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The Tooma River Project — Interdisciplinary probes into ill-defined and unpredictable contamination

John Harris, Lee Bowling, Reuben Keller, Robert Keller, Jessica Kress, P.S. (Sam) Lake and D.C. (Bear) McPhail

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CRC FOR FRESHWATER ECOLOGY

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Department of AGRICULTURE FISHERIES & FORESTRY – AUSTRALIA

Natural Heritage Trust

Helping Communities Helping Australia

John Harris[1], Lee Bowling[2], Reuben Keller[3], Robert Keller[4], Jessica Kress[4], P.S. (Sam) Lake[3] and D.C. (Bear) McPhail[5,6]

[1]Cooperative Research Centre for Freshwater Ecology and NSW Fisheries
[2]Centre for Natural Resources, NSW Department of Land and Water Conservation
[3]Monash University and Cooperative Research Centre for Freshwater Ecology
[4]Department of Civil Engineering, Monash University
[5]School of Geosciences, Monash University
[6]Department of Earth and Marine Sciences, the Australian National University

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1. Summary and introduction

The Tooma River project investigated apparent contamination of the Tooma River in alpine New South Wales (NSW). The aim of the project was to identify potential causes of poor ecological condition in the Tooma River, and possible reasons for fish-kills reported by local landowners.

The river's ecological condition was observed during an expert-panel study of the environmental-flow requirements of rivers in the Snowy Mountains region of NSW in preparation for the corporatisation of the Snowy Mountains Scheme. The panel, coordinated by the NSW Department of Land and Water Resources (Bevitt et al. 1998), and with expertise in river ecology, aquatic biology, hydrology and geomorphology, was studying river sites below dams in headwater streams of the Snowy, Murray and Murrumbidgee river systems, one of which is the Tooma River. The panel visited four sites in the Tooma River in January 1998. Brief sampling of the fish and macroinvertebrate faunas of the Tooma River indicated, somewhat unexpectedly, a poor ecological condition that appeared more widespread and severe than would be anticipated from the impacts of flow diversion alone.

Because of this, the river's ecology was further investigated with three additional sampling visits up to May 1999. The samples strengthened the conclusion that the river's aquatic biota were ecologically impoverished, with low abundance and diversity, despite the existence of good-quality habitats in some areas. Furthermore, landowners downstream reported occasional fish-kill events over the preceding decade, with dead fish having bled from the gills, and the water having bluish discolouration.

Because of concerns over the river's environmental condition, funding for a research project was obtained through the *MD 2001 – FishRehab* Program of the Natural Heritage Trust. The funded project aimed to investigate the possibility that the Deep Creek waste-rock dump was the source of downstream contamination through oxidation of exposed minerals, possibly accelerated by microbial oxidation, or through the release of other contaminants in the dump.

1.1. Project components

The Tooma River Project comprised several discrete components, described in the five separate reports collected here (Sections 2–6). Preliminary investigations, detailed in Section 2, sought to elucidate the ecological condition of the river below the dam. The funded research project then made an experimental assessment of the effects of the Deep Creek waste-rock dump, including biological investigations (Section 3), hydrogeological investigations (Section 4) and water-quality investigations (Section 5). The downstream effects of water releases from Tooma Dam were also assessed experimentally.

The project included a hydrogeological study that investigated the Tooma region and surveyed waste-rock dumps throughout the Murray-Darling Basin (MDB) (Section 6). A total of 153 sites were identified across the MDB and their characteristics were recorded. The great majority of waste-rock dumps listed are associated with substantial mines located in the main geological regions: the Lachlan Fold Belt, the New England Fold Belt, and the Kanmantoo and Broken Hill blocks.

1.2. Preliminary investigations

In the preliminary investigation of the Tooma River (Section 2), the results of fish sampling strongly suggested that a series of infrequent major mortalities among fish populations had occurred in the river, with subsequent recoveries. The results for macroinvertebrates suggested that the Tooma River's macroinvertebrate fauna downstream of Tooma Dam was disturbed and of low diversity. Chemical analyses of sediments, yabbies and a dead fish did not find any evidence of contamination. Nevertheless, our preliminary conclusion was that sampling data had corroborated the landowners' reports of fish kills and that the available evidence was consistent with episodic occurrence of toxic conditions.

After helicopter and ground searches of the catchment, the only site that could be considered a possible source of contamination was the Deep Creek waste-rock dump — an extensive spoil dump in the creek bed downstream of the Deep Creek Aqueduct, left after tunnelling operations for the Snowy Mountains Scheme. The dump is actively eroding, with material being entrained into the stream channel.

1.3. The Deep Creek irrigation experiment

In an experiment in April 2001, the project team irrigated parts of the Deep Creek waste-rock dump to test the hypothesis that heavy rain may flush contaminants from the dump into Deep Creek and the Tooma River. Assessments were made on the effects of the irrigation experiment on stream biota, water quality, hydrogeology and stream flow, but no important impacts were found at that time.

Biological assessments

Deep Creek contained a population of mountain galaxias (*Galaxias olidus*; small native fish) and a macroinvertebrate fauna typical of streams in the Australian alpine area. These biota were monitored before, during and after the experiment, and overall the irrigation experiment had no detectable effect on either invertebrate abundances or galaxiid populations.

