Environmental impact and remediation of acid mine drainage: a management problem

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Abstract Work carried out at the abandoned copper (Cu) and sulphur (S) mine at Avoca (south east Ireland) has shown acid mine drainage (AMD) to be a multi-factor pollutant. It affects aquatic ecosystems by a number of direct and indirect pathways. Major impact areas are rivers, lakes, estuaries and coastal waters, although AMD affects different aquatic ecosystems in different ways. Due to its complexity, the impact of AMD is difficult to quantify and predict, especially in riverine systems. Polutional effects of AMD are complex but can be categorized as (a) metal toxicity, (b) sedimentation processes, (c) acidity, and (d) salinization. Remediation of such impacts requires a systems management approach which is outlined. A number of working procedures which have been developed to characterise AMD sites, to produce surface water quality management plans, and to remediate mine sites and AMD are all discussed.

Key words Acid mine drainage · Acid rock drainage · Environmental impact · Management systems

Acid mine drainage

In the past two decades there has been increasing public awareness of the potential environmental hazards arising from mining activities, in particular acid mine drainage (AMD). Although any mineral deposit which contains sulphide is a potential source of AMD, certain types of mining are more prone than others. There are records of acid drainage where coal, pyritic sulphur, copper, zinc, silver and lead among others have been mined. Coals and shales of marine origin tend to contain higher concentrations of sulphide than strata from freshwater palaeoenvironments (Sullivan and others 1995). Some of the more important sulphide minerals are listed in Table 1.

Iron disulphide (FeS_2), or pyrite, is the most important mineral associated with AMD generation. The breakdown of pyrite is affected by variations in its morphology such as crystallinity, particle size and reactivity; crystalline forms in particular are less subject to weathering and oxidation than amorphic forms (Riley 1960; Barnes and Romberger 1968). The reactions involved in the breakdown of pyrite in the presence of water and oxygen to yield sulphuric acid are well known (Singer and Strumm 1970).

$$FeS_2 + {}^7/_2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4{}^{2+} + 2H^+ \quad (1)$$

$$Fe^{2+} + {}^1/_4O_2 + H^+ \rightarrow Fe^{3+} + {}^1/_2H_2O \quad (2)$$

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_2 + 3H^+ \quad (3)$$

$$FeS_2 + 14Fe^{3+} + H_2O \rightarrow 12Fe^{2+} + 2SO_4{}^{2+} + 16H^+ \quad (4)$$

From these reactions it is clear that the pyrites can remain in their reduced state in undisturbed strata so long as they are anaerobic. While there are a few cases of naturally occurring acid streams, most occur as a result of mining activities.

The rate-limiting step has been shown by Singer and Strumm (1970) to be the oxidation of the ferrous iron. There is a propagation cycle between reactions (2) and (4) where Fe^{3+}, one of the products of reaction (2), acts as an oxidant of the pyrite in reaction (4), and Fe^{2+} pro-

Table 1
Major minerals associated with AMD with those that occur in the Avoca region in *italic print*

Mineral	Composition
Arsenopyrite	$FeS_2 \cdot FeAs$
Bornite	$CuFeS_4$
Chalcocite	Cu_2S
Chalcopyrite	*$CuFeS_2$*
Covellite	CuS
Galena	*PbS*
Millerite	NiS
Mobybdenite	MoS_2
Pyrite	*FeS_2*
Pyrrhhdite	$Fe_{11}S_{12}$
Sphalerite	*ZnS*

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duced by this reaction can be used as a reductant in reaction (2). As the process is limited by the oxidation of pyrite, the surface area available for oxidation determines the rate of the reaction (Gotschlich and others 1986).

Environmental impact of acid mine drainage

Acid mine drainage affects lotic systems in numerous and interactive ways. This results in multiple pressures, both direct and indirect, on the organisms comprising the community structure of the ecosystem. These effects can be loosely categorized as chemical, physical, biological and ecological, although the overall impact on the community structure is the elimination of species, simplifying the food chain and so significantly reducing ecological stability (Fig. 1). In essence, ecological stability increases with food chain complexity, and this complexity allows lotic communities in particular to cope with pollutants (e.g. organic matter, solids deposition and degradation, temperature, etc.), and to recover once the pollutional input has ceased or has been either biologically degraded or removed by physico-chemical processes. However, the effects of AMD are so multifarious that community structure collapses rapidly and totally, even though very often no single pollutant on its own would have caused such a severe ecological impact. Recovery is suppressed due to habitat elimination, niche reduction, substrate modification, the toxic nature of sediments, and bioaccumulation of metals in the flora (in particular the periphyton) and fauna.

