1 Blackwater Drainage Scheme

Phase 1 of the drainage scheme carried out in the 1960s drained an area of 533 km² at the lower end of the catchment, while Phase II, implemented in 1985, took in the remaining 957 km² of land, with 568 km² in N Ireland and 389 km² in ROI. Phase II involved the drainage of 60km of main channel along with 296km of additional watercourses in NI and 256km in ROI. The objectives of the scheme were that:

- watercourses should be capable of containing a 1 in 3 year flood
- the water level in the dry season should give sufficient freeboard to allow free discharge of field drainage systems

Prior to Phase II it was known that the soils of the area were potentially rich, with large areas of brown earths and low humic clays (Johnston *et al* 1994). It was considered that better drainage would lead to biological improvement of the soils and improved trafficability, which would enable the land to be farmed to its full potential.

The scheme was commenced in 1985 and substantially completed by 1989, with works continuing into the early 1990s on minor watercourses. Deepening of the main channel by up to 2.75m (9 feet) was carried out in some areas. Fisheries mitigation and remedial measures were incorporated into the scheme, but additional enhancement measures were implemented subsequent to the completion of drainage works (see Section 6.4).

9.2.2 Impacts: Sediment transport

The impacts of increased sediment transport and deposition on river ecology have been outlined in Section 4, along with the impacts of increased turbidity and high levels of suspended solids on survival and abundance in the aquatic community. An indication of the level of sediment transport before, during and after the Blackwater Drainage Scheme can be inferred from routine measurements of suspended solids recorded by EHS from several locations on the river, some dating bank to 1973. Samples were generally collected on a monthly basis with 10-12 samples per year although in some years more than 20 measurements were recorded.

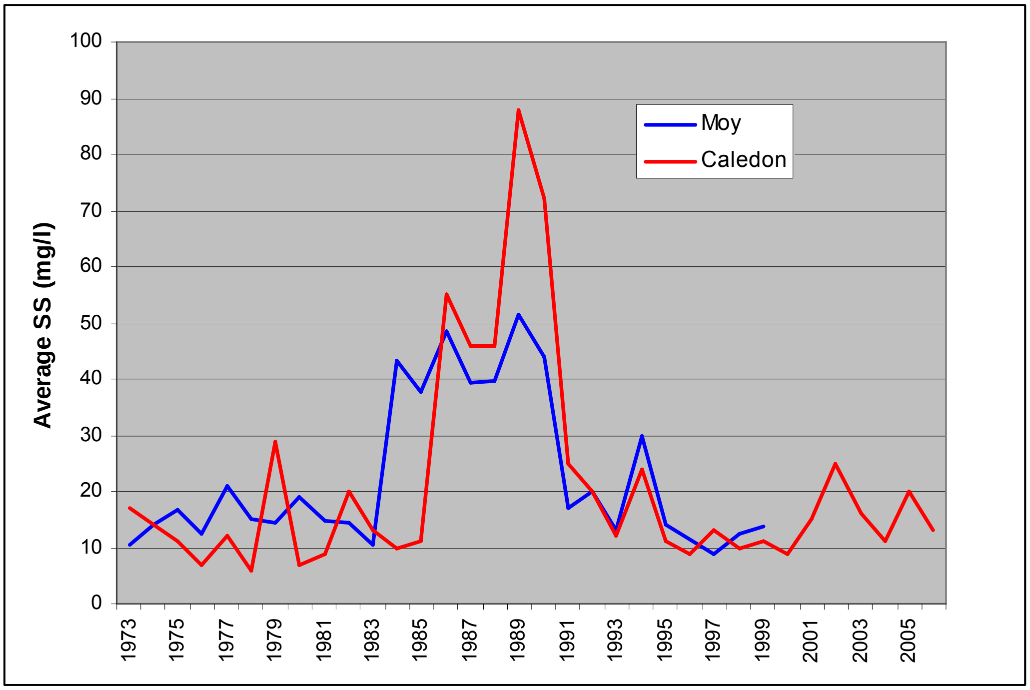

Figure 4 Average annual SS concentrations on the R Blackwater, 1973-2006 (Source: EHS)

Average annual SS concentrations from 2 sites spanning this period are shown in Figure 4. It is clear that, during the drainage scheme (1985-90), there was a significant elevation in suspended solids and the level of sediment transport. The EC Freshwater Fish Directive (78/659/EEC) specifies a guideline value of 25 mg/l for both salmonid and cyprinid waters and, outside of the drainage period, the Blackwater has on average remained broadly within this limit.

9.2.3 Impacts: Macrophytes

Macrophytes are an important component for aquatic ecosystems and are widely used to establish ecological quality and as indicators of environmental change. Most are non-mobile and therefore cannot avoid changes in environmental factors - the perennial species are then good indicators of more persistent and constant habitat change.

To examine the impacts of the drainage scheme, data from the EHS monitoring programme was used to compare macrophyte assemblages from the Blackwater and the Finn River (Co Fermanagh), an un-drained river system. Both are lowland calcareous river systems and the two catchments are located adjacent to each other and straddle the international border (Figure 5). The Finn was scheduled for a drainage scheme to follow the Blackwater Scheme but this has never been implemented.