Hydrogeological, geochemical and water quality assessments

Water temperature, pH, dissolved oxygen (DO) and electrical conductivity (EC) were monitored in Deep Creek and samples were taken and analysed for the concentrations of dissolved anions and major and some minor and trace elements, before, during and after the irrigation experiment. The null hypothesis tested had been that there would be no change in the concentrations of water-quality variables in Deep Creek downstream of the waste-rock dump, compared with concentrations in the creek upstream, following irrigation of portions of the dump. Irrigation of the dump resulted in an increase in electrical conductivity and in the concentrations of most of the cations and anions measured at the Deep Creek site immediately downstream of the dump. The irrigation also caused a decrease in silicon concentrations at the site.

The results indicated the impact of the experiment on water quality in Deep Creek and the Tooma River was small. But hydrologic budget calculations suggested irrigation water had been retained in the dump, or had entered the deeper groundwater system, so that possible contamination may not have been evident at the sites we monitored. Furthermore, practical limitations prevented the irrigation experiment from fully mimicking the effects of heavy rainfall over the whole sub-catchment. It therefore remains possible that heavy rainfall on the rock dump can cause the leaching of elements from the dump and, if associated with more toxic leachate from other areas of the dump, may cause episodic contamination affecting the fish and macroinvertebrate fauna downstream.

1.4. Tooma Dam experimental water releases

A brief experiment and a review of maintenance records indicated that releases of water from the dam during maintenance are not responsible for the downstream impacts, as no effects on biota were detected after the releases.

1.5. Survey of waste-rock dumps in the Murray-Darling Basin

The Survey of Waste-rock Dumps in the MDB, conducted between 11 March 2002 and 11 July 2002, identified waste-rock dumps and the streams below them; characterised the dumps in terms of their size, volume, and composition; and identified environmental impacts of the waste-rock dumps, especially those resulting from mineral oxidation. The objective was to identify streams that may be at risk from metal or acid contamination at waste-rock dumps associated with mines or tunnels.

Information was collated in a spreadsheet with the aim of documenting and characterising dumps (see http://freshwater.canberra.edu.au/publications.nsf/TR?OpenView). It has been designed to be expanded to incorporate future research as information becomes available.

1.6. Overall conclusions

The Deep Creek experiment produced generally inconclusive results in terms of its main objective. Statistical analyses showed there were water-quality changes; hydrogeological effects were detected and some potentially toxic materials were identified. Nevertheless, there was no clear evidence of toxic effects occurring in the Tooma River. While many potentially toxic materials such as aluminium, copper, lead and cadmium were identified in samples of water, rock or sediment, sometimes at levels exceeding water-quality guidelines, their likely impacts on downstream aquatic life could not be determined. Downstream dilution factors, precipitation in altered pH conditions, binding in sediments and varied oxidation conditions all contrived to prevent definitive conclusions. Limited understanding of the time-course of microbial oxidation of exposed minerals and its relationship to antecedent flushing by rainfall also interfered with interpretation of results.

Thus the main working hypothesis of the experiment, i.e. that water percolating through the dump would release contaminants that would produce biological impacts, was not supported by the results of this study. There are several reasonable explanations for this outcome, all of which relate to the limited scope of our intervention and our practical inability to replicate fully the effects of a severe rainstorm on the whole sub-catchment. There may still be toxic materials in the dump, or in the sub-catchment, which were not discovered.

Recent initiatives within NSW Department of Primary Industries (Fisheries) and the Murray-Darling Basin Commission (MDBC) are responding to the urgent need for good recording of fish kills and effective responses to such events. NSW Fisheries has established a formal procedure for recording fish kills and MDBC has facilitated a consistent system across the Basin based on this model.

The survey of waste-rock dumps in the MDB shows that it is important to identify the extent and environmental consequences of contamination arising from waste-rock dumps. The survey data can be used as a basis for improving detailed knowledge and to guide remedial work on the dumps.

The project has highlighted the difficulty of assessing rare and unpredictable contamination events. While it was technically feasible to address the problem of water-quality impacts in the Tooma River by installing automated monitoring equipment for sampling and analysing water quality, such samplers would have been needed at several relatively remote sites in the catchment, and their installation and operation, probably for a period of years, was considered to be prohibitively expensive. This drove the decision to adopt an experimental approach at the Deep Creek dump, despite its difficulties.

A lesson to be learnt from the project is that local rural communities may be best equipped to investigate similar situations, provided that they are given suitable support, training and facilities. With such guidance and support, the community's daily surveillance and their appreciation of their natural environment's values would provide a good basis for thorough investigation at an achievable cost.

1.7. Postscript

The occurrence of another fish kill in the Tooma River in May 2002 led the team to make renewed investigations and laboratory analyses, not reported here, but again they were retrospective and inconclusive.

The bushfires of January 2003 which swept through the Kosciuszko National Park and the Deep Creek catchment had a profound impact on the region's eucalypt forests. The fires were followed within weeks by a severe storm that tore through the creek's now destabilised headwaters, causing major landslips and erosion below the Deep Creek aqueduct, and demolishing much of the waste-rock dump. It is estimated that between one-third and one-half of the total dump volume was washed downstream. No reports of dead fish were received.

In May 2004 the site remained unstable, with expanses of exposed waste rock extending many tens of metres downstream and no evidence of surface flows in the remnants of the creek channel.

2. Preliminary investigations of the ecology of the Tooma River

John Harris[1]

2.1. Location

The Tooma River flows from the precipitous western slopes of the Snowy Mountains section of the Great Dividing Range, following a generally steep, short course through alpine herbfields, eucalypt forests and cleared land to join the River Murray downstream of Khancoban (Figure 2.1). The main stem of the river rises in the highland plateau at about 1800 m altitude, where the catchment is protected by Kosciuszko National Park. Above Tooma Dam, at 1290 m altitude, the river and sub-catchment are in near-pristine condition, except for the dominance of the fauna by trout, and the catchment vegetation comprises open alpine woodlands with heath communities in frost hollows. Sclerophyll forests are predominant below the dam. Forested catchment areas give way to cleared pastures as the river meanders to its junction with the upper River Murray at about 200 m altitude.