Acid mine drainage is recognized as a multi-factor pollutant and the importance of each factor varies within and between affected systems. The main factors are the acidity itself, salinization, metal toxicity and sedimentation processes (Figs. 2–4). The overall impact is very largely controlled, not so much by the nature of the leachate draining from the mine adits, but by the buffering capacity of the receiving water and available dilution. Soft poorly buffered rivers are more severely affected than hard well-buffered systems, where the impact may be more restricted with sedimentation being the major mode of impact.
The impact of AMD is very difficult to predict due to the variability of discharge from adits, variation in adit strength and composition which varies seasonally, the effect of surface runoff from exposed areas of the mines during heavy rainfall, and the effect of the catchment discharge characteristics affecting dilution and the concentration of organic matter in the water chelating soluble metals present. Assessment is also difficult due to the complexity of the impacts, although diversity and abundance are key variables for biotic evaluation. There are no specific indicator species for AMD in affected rivers, although oligochaetes and dipterans, and chironomids in particular, are generally the dominant macro-invertebrate groups found downstream of AMD discharges. Ephemeropterans are particularly sensitive to AMD and are among the last group to recolonize rivers after contamination. Fish movement and migration is also a useful indicator. There has to be a balance/compromise drawn between simplicity and actual interactions. Actual systems may be so complex that no useful information can be obtained from attempting to model them. A simpler ap-