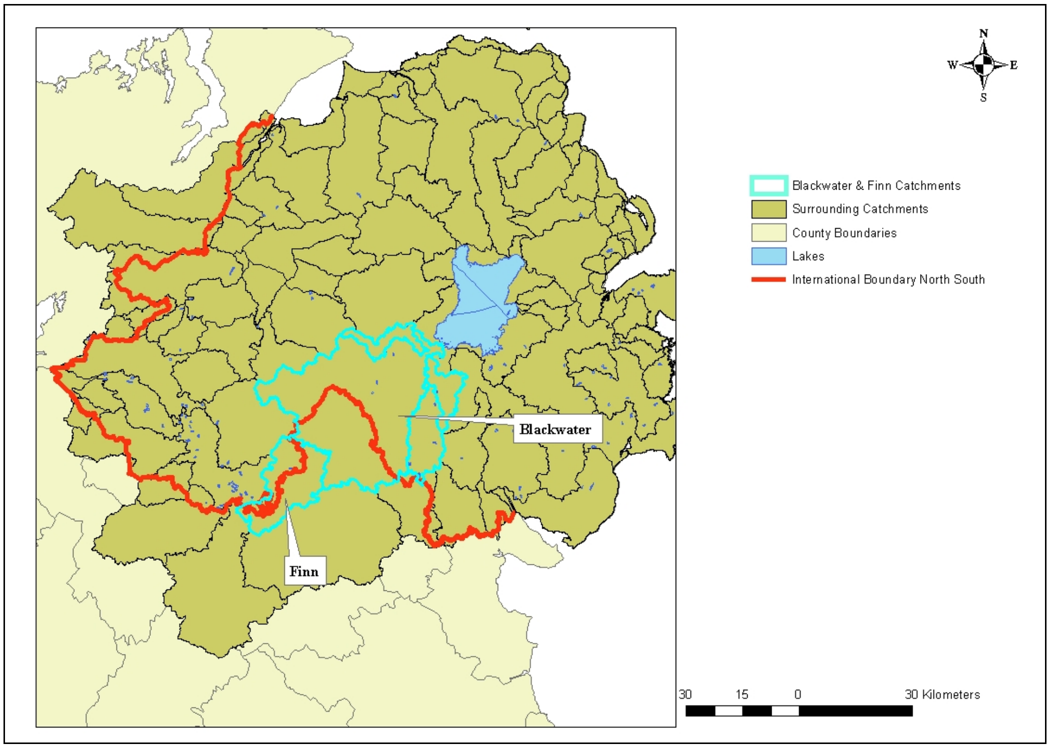

Figure 5 Location of Blackwater and Finn catchments

A single site was selected from each river with similar general characteristics in that they were both located in lowland areas with low gradient and at the lower end of their respective catchments. The objectives of this investigation were:

- to establish any differences in the abundance and diversity of macrophytes between the two sites
- to ascertain the main species differences "before and after" drainage of the Blackwater
- to establish if a pattern of recovery can be detected in the Blackwater based on a comparison of field results from 1998, 2002 & 2006.

9.2.3.1 Datasets and methods

All results used in this study were obtained from the Environment and Heritage Service (EHS) and form part of their annual river monitoring programme. A single site from each river has been sampled by EHS - both have similar general characteristics in that they were located in lowland areas with low gradient and at the lower end of their respective catchments. Data on the macrophyte assemblages at each site had been collected according to the Mean Trophic Rank (MTR) methodology for assessment of trophic status as an indicator of biological quality.

The MTR system is based on the tolerance of different species to eutrophic waters, but for this exercise only data on species presence and percentage cover was required. The percentage cover recorded in the field sheets was used to examine differences in species diversity and abundance between the Blackwater and Finn sites which, in their natural state, should be broadly similar in terms of aquatic flora. Community types were assessed and details drawn out as to the whether the morphological impacts of drainage have altered the macrophyte community in the Blackwater based on a comparison with the Finn.

The macrophyte species lists from the 2 sites are shown in Tables 3 and 4, along with the percentage cover for each species – the numbers of species observed at each site for the 3 sample years over the 10 year period are illustrated in Figure 6.

Location	**Blackwater at Bonds Bridge**			
EU Code	**GBNI1NB030307132**			
IGR	**H 8730 5861**			
Survey Year		**1998**	**2002**	**2007**
			Percentage cover	
Species	*Angelica sylvestris*			0.01
	Epilobium hirsutum			0.01
	Myosotis scorpioides		0.01	
	Nuphar lutea	0.5	0.01	8
	Oenanthe crocata			0.01
	Solanum dulcamara	0.1		0.01
	Butomus umbellatus	0.2		1
	Elodea nuttallii			1
	Lemna minor	0.01	0.5	0.01
	Lemna polyrhiza		0.1	0.01
	Phalaris arundinacea	0.1	1	3
	Potamogeton lucens	0.5		5
	Potamogeton natans	2	3	15
	Sparganium emersum	0.5	0.01	
	Sparganium erectum	2	5	12
	Cladophora glomerata			0.01
	Amblystegium riparium		0.01	
	Cinclidotis fontius	0.05		0.1
	Polygonum amphibium	0.01		
	Combined	**5.97**	**9.64**	**45.17**

Table 3 Percentage cover of macrophyte species at Bond’s Bridge, R Blackwater, 1998, 2002 & 2007 (Source: EHS)