The Tooma River catchment is predominantly located on granitic bedrock of the Maragle Batholith, part of the Lachlan Fold Belt emplaced during the early Devonian (Wyborn et al. 1990). Sections of the river in the upper catchment flow through Ordivician sedimentary rock and the discontinuous floodplains of the river consist of Quaternary alluvium. Further geological details are given in Kress (2004). Being situated on the western edge of the Great Dividing Range, the Tooma River experiences orographic rain in the belt of westerly weather systems, with greater precipitation at higher altitudes. Mean precipitation at Cabramurra varies from 66 mm in February to 205 mm in August, falling as snow in winter months. At lower altitudes near Khancoban, precipitation varies from 44 mm in February to 80 mm in August (Kress 2004). Mean daily temperatures at Cabramurra vary from 19.9°C in February to 3.1°C in July.

Six major rivers in the Snowy Mountains Scheme, including the Tooma River, are intensively regulated for hydro-electricity generation and irrigation water supply. Tooma Dam, together with weirs and aqueducts on all streams feeding the major tributaries, Ogilvies Creek and Deep Creek, diverts all flows from upstream catchments except for large floods. The system is connected with the Snowy-Tumut segment of the scheme through tunnels.

2.2. Habitat conditions

The river in its middle and lower reaches is of particular interest because of its potential value as habitat for rehabilitating the threatened fish species trout cod (*Maccullochella macquariensis*) and Macquarie perch (*Macquaria australasica*). Below Tooma Dam, the loss of natural flows has profoundly

[1]Cooperative Research Centre for Freshwater Ecology and NSW Fisheries

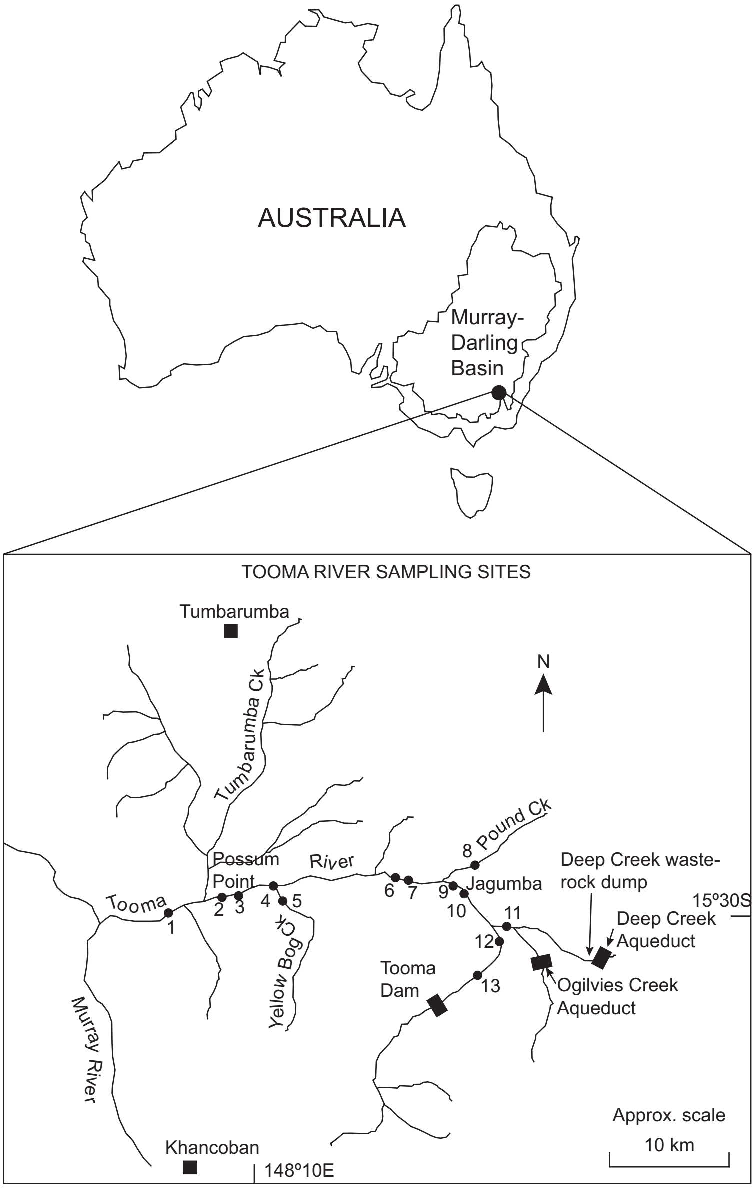

Figure 2.1. Map of the Tooma River region showing the Deep Creek waste-rock dump, Tooma Dam and the 13 other sampling sites investigated at various stages during the project

affected the river, with greatly diminished habitats, suppressed flow variability, terrestrial vegetation invading the channel, and excessive algal growth.

Further downstream, groundwater flow and minor tributaries restore significant flows below the junction of Deep Creek, which lies in the upland gorge area known as 'World's End', above Jagumba Station. In this reach, steep gradients and boulder substrates produce rapid, turbulent habitats that extend into an extensive bedrock gorge between Jagumba and Possum Point. In the river at Jagumba and downstream in the gorge, physical habitat conditions for fish and macroinvertebrates are good, except for a somewhat reduced flow variability, suppression of moderate-level flooding and some areas of sedimentation resulting from cattle grazing.