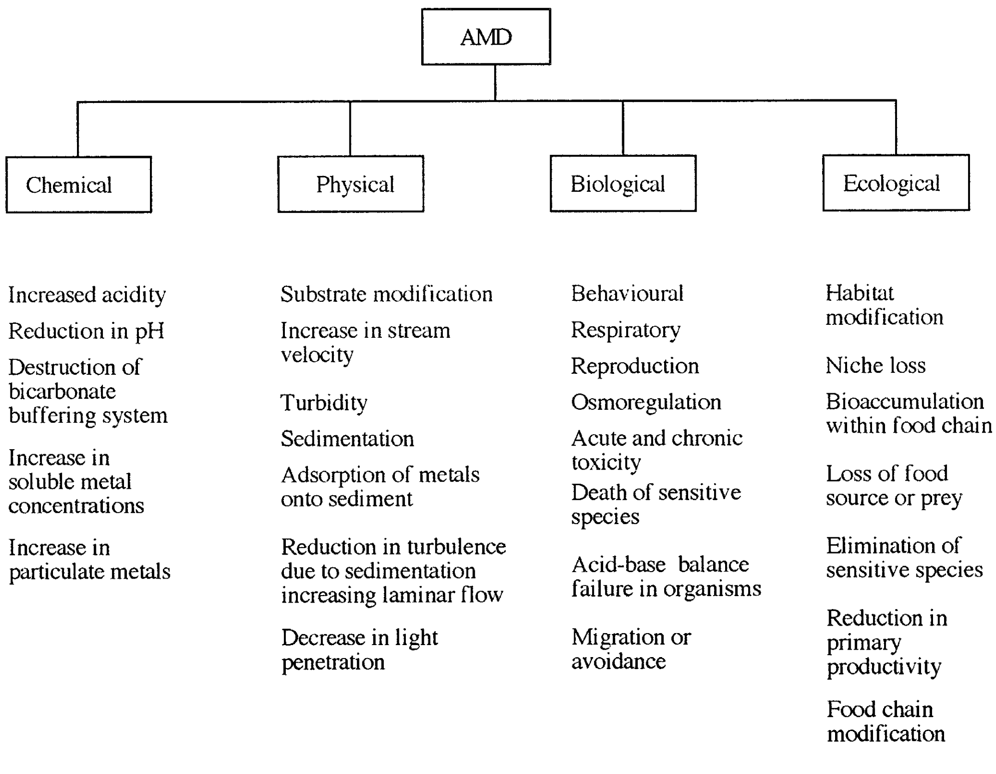

Fig. 1
The major effects of AMD on a lotic system

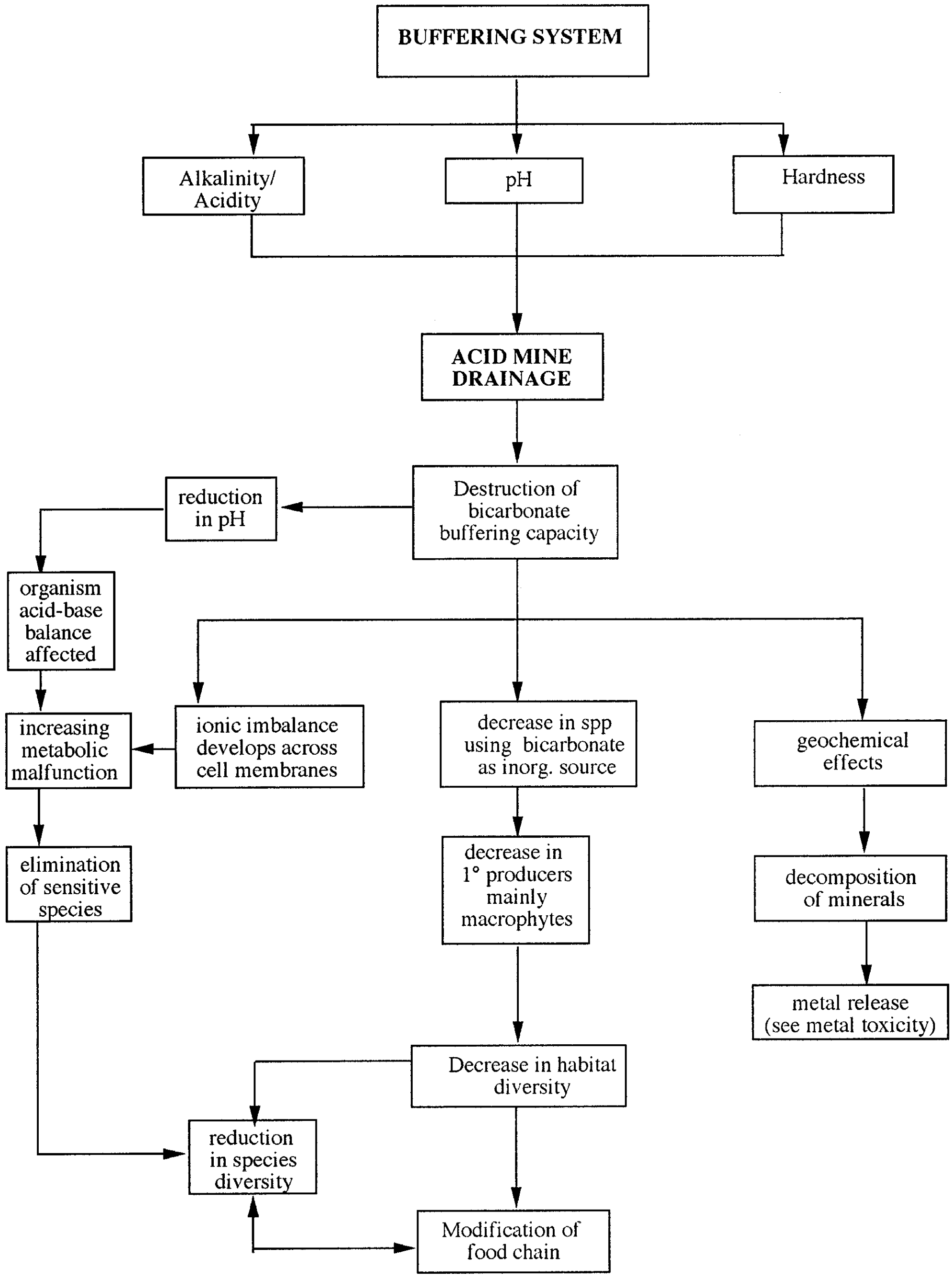

Fig. 2
Impact of acidity arising from AMD on lotic (river) systems

proach, concentrating on the major interactions, e.g. toxicity of key metals or the degree of substrate modification caused by iron precipitation which is directly linked to pH (Gray 1996), may prove to be more useful in understanding AMD impacts and predicting them.

Management approach to remediation

In order to develop cost-effective and environmentally sound strategies for the management of AMD discharges from abandoned and active mines, a systems approach to developing a protocol has been adopted. The protocol is primarily concerned with assessing the impact of AMD on surface waters, making use of the new procedures and tools developed during the Avoca project, a study on the abandoned Cu and S mines at Avoca, southeast Ireland (Fig. 5; Gray 1995a).

An acceptable protocol must achieve the following:

1. Define the area causing the problem.
2. Define the impact. It is critical to establish natural background levels.
3. Identify potential remediation goals. This is done by using various criteria for water use. The critical ques-