Location	**FINN (ERNE) R AT WATTLE BR**			
EU Code	**GBNI1NW363602069**			
IGR	**H4250 2030**			
Survey Year		**1998**	**2002**	**2007**
			Percentage cover	
Species	*Alisma lanceolatum*	0.01		
	Alisma plantago aquatica			0.01
	Amblystegium fuviatile		0.01	
	Angelica sylvestris			0.01
	Apium nodiflorum	2	0.01	0.1
	Berula erecta	0.1	0.1	0.5
	Bidens tripartia			
	Butomus umbellatus		0.3	0.3
	Callitriche obtusangula	0.01	0.05	
	Callitriche spp		0.01	0.01
	Cladophora glomerata	5	1	
	Elodea canadensis		0.01	
	Equisetum fluviatile	0.5		0.2
	Fontinalis antpyretica		0.01	
	Glyceria fluitans	5	0.1	0.1
	Glyceria maxima			
	Iris pseudacorus			0.01
	Lemna trisulca		0.1	0.01
	Lemna minor	0.01	0.1	0.1
	Lemna polyrhiza		0.1	0.1
	Mentha aquatica	0.1		
	Menyanthes trifoliata	1.5	0.01	0.5
	Myosotis scorpioides	0.5	0.01	0.01
	Myriophyllum alternifolium		0.1	
	Myriophyllum spicatum	0.01		
	Nuphar lutea	1.5	5	1
	Phalaris arundinacea		0.2	0.5
	Phragmites australis	1		0.2
	Potamogeton lucens	0.1	0.01	0.1
	Rhytidiadephus	0.01		
	Rorippa amphibia		0.1	0.8
	Rorippa nasturtium-aquati		0.05	0.1
	Schoenoplectus sp.	4	2	5
	Sium latifolium	0.1	0.01	0.2
	Sparganium emersum	1.5	1	0.1
	Sparganium erectum	2.5		0.3
	sponge	5		
	Stachys palustris			0.01
	Typha latifolia			0.1
	Veronica anagallis-aquatica	0.1	0.01	0.01
	Combined	**30.55**	**10.4**	**10.38**

Table 4 Percentage cover of macrophyte species at Wattle Bridge, Finn R (co Fermanagh), 1998, 2002 & 2007 (Source: EHS)

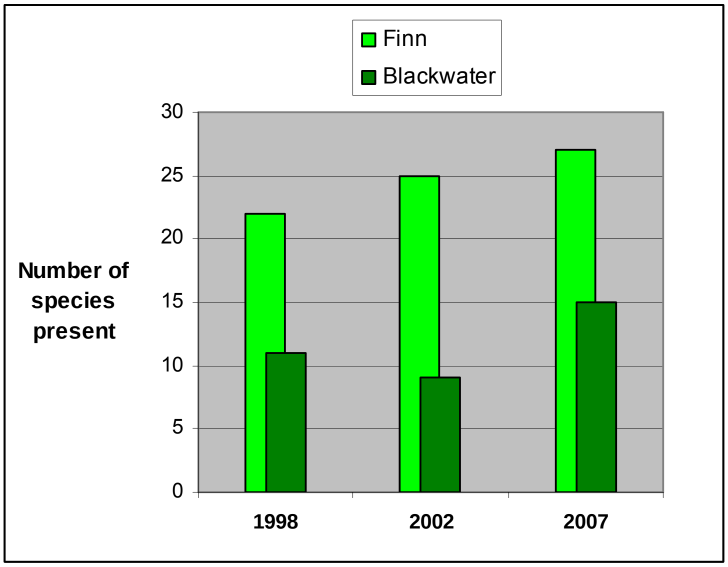

Figure 6 Abundance of Macrophyte species (Source: EHS)

9.2.3.2 Macrophyte assemblages

Clearly there has been a greater number of macrophyte species observed at the Finn site on all sampling occasions than at the Blackwater site.

The Finn overall supports a community characterised by a large mixed assemblage of emergents (*Berula* sp., *Glyceria* sp., *Mentha aquatica*, *Phragmites* sp., *Phalaris* sp., and *Menyanthes trifoliata*), free floating (*Lemna trisulca* and *Lemna minor*), floating leaved (*Glyceria* sp., *Nuphar lutea*, *Menyanthes trifoliata*, *Sparganium erectum* and *Sparganium emersum*) and submerged species (*Myriophyllum spicatum*). The filamentous green alga *Cladophora* sp. was also abundant in 1998 but showed a marked decrease from 1998 to 2002 followed by no record for the 2007 results. The yellow water lily (*Nuphar lutea*) was particularly abundant throughout the three survey years.

The Blackwater, in contrast, does not support a large mixed assemblage of emergents, but is essentially dominated by marginal species, initially *Sparganium emersum* and *Potamogeton natans,* with *Phalaris arundinacea* and *Nuphar lutea* increasing their coverage by 2007. A number of additional marginal and bankside species have been detected at a low level in some years (*Solanum dulcamara, Butomus umbellatus, Myosotis scorpioides*), while others have appeared for the first time in 2007 (*Angelica sylvestris, Epilobium hirsutum, Oenanthe crocata*).

The Blackwater has less than half the total number of species of the Finn in 1998. It also shows a slight decrease from 1998 to 2002 which may be due to other external environmental factors such as pollution incidents or a change in the hydrological flow regime. The 2007 figures do however show an overall increase from 1998 but are still significantly lower than that of the un-impacted Finn site.