The largest tributary, Tumbarumba Creek, drains from the north where the catchment has been severely degraded by clearing, erosion and livestock grazing, and habitat values are low. The lowland reach of the river itself, beginning at Possum Point, has been similarly degraded, as has another tributary, Pound Creek, which joins the river at Jagumba. But Yellow Bog Creek, flowing steeply into the gorge from the national park in the south, is in near-pristine condition.

2.3. Initial sampling

Four preliminary sampling visits were made to elucidate the environmental condition of the Tooma River below Tooma Dam. Sampling of aquatic fauna during the visit of the Snowy Environmental-flow Expert Panel in January 1998 included brief fish surveys with backpack electrofishing, plus sweep and kick samples for benthic macroinvertebrates. Samples were taken in the main river channel at Sites 1, 2, 6 and 13 (Figure 2.1). Remarkably few fish, all of which were small rainbow trout (*Oncorhynchus mykiss*), were collected, even in Sites 2 and 6 where physical habitat conditions were considered fair to good and where there was no obvious evidence of physical disturbance other than river diversion a substantial distance upstream. And, at Site 6, only very young fish (less than one year old) were found; there was no sign of more-mature fish. The macroinvertebrate communities at these sites were also considered to be showing signs of disturbance (Campbell et al. 1986), with relatively low numbers of families and dominated by hardy insects.

To check on the result of these first samples and investigate further, a second visit was made in March 1998. Four sites (Sites 5, 6, 8 and 9) were again sampled for fish, using five 5-minute backpack electrofishing shots at each site, and for macroinvertebrates, using sweep and kick samples. The two Tooma River sites near the head of the gorge section (Sites 6 and 9) showed biotic sample results similar to those of the first visit, with low abundances of the two alien species rainbow trout and brown trout (*Salmo trutta*). In contrast, the two tributary sites, Yellow Bog Creek and Pound Creek, had abundant, diverse fish and macroinvertebrate faunas. Two-spined blackfish (*Gadopsis bispinosus*) and the two trout species lived in Yellow Bog Creek, while dense populations of trout of both species were in Pound Creek. There were extremely few fish in the main channel of the river relative to these tributaries, and the river fish were all small, young individuals. Only one larger fish was in the main channel — a rainbow trout at Jagumba — which was found dead.

2.4. Subsequent sampling

The third visit, in March 1999, was made to assess the spatial scale of the apparent disturbance with the aim of identifying likely sources of the problem. A small boat electrofisher was used to provide more-powerful sampling in larger habitats, in addition to the previous backpack electrofishing. Bad weather prevented the planned use of a helicopter to access remote habitats in the gorges and sampling was completed only in more-accessible areas at Sites 2, 3, 6, 7, 9 and 10. More fish of more species were recorded in the main channel than previously, with a greater representation of older individuals. Newly recorded species in the main channel included Macquarie perch (*Macquaria australasica*, one individual at Site 2), two-spined blackfish and two alien species: redfin perch (*Perca fluviatilis*) and common carp (*Cyprinus carpio*). These increases in diversity and abundance were particularly evident downstream, in Sites 2, 3, 6 and 7.

At Site 2 the macroinvertebrate fauna was impoverished (in both abundance and diversity) but it was diverse at both Sites 3 and 10, although abundance was low at Site 10. The low SIGNAL score for macroinvertebrates (Chessman et al. 1997) downstream was assumed to reflect the poor physical condition of the habitats, largely due to sedimentation.

The owner of Possum Point Station, where Site 2 was located, subsequently reported a high-flow event had occurred in March, soon after our third visit, with a bluish discolouration in the water. Experienced local anglers reportedly spent the subsequent long weekend (24–26 April) around Site 3 and neither caught nor sighted any fish. This contrasted sharply with our third-visit sampling results five weeks earlier, when many fish were caught and large common carp were readily visible at the site.

To complete the planned helicopter sampling and to check on this apparent change in fish abundance, a fourth visit was made in May 1999. We sampled fish and macroinvertebrates at Sites 3, 4, 11 and 12. In the small upland habitats of Sites 11 and 12, fish were sought by direct observation in the shallow, clear water, while the boat electrofisher sampled downstream using helicopter transport. Results were sharply different from those of the preceding visit in March, two months earlier. Extremely few fish were recorded in the main Tooma River channel downstream of the Deep Creek junction. In the extensive, good-quality physical habitat of the gorge pools of Site 4, and despite intensive sampling, only one fish, a redfin perch juvenile, was caught. At Site 3, we recorded only about one-quarter of the fish abundance of the previous visit, and two of the four species present in March. The two native species, Macquarie perch and two-spined blackfish, were no longer sampled in May.

Sites 11 and 12 in the upstream gorge between Tooma Dam and Jagumba were sampled to clarify the spatial pattern of the faunal disturbances that were becoming apparent. Site 12, in the Tooma River just upstream of the Deep Creek junction, showed evidence of flow deprivation, but a small number of sizeable, older trout were recorded. This observation coincided with the earlier sampling at Site 13 upstream and indicated reasonable water quality and habitable conditions for trout over a substantial preceding period. But in neighbouring Deep Creek, at Site 11, no fish or macroinvertebrates were recorded and the stream bed was almost devoid of algae and macrophytes.

Invertebrate results were difficult to interpret. In Site 4, at the junction of Yellow Bog Creek, the fauna was diverse (29 families) with a high SIGNAL score (6.6). Downstream of the Deep Creek junction the fauna had a moderate diversity and a medium SIGNAL score of 5.5, indicating water of doubtful quality. Deep Creek itself had a SIGNAL score of 6.3, indicating clean water. The Tooma River above the junction had a low diversity and low SIGNAL score (5.3) indicative of mild contamination.