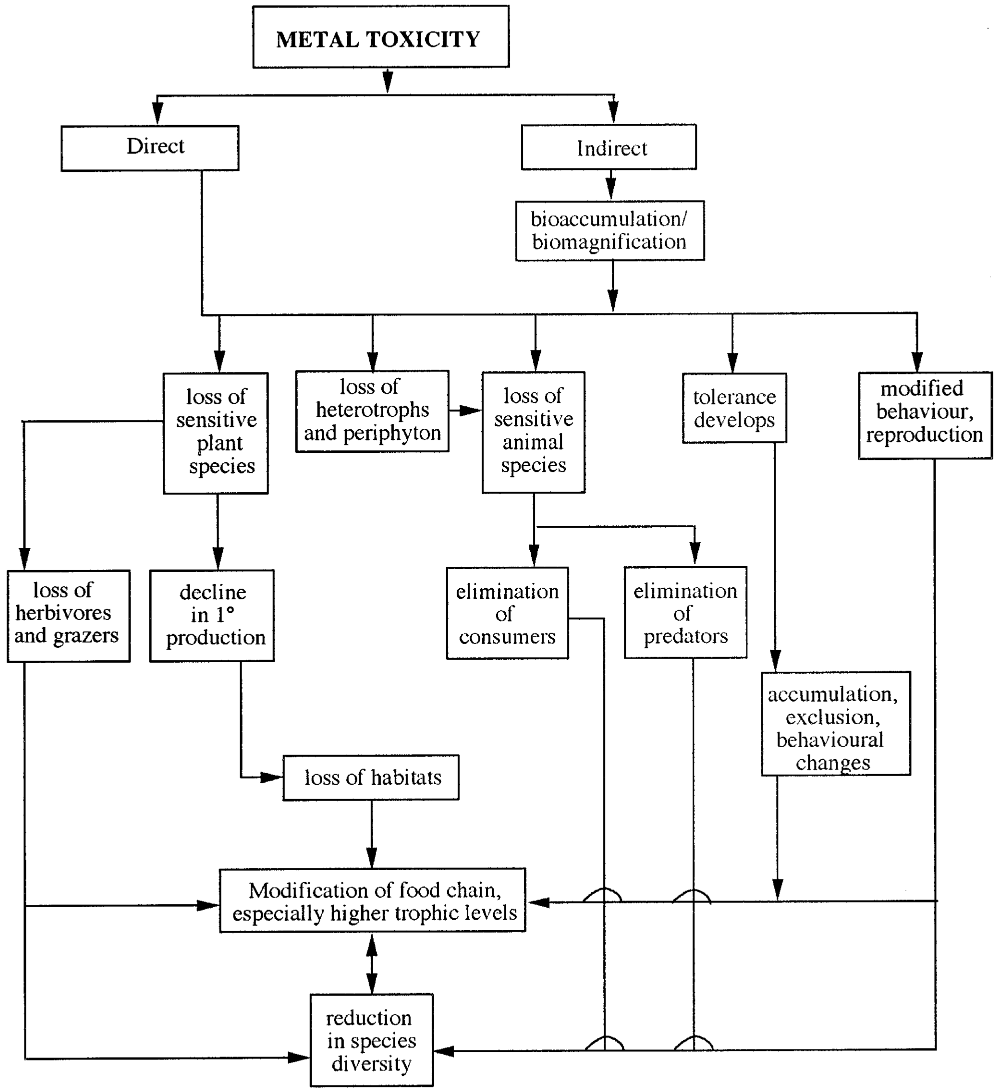

Fig. 3
Impact of heavy metals arising from AMD on lotic (river) systems

tion is whether or not the AMD discharge needs to be controlled. If the answer is yes, then the reasons why need to be clearly specified. From this, specific usage of the surface water must be specified, e.g. abstraction, amenity, recreation, salmonid-cyprinid fisheries, etc. Each water usage has its own set of water quality criteria from which standards can be formulated. The critical and physico-chemical indicators of AMD pollution must be identified (e.g. pH, acidity, SO_4, Fe, Zn, Cu, Cd, Al, As ,etc.). These are the parameters actually modified by AMD and so are the ones of primary importance in terms of regulation. The I and G values for these key parameters, under the various EU directives or other legislation, will normally be the same for adopted standards. However, if it is the biota only that is to be preserved, excluding fish which is covered by the EU Freshwater Fish Directive, then criteria must be established using toxicity testing.

4. Management. The key areas here are:
   (i) Data collection, storage and manipulation.
   (ii) Modelling data to simulate impact and establish remediation guidelines (e.g. levels of reduction of specific metals or pH, in order to achieve objectives).
5. Remediation. If remediation is required the alternatives are:
   (a) Treat all AMD from site.
   (b) Try to reduce AMD generation to acceptable levels for safe discharge.
   (c) Try to reduce AMD generation by remediation of the site (e.g. re-vegetation), to a level which can be treated prior to discharge.
   (d) Do nothing and accept permanent reduction in environmental quality.

The nature (strength) and volume of AMD can be altered by controlling generation and dilution on site. The optimum strategy for AMD reduction/modification by site remediation and the level (and type) of treatment required must be identified through cost-benefit analysis. Some remediation strategies may have adverse effects on the environment and this should be assessed using standard risk-benefit analysis. Figure 6 summarizes the major steps