Figures 7-9 illustrate the relative species coverage between the Finn and Blackwater from the 1998, 2002 and 2007 field results. The Finn displays a greater number of species with a range of different values for percentage cover, in contrast to the Blackwater which is dominated by a limited range of species (*Potamogeton natans*, *Sparganium erectum, Nuphar lutea, Potamogeton lucens* & *Phalaris arundinacea*), apparently becoming increasingly dominant over the 10 year period.

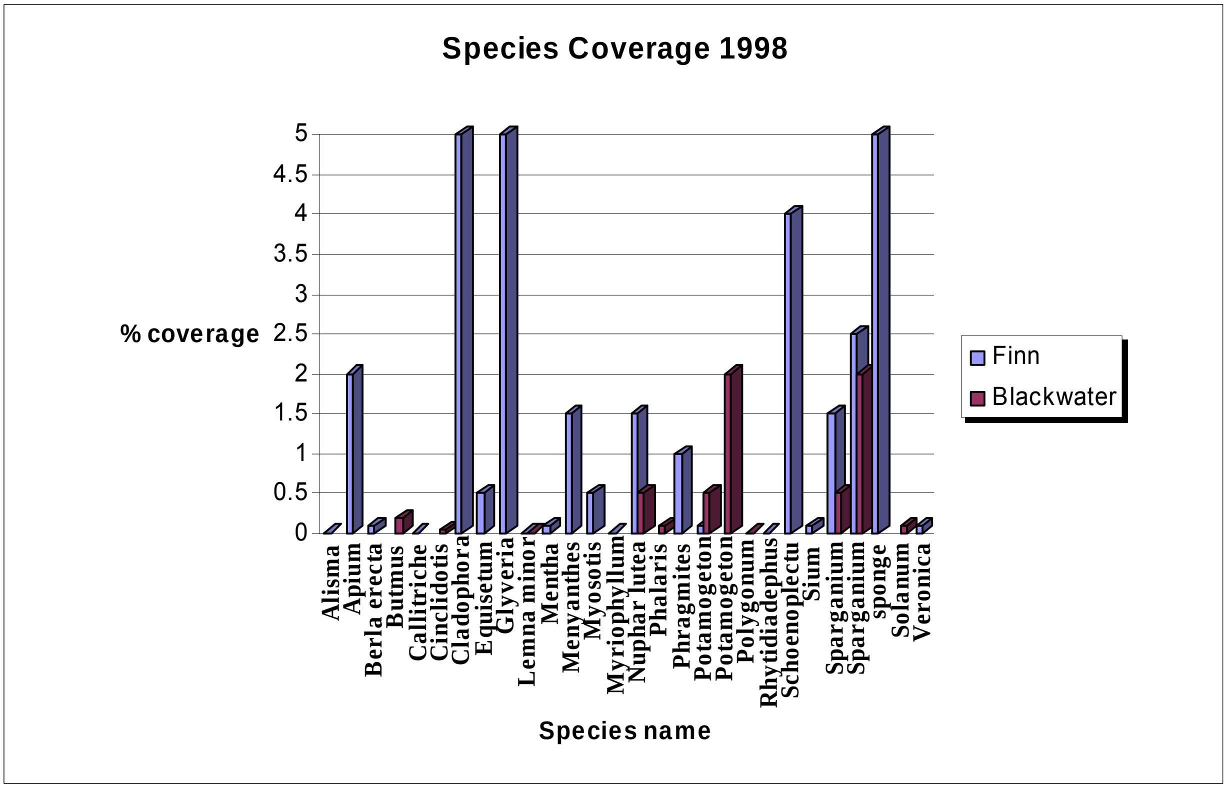

Figure 7 Macrophyte species coverage at sampling sites on the Finn and Blackwater, 1998 (Source: EHS)