2.5. Chemical analyses

In March 1998, to assess suspected contaminants, sediments were collected for heavy-metal analyses from Sites 5, 6, 8 and 9. Yabbies (*Cherax destructor*) taken from Site 2 were also analysed for heavy metals. Heavy metal concentrations in the sediments and yabbies were within expected levels and there was no obvious explanation for the apparent ecological disturbance.

A helicopter and ground search for suspect sites in the vicinity of the gorge and upstream areas to the Deep Creek junction, found an abandoned homestead, sheds and rubbish dump. These sites were not considered likely sources of toxicant flowing to the river.

Following the high-flow event at Possum Point in March 1999, one small, dead brown trout was collected by a local landowner. Its gut contents and liver were analysed for pesticides and limited tests for heavy metals were run on the small amount of gut contents remaining. No contaminants were detected. Samples sent for histopathology were too decomposed to be of value. Subsequently, after a period of low, stable streamflows, samples of two rainbow trout were taken by the landowner from Yellow Bog Creek, Pound Creek and the Tooma River at Possum Point. Heavy metals analyses failed to show any significant differences among fish from the three streams.

2.6. Relationship between rainfall and fish community health

To assess the apparent connection between high-flow events and sudden changes in the fish fauna, an approximate fish-health estimate with a five-point scale was developed. This estimate used a subjective integration of fish abundance and diversity data from the various preliminary samples. When data showed that an abundant, diverse community was present, a score of 4 was allocated; if a few juvenile fish of only one species were collected, a score of 1 or 2 resulted. A score of 0 indicated no fish caught. Observations from the main-channel sites below the Deep Creek junction through 1998–1999 were combined. Local rainfall records of the Blackjack Fire Tower, which is situated near the north-east limits of the Deep Creek catchment, were accessed to determine the timing of intense storms. Figure 2.2 relates these fish-health estimates and storm events and suggests that rain events were followed on two occasions by low levels of fish abundance and diversity.

2.7. Interpretation of preliminary investigations

The fish-sampling results of our preliminary investigation strongly suggested that a series of infrequent, sudden mortalities among fish populations had occurred in the river, with subsequent recovery towards the preceding condition. Landowners' reports indicated that fish kills were associated with brief high-flow events in summer, at least as long ago as the 1980s. There were visible signs of water-quality disturbance during the episodes, followed by the apparent disappearance of fish from the main river channel. These observations were supported by the fish data.

The macroinvertebrate results were less clear, and further work is necessary, but they indicated that the fauna had been disturbed. The data indicated that in both the lowland reach from Possum Point downstream, and in the upland reach from the dam to the Deep Creek confluence, the Tooma River harboured an invertebrate fauna of low diversity, at the time of sampling. The depauperate condition of the lowland section could result from poor water quality and habitat degradation through incompatible land-use practices. The disturbed fauna of the upland part of the river below the dam might be the result of deterioration of water quality caused by low flows or by the infrequent releases of low-quality water from the dam itself.

Preliminary chemical analyses of sediments and biota failed to discover any contaminants. If infrequent episodes involving brief flows of a soluble contaminant from the catchment during high-flow events were the cause, evidence of contamination may not have been detectable by the opportunistic sampling regime used. Contaminants in this scenario would be flushed rapidly downstream with the flow peak. Continual, high-frequency sampling of the water column would have been necessary to detect dissolved materials, and a sample of moribund or freshly dead fish would have been needed for pathological and toxicological analyses.

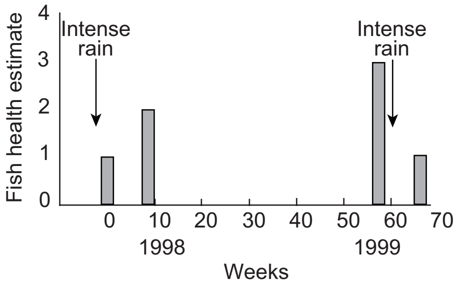

Figure 2.2. Relationship between fish health in the main channel of the Tooma River below Deep Creek and intense rainfall events in the catchment from the beginning of 1998 through part of 1999. See text for explanation of fish health estimates.

From these limited biological data our preliminary interpretation was that there are occasional fish-kills in the main river reach at long time intervals (18 months or more). Between these mortality episodes progressive re-colonisation of the river channel results from young fish moving downstream from the tributary populations. Additional fish, particularly redfin perch and carp, appear to move upstream into lowland reaches of the Tooma River from the nearby upper Murray system. The presence of mature trout upstream of the Deep Creek confluence, the absence of fish in lower reaches of the creek, and the evidence of mortalities in the Tooma River below the confluence all strongly point to the Deep Creek catchment as the likely source of contamination.

Our preliminary conclusion was that analyses of sampling data substantially corroborated the landowners' reports of fish kills and that the available evidence was consistent with infrequent toxic episodes, probably arising from Deep Creek.

3. Biological assessment of possible toxic contamination in the catchment of the Tooma River

Reuben Keller[1], John Harris[2] and P.S. (Sam) Lake[1]

3.1. Introduction

Repeated, sudden fish kills have compromised the environmental condition of the Tooma River. These disturbances, which typically occur every 1–3 years, result in extremely depleted fish populations and have been noticed by local anglers and farmers since at least the 1980s. It is suspected that toxic contamination events are causing these fish population collapses (Bevitt et al. 1998). Fish and invertebrate samples in preliminary, informal surveys suggested that a tributary of the Tooma River, Deep Creek, was the source (Harris 2000). Further investigations revealed that the most likely source of contamination in the Deep Creek catchment is a large waste-rock dump deposited during the construction of the Snowy Hydro Scheme. Fish kills have been related to severe thunderstorms in the region of the rock dump (Harris 2000) and it is hypothesised that heavy rain may flush contaminants from the dump into Deep Creek, which in turn flows into the Tooma River.