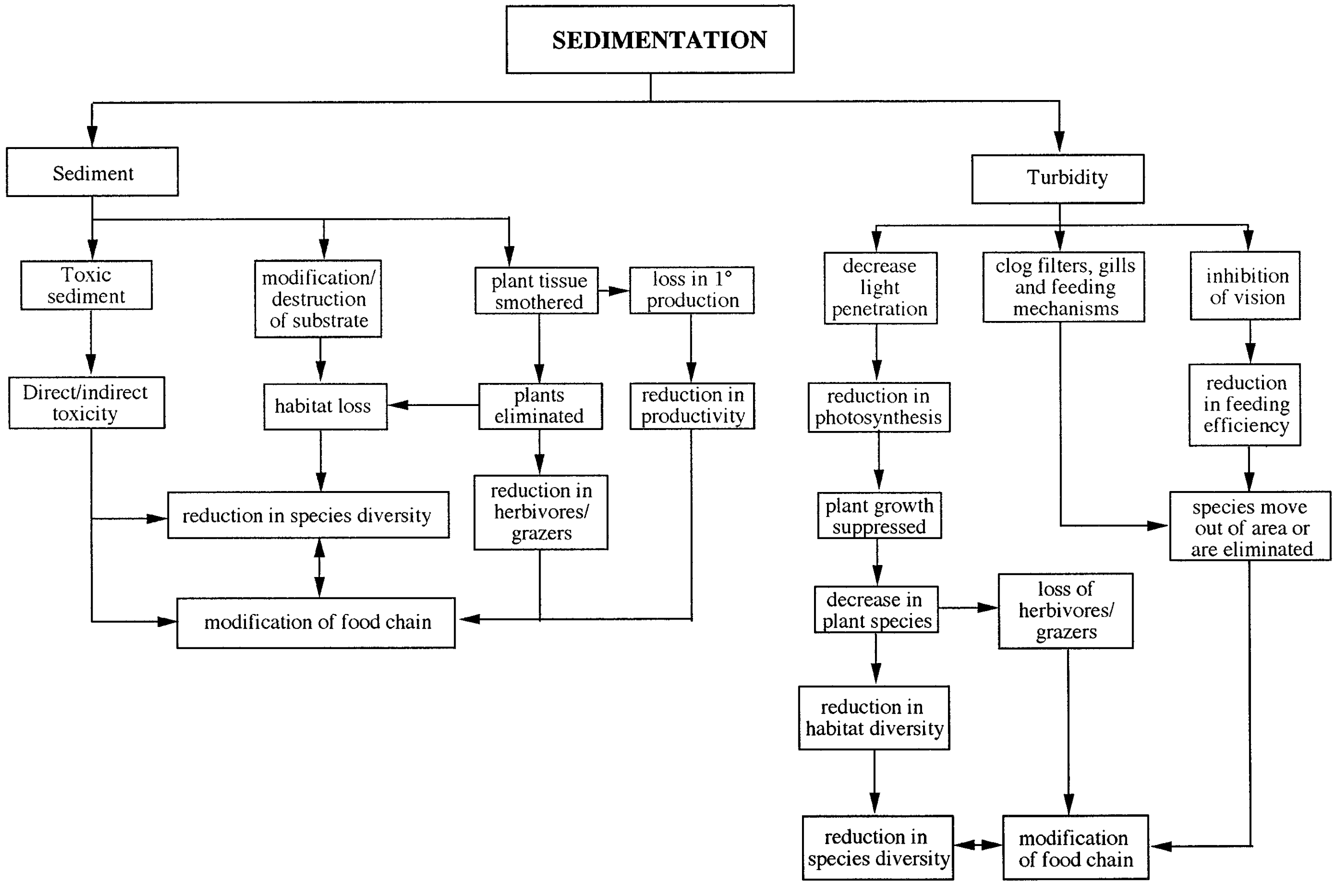

Fig. 4
Impact of sedimentation processes arising from AMD on lotic (river) systems

in the working protocol proposed at Avoca Mines to remediate AMD-impacted surface waters.

In practice, rehabilitation using the protocol described requires four discrete, yet inter-related actions. These are (a) site characterization, (b) development of an AMD water quality management protocol which should be integrated into the existing catchment water quality management plan, (c) development of a remediation strategy, and finally, (d) an implementation strategy.

A protocol for the characterization of abandoned mine sites is given by Gray and Doyle (1994) (Fig. 7), with Avoca Mines used as a worked example. The next action is the development of an AMD water quality management protocol to assess the discharges from the mines, and to predict the impact of AMD in the receiving water. An AMD water quality protocol has been prepared by Gray (1995b) which comprises five stages: (a) the establishment of water quality criteria and standards for the receiving water; (b) calculation of the natural assimilation capacity of AMD by the receiving water; (c) impact assessment, including projections over a 20-year period based on future development of the site, long-term AMD generation assessment and the effect of any site remediation work; (d) AMD control; (e) compliance monitoring and review of discharge standards. This is examined in detail below and summarised in Fig. 8.

Acid mine drainage water quality management protocol

Stage I establishes water quality criteria and standards for the river.

1. Identify beneficial uses of the river, both present and those required in future, to be protected or facilitated.
2. Compile all existing water quality data on the river, including its tributaries.
3. Examine the data collected during step 2, and determine the characteristic elements which are important in relation to AMD (e.g. alkalinity-acidity, pH, Cu, Zn, Cd, Fe, SO_4 etc.) at selected control sections along the main channel and major tributaries.
4. Define required water quality criteria to achieve water quality objectives as defined in step 1.
5. Examine international, national and local factors, including socio-economic and political factors. This will include facilitating international agreements (e.g. Paris/Oslo conventions), funding opportunities, cost-benefit analysis of remediation, etc.
6. Selection of specific water quality standards for receiving water according to step 4 with due reference to EU, national and other standards. Water quality