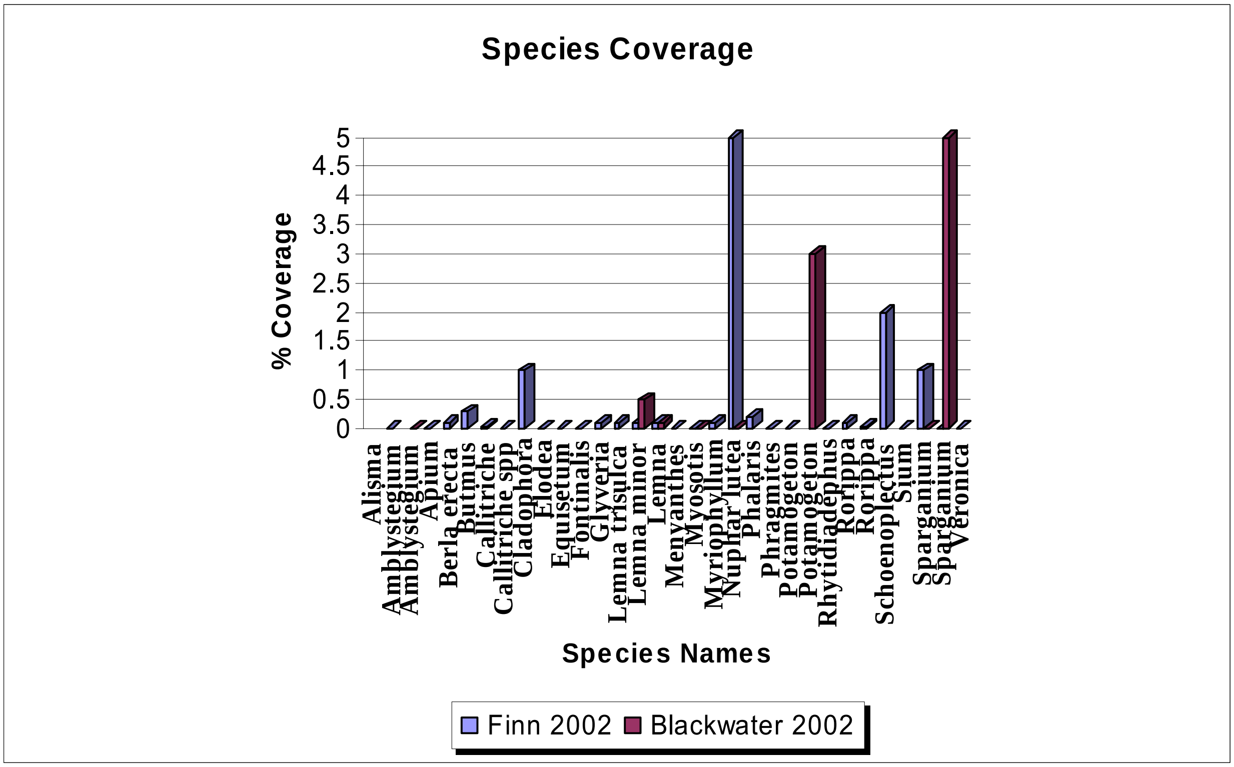

Figure 8 Macrophyte species coverage at sampling sites on the Finn and Blackwater, 2002 (Source: EHS)

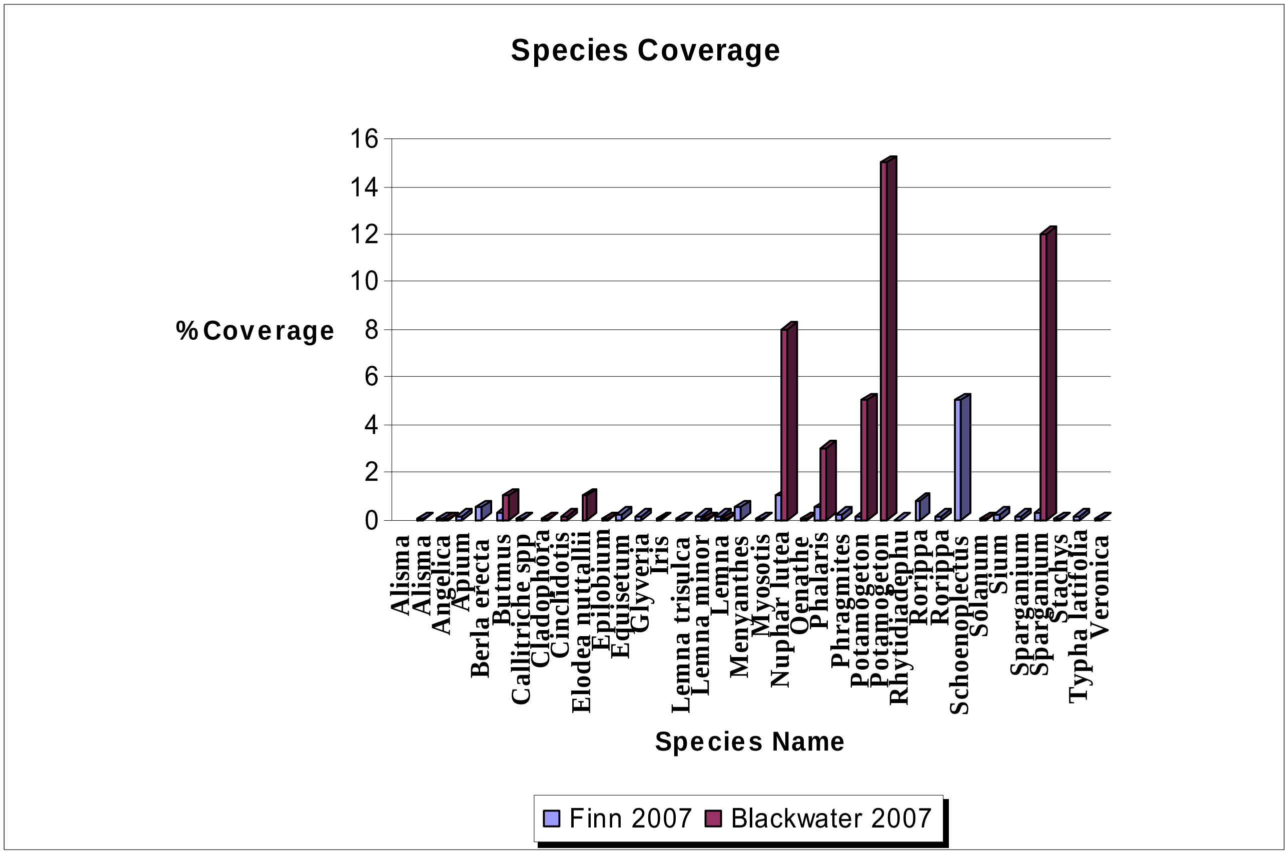

Figure 9 Macrophyte species coverage at sampling sites on the Finn and Blackwater, 2007 (Source: EHS)

9.2.3.3 Conclusions

The Finn is characterised by a mosaic of lowland species which would be expected on a lowland, calcareous river in Ireland. It has a rich variety of species, especially marginals and bankside varieties, but also including a number of aquatic species (e.g. *Callitriche, Fontinalis* & *Myriophyllum*) favouring more coarse-textured substrates.