It has also been suggested that periodic releases of water during maintenance operations at Tooma Dam could be responsible for the contamination, although maintenance schedule records provided by the Snowy Mountains Hydro-electric Authority (SMHEA) did not seem related to the occurrence of fish kills. Sediment flushed from dams during cleaning often has a very high oxygen demand and can contain toxic chemicals including heavy metals (Wood and Armitage 1997; Bednarek 2001).

Funding was obtained to conduct experiments in April 2001 to investigate whether the Deep Creek waste-rock dump could be the contamination source. The experiments involved using irrigation flows to simulate intense rainfall on two separate areas of the dump. Biological monitoring was performed before, during and after the experiments to assess changes in fish and invertebrate communities. In conjunction with these irrigation experiments, water was released from the Tooma Dam and biological and chemical monitoring were conducted to assess whether such flows from the dam could be the contamination cause.

3.2. Methods

Irrigation

The irrigation experiments were conducted during April 2001 with the guidance of senior staff from the Department of Civil Engineering at Monash University. Water was released from the Tumut–Tooma pipeline via the Deep

[1] Monash University and Cooperative Research Centre for Freshwater Ecology
[2] Cooperative Research Centre for Freshwater Ecology and NSW Fisheries

Creek Adit and from there it flowed into a small sump at the head of the rock-spoil dump. A portable pump transported the water through pipes to the lower end of the dump where it was distributed through a manifold and then into an array of ‘soaker-hose’ garden sprinklers spaced 2 m apart and arranged in parallel at right angles to the manifold. This method provided an even coverage of water over an area of the dump to simulate a rainstorm event. The manifold was 54 m long, and the array of soaker-hoses ran a distance of 30 m downhill from the manifold. Hence an area of 1620 m^2 could be irrigated to simulate intense rainfall. The total surface area of the dump was estimated to be approximately 20,000 m^2, meaning that each irrigation covered about 8% of the total area of the dump.

The first experimental site was located near the downstream end of the dump, some 400 m from the sump (see Figure 4.1). The manifold and sprinklers were then moved to the second site, 200 m from the sump. Table 3.1 gives the timing of each irrigation along with the volumes of water distributed. (See Section 4 for further details of streamflows and irrigation volumes.)

On both of the irrigated areas we distributed more water per unit area than would fall during most thunderstorm events. This was to ensure that a distinct pulse of water flowed through that section of the dump and could be detected in the stream below. Furthermore, substantial runoff from up-slope areas during storms would normally reach the dump and the extra irrigation water helped to allow for this. The local catchment from which rainfall runoff would flow onto the dump was estimated to be substantially more than ten times the surface area of the dump itself.

Biological monitoring of Deep Creek

In the weeks leading up to the experiments Deep Creek contained healthy communities of macroinvertebrates and a population of the small native fish, mountain galaxias (*Galaxias olidus*). Both macroinvertebrates and galaxiid populations were monitored before, during and after the experiment. Table 3.2 details the monitoring schedule.

Eight small plunge pools were selected for monitoring galaxiid populations: three upstream of the dump and five downstream of the dump. They ranged in area from 1 m^2 to 4 m^2 and in mean depth from 0.2 m^2 to 0.5 m^2. Fish in each pool were counted at each sampling time (Table 3.2). Galaxiids were monitored by counting the number of fish that could be seen in each pool,

Table 3.1. Experimental irrigation times and volumes on two areas of the Deep Creek waste-rock dump, with the rainfall to which the irrigations would be equivalent

Irrigation no.	Starting time and date	Period of irrigation (h)	Volume of water distributed (L)	Rain equivalent (mm)
1	0800, 20/4/01	28	783 883	484
2	0940, 23/4/01	24	639 180	394

using a counting technique that had previously been validated at the site. The technique involved approaching each pool quietly and counting fish in the clear water with the aid of polarising glasses. All fish in the pool were counted, using a hand-tally counter. This was repeated until the counts converged. Analysis of a preliminary trial of the method showed good repeatability of results.

Macroinvertebrates were sampled at three small riffles upstream and five small riffles downstream of the dump. Three macroinvertebrate samples were taken at each site on each visit, using kick samples and a hand net. Captured invertebrates were washed into white trays, where they were identified and counted before being returned alive to the stream to avoid sampling impacts on the populations.

Analysis of the results with conventional statistics was difficult because of the confounded nature of the experiments. Replication by monitoring similar streams at the same times was not feasible, nor was there any information about the Deep Creek biota before the rock dump was created.

As an alternative, a bootstrapping technique was developed which enabled us to test our hypothesis. It was based on the difference between the changes in the upstream and downstream sites from before to after the irrigation experiment. The three macroinvertebrate samples at each site were averaged into a single result giving a matrix of 32 values (8 sites × 4 sampling times). From these 32 results, 12 were from upstream, and these were considered to represent the range of all possible upstream values. Two groups of six were chosen at random (with replacement) from the 12 upstream results, and the difference between the average of these two groups was found. This was considered a ‘possible’ change from before to after the irrigation experiment. The same process was followed for the downstream sites, this time comparing the averages of two groups of 10 values. Our statistic was the difference between the computed differences in the upstream and downstream averages. This statistic was generated 10 000 times according to the above process, creating a distribution of values. By comparing the actual result from our experiments to this distribution it was possible to generate a *p*-value for the likelihood of our result. This bootstrapping test was used to assess three matrices of collected data. These were the macroinvertebrate taxa richness, macroinvertebrate numbers per sample, and the number of fish counted.