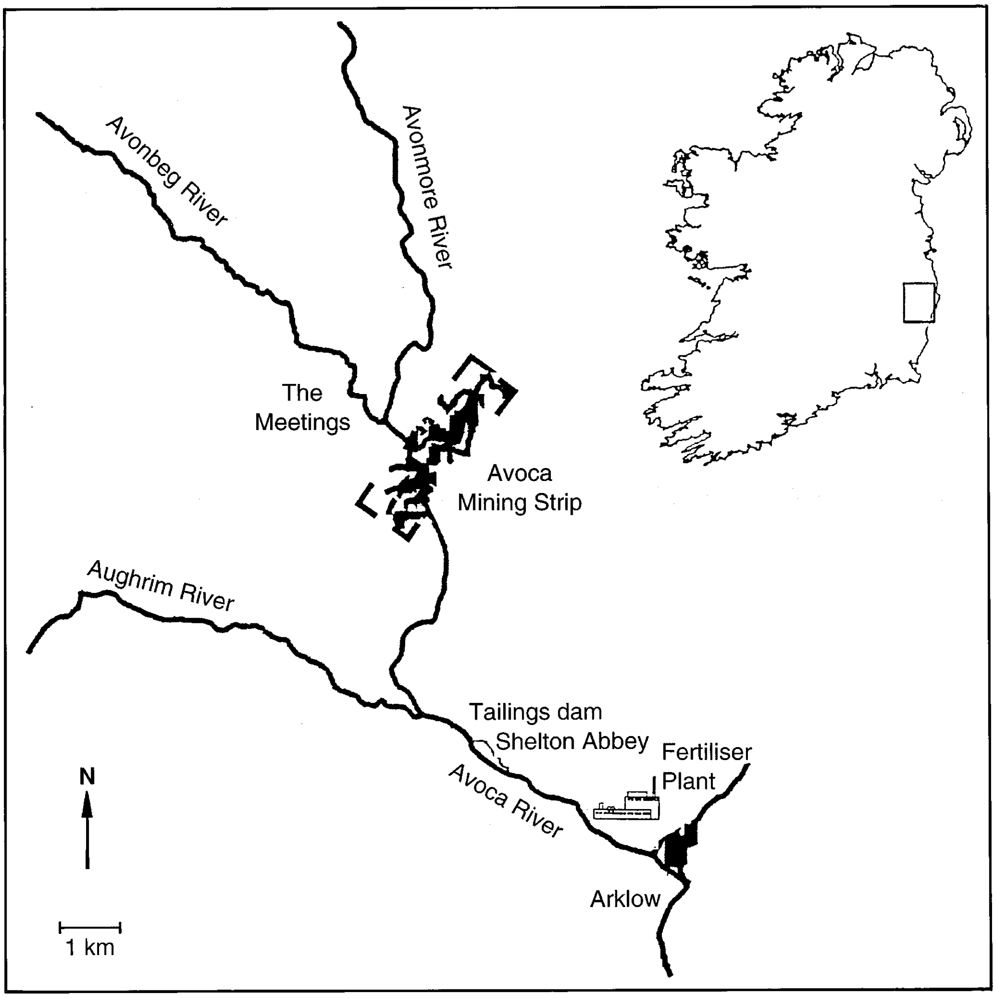

Fig. 5
The location of the Avoca Mines and the impacted Avoca River in south east Ireland, where the current study is being carried out

standards may be different to normal EU standards due to the complexity and interactive nature of the AMD and its resulting impact on the receiving water.

Stage II calculates the natural assimilation capacity of AMD by the river.

7. A hydrometric survey is required of the catchment both upstream and downstream of AMD inputs to calculate river discharge rates.
8. Water quality surveys are required to establish uncontaminated (background) chemical, physical and biological quality. These should consider the water and sediment phases separately. Establishment of the buffering capacity and key AMD parameters, flora and fauna, and sediment characteristics (including metals, particle size, etc.) are required.
9. The theoretical assimilative capacity for AMD at various points in the river should then be calculated using SO_4 (Gray, 1995a).

Stage III assesses the impact of AMD on the river.

10. The present AMD loading to the river is calculated, including diurnal and seasonal variation, in conjunction with the characterization study, by
    a) hydrometric survey of AMD-generating sites;
    b) discharge points and rate of AMD discharges calculated;
    c) chemical and physical analysis of AMD discharged at each adit.
11. The projected AMD loading is estimated for the next 20 years by
    a) examining future development of the site for mining or other uses that may alter current hydrological characterization of the site;
    b) examining long-term generation of AMD, using current models;
    c) estimation of effects of site remediation activities.
12. Using the information in steps 10 and 11, the AMD waste load to the river is calculated and projected over the next 20 years.
13. The actual impact on the river is assessed, including any recovery by a full chemical and biological assessment. The water and sediment phases are considered separately.

Stage IV sets AMD discharge consents.