The Blackwater, in contrast, has a limited flora which is essentially limited to marginal and bankside species, 3 of which dominate the macrophyte community (*Potamogeton natans*, *Sparganium erectum* & *Nuphar lutea*). This is consistent with observations in other lowland drained channels in which conditions may be altered in favour of low species diversity regimes as outlined in Section 5.4.1.

After widening and deepening of the channel, clays are exposed and present a difficult medium for plants to colonise, resulting in a barren or sparse macrophyte assemblage. However the channel gradually accumulates deposited material along the margins, and this material can be colonised by marginal plants, which in turn promote further siltation and increased macrophyte growth.

The macrophyte community of the Blackwater at this location therefore appears to be undergoing a process of recovery in line with the changing physical characteristics of the channel. Clearly the marginal and bankside species are the first to recover, and the site is now dominated by a limited range of species, in contrast to the relatively species-rich assemblage observed on the un-drained R Finn. The persistence of these impacts on the macrophyte community more than 15 years after completion of the drainage scheme indicates that ecological recovery in this area of the catchment may take many years.

9.3 River Maine

The Maine is approximately 50 km in length and drains a catchment of 700 km² before discharging to the north eastern corner of Lough Neagh (Fig 10). There are 3 major tributaries which flow off the Antrim Plateau to join with the Maine. In the upper reaches there is an extensive area of peat bog with a very shallow gradient of 1 in 10,000 (0.01%), while the middle reach falls through an area in which the gradient rises to 1 in 200 (0.50%). It is an area of high annual rainfall which regularly exceeds 1600 mm. The fish fauna is dominated by salmonids.

9.3.1 River Maine Drainage

An initial drainage scheme on the Maine took place on the lower reaches between 1958 and 1963. Works were undertaken on the main channel from its confluence with the Braid, and extended downstream of Randalstown close to L Neagh. Further works in connection with this early scheme were carried out on the Braid tributary up to the town of Ballymena.

The subsequent River Maine Drainage Scheme related to the upper reaches of the river and was the subject of a Public Inquiry in 1971 (Hutton 1972). The works involved channel widening, deepening and straightening over 26 km of channel between Ballymena and Dunloy. By lowering outfalls and increasing channel capacity, the scheme was designed to provide a drainage benefit to 4300 ha and to reduce flooding on 730 ha of agricultural land (Wilcock & Essery 1991a). Various fisheries mitigation measures were incorporated in the scheme during the programme of works including the construction of groynes, pools, deflectors and fish passes along with re-stoning of the bed and the placement of large rocks. In addition, the engineering works were carried out from one bank only to preserve tree growth and reduce the overall environmental impact. The drainage scheme was commenced in the mid 1970s and completed in 1987.

The impacts of the Maine Drainage Scheme on sediment transport as outlined by Wilcock & Essery (1991a) have been described in Section 4.3.2. Data is presented here which suggest long term morphological impacts with an indication of reduced fish holding capacity.

9.3.2 Datasets and methods

Two tributaries were identified with differing drainage histories - the River Braid has undergone an extensive drainage programme in its lower reaches during the earlier Maine Scheme, while the Kells Water has been subject only to minor localised drainage works. These two rivers represent parallel flowing, adjacent tributaries of the River Maine and are similar in terms of catchment area, overall length, land use and geology (Figure 10; Table 5).

Similar sections of the 2 tributaries were selected in terms of length, width, gradient, height above sea level and channel region (in both rivers the bottom sections which drain into the River Maine were selected). The physical dimensions of the catchments and selected sections are listed in Table 5.

Fisheries data collected on both sections were identified from the Salmon Management Plan for Northern Ireland and tabulated. Habitat information was available for each stretch and was based on the Life Cycle Unit method (Kennedy 1984). This data was available in GIS format and detailed the area of different grades and quality of salmonid habitat available in each stretch (Figure 11). Information was available from 0+ semi-quantitative electric fishing surveys from 2002-06, with six sites conducted annually within each stretch detailing the abundance of trout and salmon (Figures 12 & 13). This survey methodology has been calibrated to provide a fry abundance index (Table 6) based on the numbers of 0+ salmon or trout caught during the 5 minute survey (Crozier & Kennedy 1994).

9.3.3 Observations

Habitat

Examination of the quality and type of habitat available at the 2 sites (Figure 11) indicates that the Braid is characterised by:

- a significant area of unclassified (27%), poor quality habitat
- large areas of grade 3 spawning habitat (28%) and nursery (18.5%)
- small areas of grade 2 and 3 holding water.

These characteristics indicate that this of section of river, which was drained in the 1960s, is lacking in diversity with a rather uniform substrate with significant areas of fine gravel and a shortage of coarser substrates and deeper pools.

The Kells, on the other hand, is characterised by:

- substantial areas of grade 2 nursery (23%) and pool habitats (23%)
- an adequate area of grade 2 spawning habitat (7.5%)
- a negligible area of unclassified poor quality habitat (2%).

These characteristics are indicative of a more balanced ecosystem with greater instream diversity, more suited to the range of habitat requirements specific to the different stages of juvenile salmon and trout.