Table 3.2. Times of invertebrate and fish sampling at the eight sites on Deep Creek

Sampling time in relation to irrigation	Galaxiids	Macroinvertebrates
Before 1st	4/4/01	3–4/4/01
Before 2nd	19/4/01	20/4/01
After 1st	22–24/4/01	22/4/01
After 2nd	26/4/01	26/4/01
Follow-up	4/6/01	4/6/01*

*Macroinvertebrates sampled only briefly at this time

Tooma River fish and macroinvertebrates

For the duration of the Deep Creek irrigation experiments, water was released from Tooma Dam at a rate of approximately 20 ML/day. This flow served to dilute, by roughly 20–40 times, any toxic materials from Deep Creek that might have flowed into the Tooma River. The dilution flow from the dam was designed to reduce the chance of large downstream impacts such as those seen previously. It was documented through an ecological risk assessment procedure.

Releases of water from Tooma Dam allowed us to test the hypothesis that water discharged during dam maintenance operations could be responsible for the observed biotic disturbances in the Tooma River. The test involved sampling macroinvertebrates, fish and water quality near the dam wall before and after the releases. Monitoring was done at a site roughly 500 m downstream of Tooma Dam and further downstream, at Site 10 at Jagumba (see Figure 2.1). Four kick samples for macroinvertebrates were taken before water was released from the dam. A further four samples were collected after the flows were stopped. Fish were sampled at the same times using a backpack electrofisher, making three 5-minute passes in the limited available habitat. Downstream, in the larger habitats at Site 10, fish and invertebrates were monitored in the same way and at the same times, but with six invertebrate samples taken at each time and five 5-minute passes with the electrofisher.

3.3. Results

Deep Creek macroinvertebrates

The macroinvertebrate fauna at the Deep Creek sites was dominated by the larvae of caddisflies (Trichoptera), mayflies (Ephemeroptera), stoneflies (Plecoptera), true flies (Diptera) and beetles (Coleoptera). This is a typical fauna for streams in the Australian alpine area (Campbell et al. 1986). A full list of taxa sampled at each site in Deep Creek is given in Appendix 1. Over the period of the experiments the taxon richness of the upstream sites increased significantly while the taxon richness of the downstream sites remained static (Table 3.3). The release of materials caused by irrigating areas of the dump did not cause any decrease in the downstream macroinvertebrate communities. Instead, the upstream communities increased in taxon richness. We concluded that natural variation over time,

Table 3.3. Average invertebrate taxon richness per site of upstream and downstream sites in Deep Creek before and after each sampling time (1st and 2nd)

	Sampling time in relation to irrigation			
	Before 1st	Before 2nd	After 1st	After 2nd
Upstream sites	2.67	2.33	6.67	5.67
Downstream sites	6.2	7.8	8	5.6

possibly associated with the small number of upstream sites, was responsible for the increase in upstream taxon richness.

Nor was any effect of the irrigation detected on the abundance of invertebrates captured at each site at each time. Abundance increased slightly in downstream sites, while there was a slight decrease upstream. This effect cannot be explained by the experimental irrigations.

Galaxiid populations

There was no detectable response to the irrigation experiments in the fish populations. No effect on galaxiid populations was detected using the bootstrapping technique. At the final sampling time six weeks after the experiments, numbers of fish were reduced at some sites, both upstream and downstream. This may have been an effect of colder weather reducing fish activity and thus making them harder to see. Sampling was conducted at this six-weeks point to ensure that if contaminants were released and acted slowly we could still detect the effect. Although numbers were down there is no clear evidence that the experiments had caused that to happen.

Tooma River sites

Limited time and resources precluded an experimental design that could be statistically analysed at the Tooma River sites. Despite this, it is evident that macroinvertebrate and fish populations at these sites were not affected by the experimental flow releases from Tooma Dam (Table 3.4). This suggests that releases from the dam are not responsible for biota collapses in the Tooma River, a conclusion that is supported by the lack of apparent relationship between previous fish kills and the dam's maintenance-release schedule and by the presence of mature trout downstream. Appendix 1 lists the macroinvertebrate taxa sampled at the Tooma River sites. All fish caught at both sites in the Tooma River in this experiment were rainbow trout (*Oncorhynchus mykiss*).

Table 3.4. Results from monitoring of fish and invertebrates at two sites on the Tooma River in response to experimental releases of water from Tooma Dam

Site	Invertebrate taxa richness		Fish numbers	
	Before release	After release	Before release	After release
Tooma Dam	22	29	4	3
Jagumba	32	34	27	21

3.4. Discussion and conclusions

Our irrigation experiments did not show any biological impacts arising from the Deep Creek waste-rock dump. This may simply indicate that the dump is not the source of contaminants causing episodic fish kills and disturbed macroinvertebrate communities in the Tooma River. But the results are inconclusive for several reasons, and therefore do not eliminate the rock dump as a source of contamination.