14. The key AMD and river parameters are modelled, using assessment where no standards exist, to assess

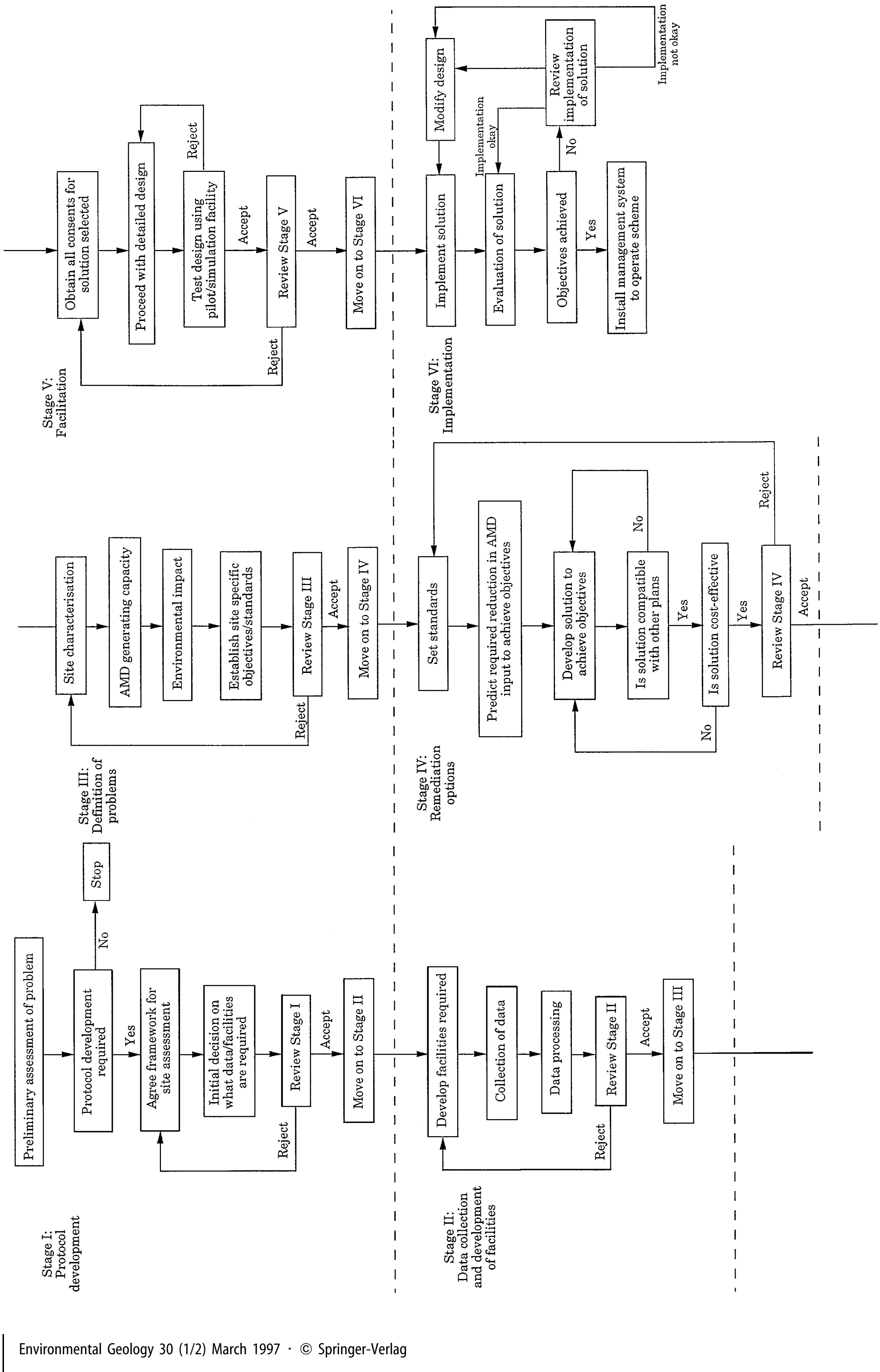

Fig. 6
Schematic layout of the proposed protocol for the remediation of AMD impacted surface waters

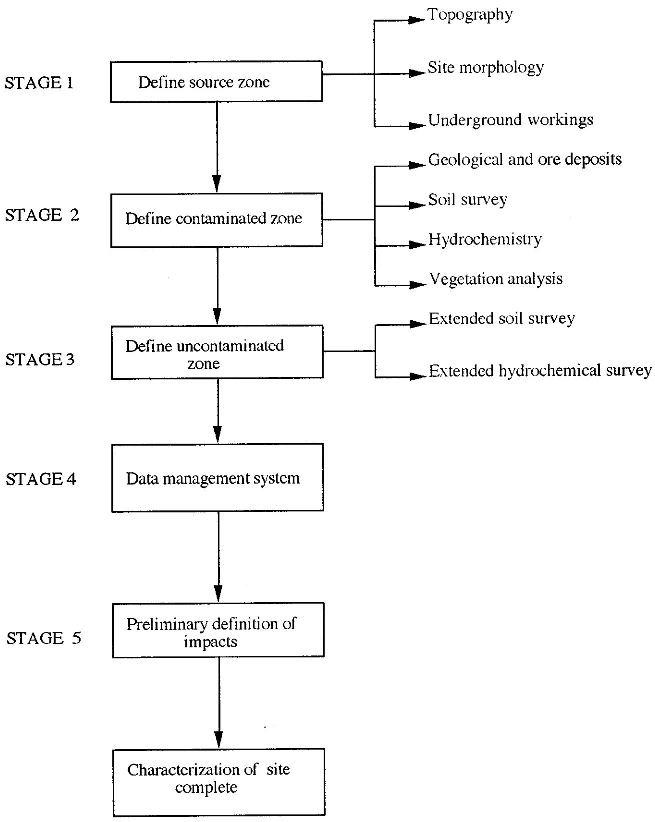

Fig. 7
Major stages and steps in the characterization of an acid mine drainage site (Gray and Doyle 1994)

the required reduction of AMD discharge to the river, in order to achieve water quality objectives as identified at step 1.

15. Final AMD discharge standards can then be specified to achieve water quality objectives.

Stage V implements a monitoring programme and review procedure of the standards set.

16. A long-term monitoring strategy is designed and implemented in order to ensure compliance with AMD discharge standards and to check that receiving water objectives are achieved. This is done for water and sediment phases.
17. Monitoring data is assessed in order to review AMD discharge standards. This may eventually lead to a revision of water quality objectives.