Parameter	**Braid**	**Kells**
	Catchment	
Catchment area	17600	12800
Total channel length	249	183
Land Use	Agricultural/Urban	Agricultural
Geology	Basalt	Basalt
	Comparison Stretches	
Section length	4170	3810
Mean width	17	14
Max width	20	16
Gradient (cm/100m)	23 (0.23%)	29 (0.29%)
Max Height above sea level	41.59	41.23
Min Height above sea level	31.9	30.14
Total area	72648	52159
Biological Quality: upstream (Grade)	A	B
Biological Quality: downstream (Grade)	C	B

Table 5 General characteristics of Braid & Kells catchments; physical features and biological quality of comparison stretches

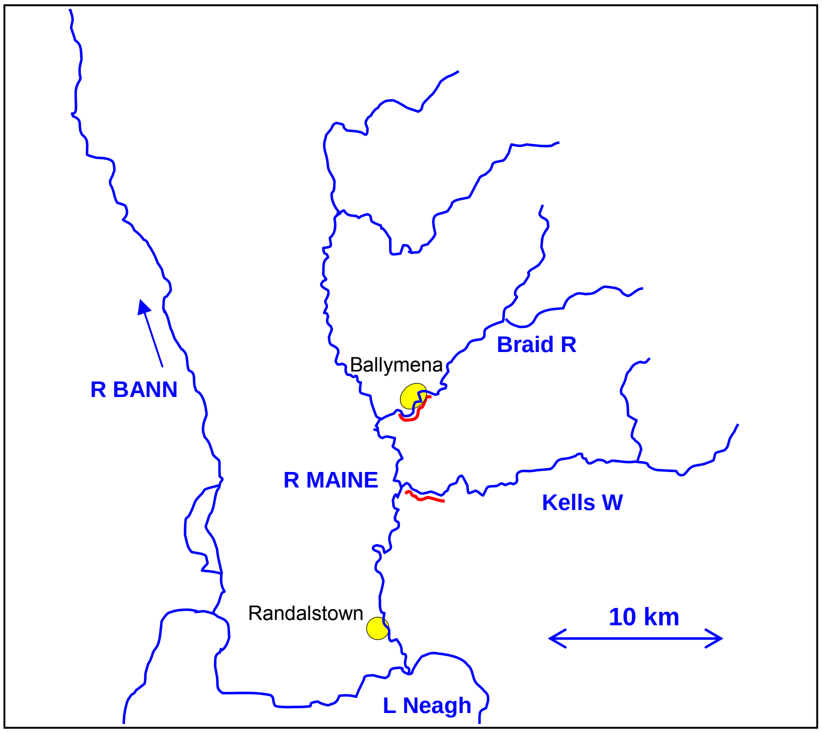

Figure 10 R Maine catchment with location of comparison stretches on R Braid and Kells W

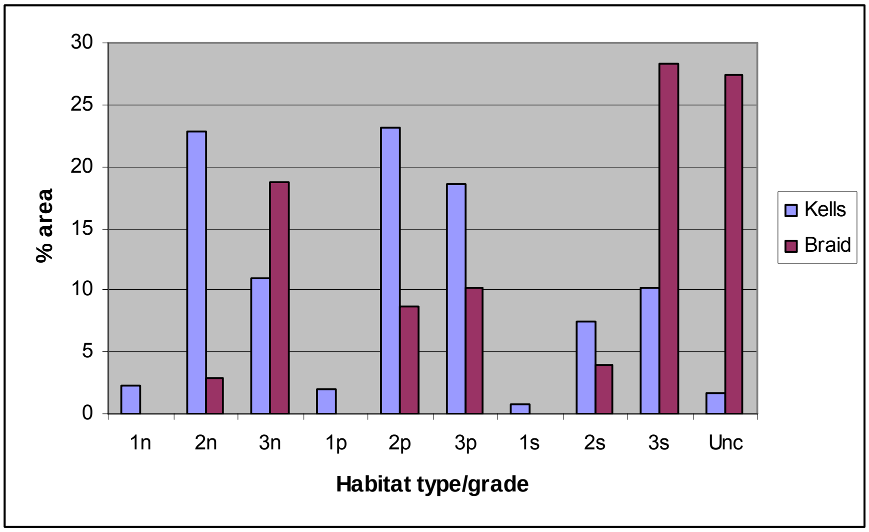

Figure 11 Relative areas of different habitat type/grade stretches of the Kells & Braid Rivers (Habitat types: n = nursery; p = pool/holding; s = spawning; Unc = unclassified/v poor; 1n = grade 1 nursery; 2n = grade 2 nursery etc)

The difference in habitat quality between these two stretches on adjacent rivers becomes clearer when habitat types are combined according to grade for each river; the Kells stretch is made up predominantly of Grade 2/3 habitat while the Braid is predominantly of Grade 3/4 habitat (Figure 12).