Geographical information systems

Geographical information systems (GIS) have become the modern way to carry out spatial examination of data within a geographical context. A protocol for monitoring and predicting the impact of AMD using GIS is presented by Doyle and Gray (1995). The decision to use a GIS is one that requires serious consideration due to the financial and time costs which may well exceed many other considerations in the assessment of a site for its acid-mine-drainage-producing potential. A relatively new technology, GIS is still in the developmental phase, particularly in relation to its use for modelling purposes, which is still very much in its infancy. The major factors for consideration include purchase or hiring of hardware and software, and hiring of specialised personnel to carry out the design and compilation of the database. Doyle and Gray (1995) also give details of software available for consideration, the type of platforms required to run the software on and sources for information to aid the decision process for establishing a GIS database. The most important aspect in the establishment of a fully functional and accessible GIS is the design of the database. The design stage requires serious consideration of the exact questions to be asked of the data once it is entered into the database. These decisions will play a large part in determining the particular GIS most suitable for querying and storing the information. ARC/INFO, a GIS software package, was used to set up a database for the current project on the Avoca mines. The paths taken in each decision process during the establishment of the GIS are described and problems encountered are documented. The GIS was used to identify potential sources of acid mine drainage production and examine the effect of these sources on the surrounding environment. The GIS proved useful for certain aspects of the interpretation of the data collected during the detailed examination of the site. Apart from its use in cartography, GIS was used primarily for examining spatial data collected during the soil and vegetation study and the effects of mixing of the leachate from the deep adit in the river. The visualisation of the site in 3D was also an important feature, as was the ability to examine the effect of physical remediation on the landscape of the site.

Conclusions

Using a systems approach, a number of new procedures have been developed to successfully characterize, manage and rehabilitate AMD-generating mine sites and to protect surface and groundwaters from environmental damage. The importance of an interactive protocol with clear management objectives and procedures is vital to successful rehabilitation of such sites and long-term protection of the environment.

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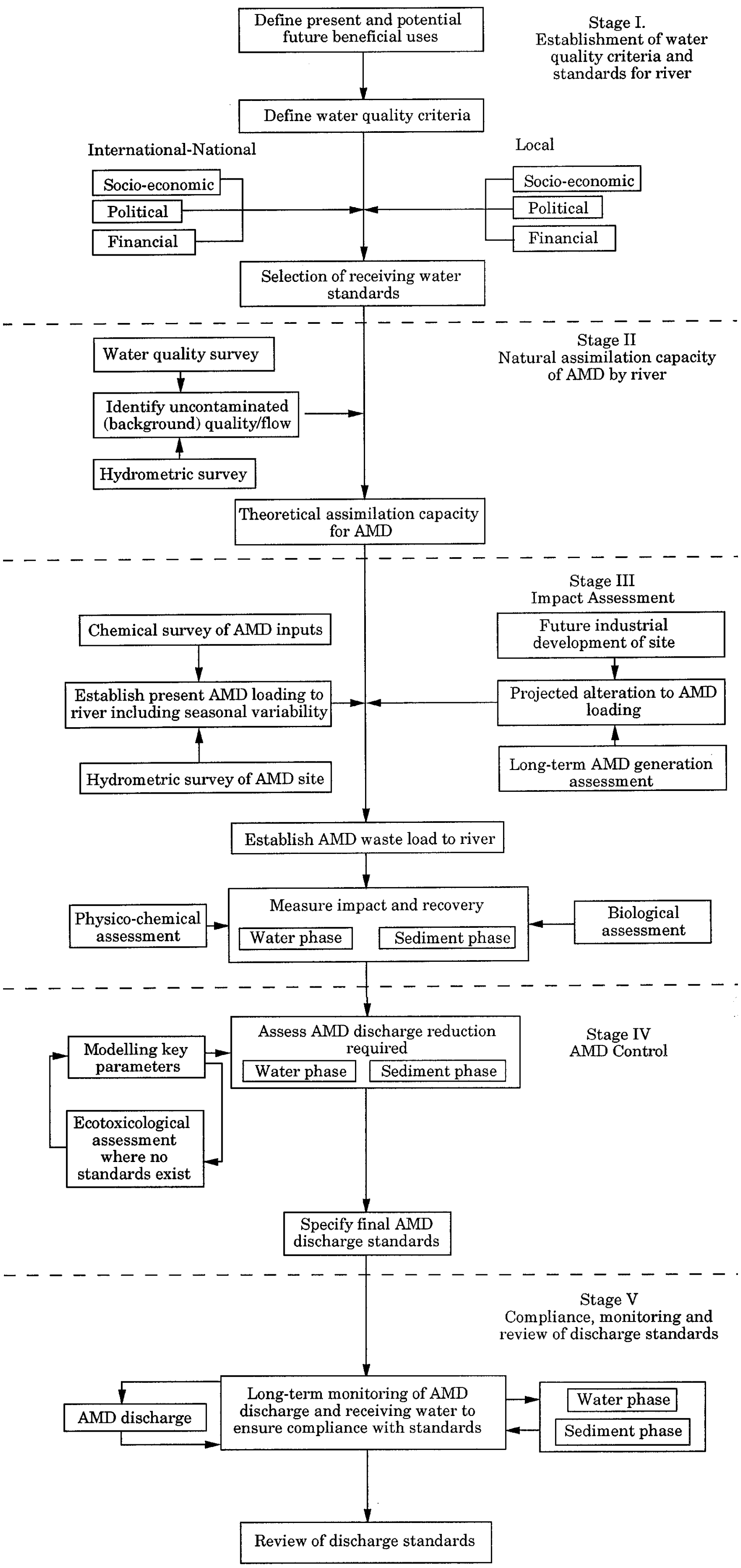

Fig. 8
The acid mine drainage water quality management procedure (Gray 1995b)

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