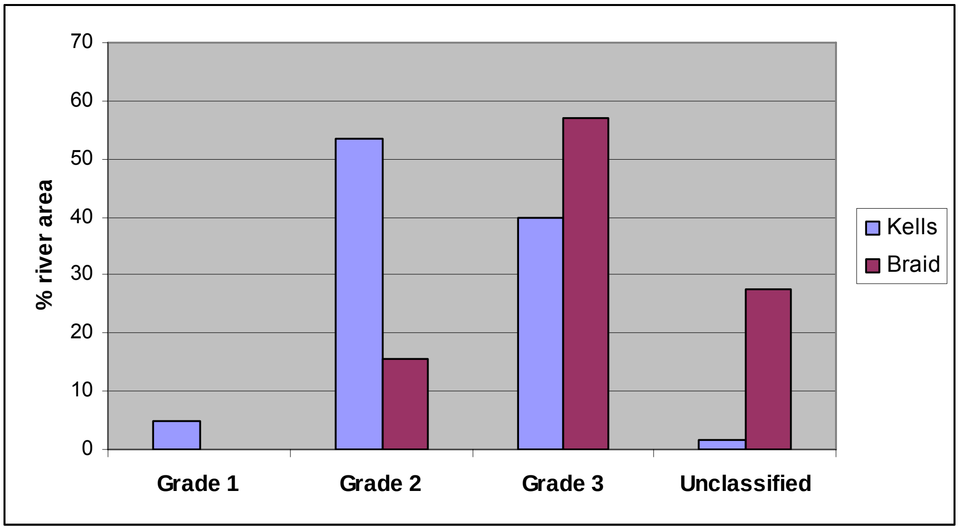

Figure 12 Comparison of habitat quality on stretches of the Kells & Braid Rivers

Fish abundance

The annual semi-quantitative electrofishing data for 0+ salmon from the 2 rivers (Figure 13) would suggest a consistent presence of salmon at the natural Kells site, although at a low level, while salmon were only occasionally detected at the drained Braid site, and at very low densities.

The electrofishing data for trout in the 2 rivers (Figure 14) suggest a continuous presence of 0+ fish at the Kells site at “poor” to “fair” densities, while abundance never rose above the “poor” category at the Braid site, and 0+ trout were completely absent in one year.

Clearly the abundance of both salmon and trout is, on average, slightly higher at the un-drained Kells site than at the drained Braid site, although this does not fully reflect the significant differences in habitat type and quality.

9.3.4 Conclusions

Major differences in habitat type and quality are evident between two geographically comparable sections of adjacent tributaries of the R Maine, which are similar in terms of catchment area, overall length, land use and geology. The impact of drainage on the lower reaches of the Braid appears to have persisted for more than 40 years in a relatively high gradient area. Morphological recovery in this stretch of river appears to be an extremely slow process, possibly due to excess widening of the channel. This is reflected to some degree in the salmonid fish populations although, in both sections, the juvenile salmonids must be regarded as at sub-optimal levels of abundance.

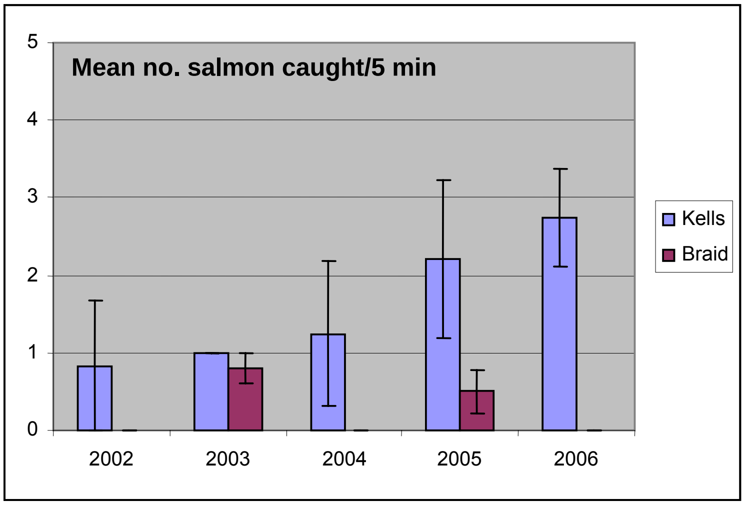

Figure 13 Abundance of 0+ salmon at sampling sites on the Kells and Braid Rivers

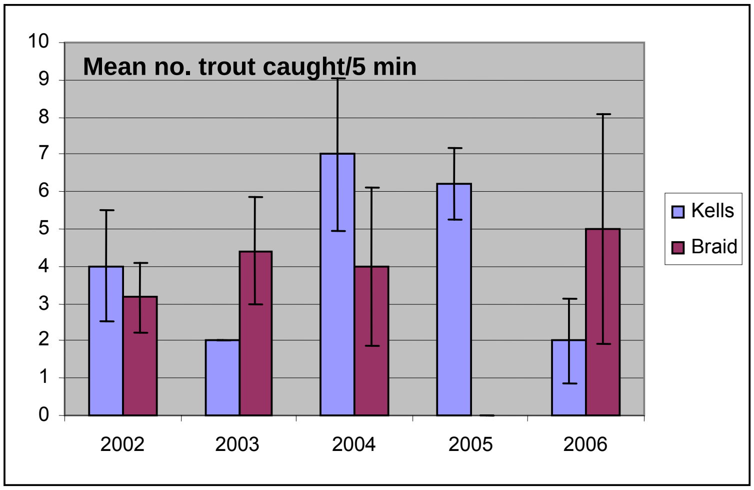

Figure 14 Abundance of 0+ trout at sampling sites on the Kells and Braid Rivers

No. 0+ fish/5 min	Classification
≥ 25	Excellent
15-24	Good
5-14	Fair
1-4	Poor
0	Absent

Table 6 0+ abundance classification for semi-quantitative electrofishing

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