Material in the dump is heterogeneous, produced from the 14 km-long Tooma–Tumut tunnel of the Snowy Hydro Scheme as it progressed through varied geological formations. This geology has led to the development of a number of metal mines in the area, especially for gold and copper. Waste-rock material was dumped progressively, along with engineering rubbish and other wastes. Thus it cannot be assumed that the two areas of the dump that were chosen for the irrigation experiments necessarily represented all of the dump's range of waste materials. The representation of materials within the dump could only be fully determined by using geological drilling over a fine-scale comprehensive grid pattern, and this was prohibitively costly. It is possible that one portion of the dump contains contaminants that were missed by irrigated flows, as only 8% of the total dump area could be irrigated at any one time.

Furthermore, while we exceeded the volumes of water that might fall directly onto the irrigated areas during severe rainstorms, it was impossible to mimic the additional runoff from the large, precipitous surrounding catchment. These catchment flows would be more than ten times as great as the direct surface fall, and would flow over and through the rock dump.

For these two reasons, our experiments have not shown that the Deep Creek waste-rock dump can be totally dismissed as causing toxic contamination and as the source of the observed downstream environmental impacts.

The consequences of the experimental releases of water from Tooma Dam were more conclusive. Where such releases have been responsible for ecological impacts elsewhere, with high sediment loads and/or low-quality water, their effects are severe and obvious (Wood and Armitage 1997; Bednarek 2001). The experimental releases at Tooma Dam indicate that releases of water from the dam during maintenance are not responsible for the downstream impacts, as no effects on biota were detected after the releases.

4. Hydrological and hydrogeochemical assessment of contamination and remediation in the Tooma River

D.C. (Bear) McPhail[1,2] and Jessica Kress[1]

The hydrology and geochemistry of the Deep Creek waste-rock dump and surrounding waters were studied during the irrigation experiments in April 2001. Three irrigation experiments were run. The first two were run on 54 m × 30 m sections of the dump (Figure 4.1) and the third was run on a small section at the toe of the dump, where sulfide minerals were observed in the waste rock. Two rainfall events occurred during and between the three experiments, which complicated the interpretation of the hydrology and water geochemistry because of the added amount of water infiltrating the dump and the overall water flow in the streams.

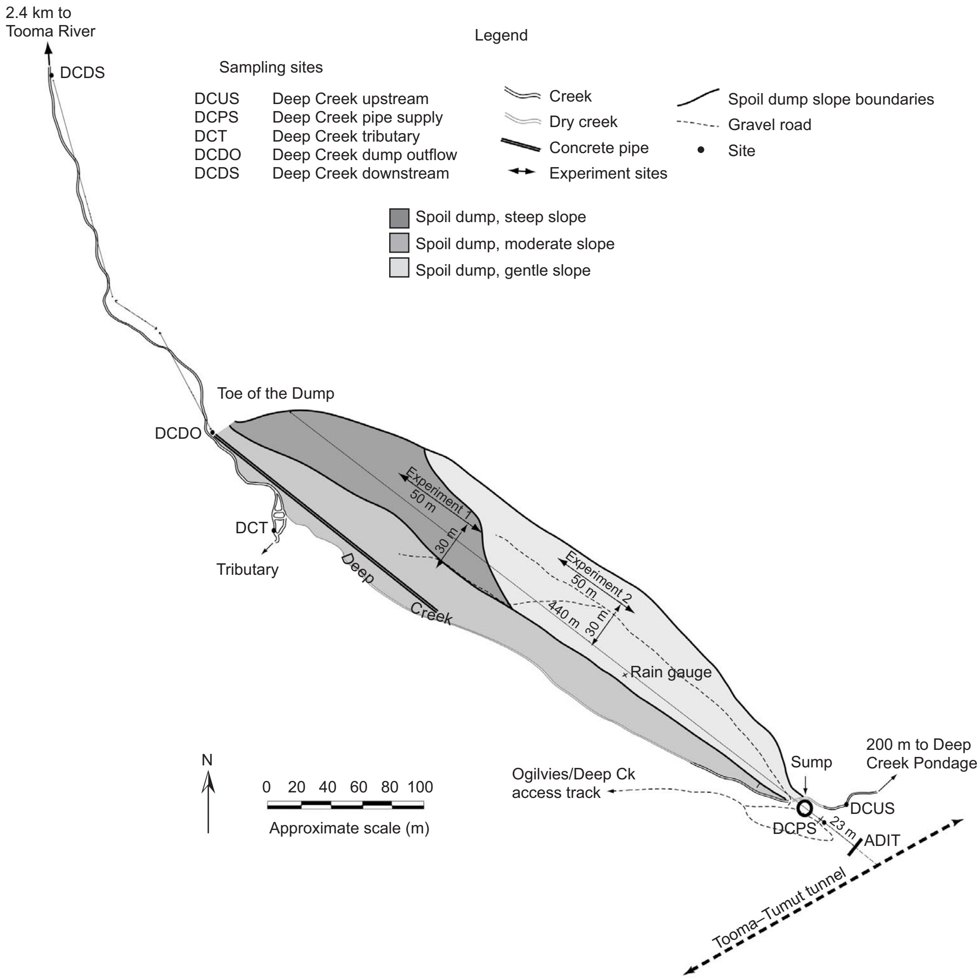

Figure 4.1. The Deep Creek Adit Spoil Dump, showing locations of sampling sites and irrigation experiments 1 and 2 (adapted from CH2MHILL 2000)

[1]School of Geosciences, Monash University
[2]Cooperative Research Centre for Landscape Environments and Mineral Exploration and the Department of Earth and Marine Sciences, The Australian National University

In cooperation with other people and agencies participating in the overall project (see Sections 3 and 5), the streamflow was monitored at several sites on Deep Creek (Figure 4.1): upstream of the waste-rock dump (DCUS), at the pipeflow supplying water for the irrigation experiments from the Deep Creek adit of the Tooma–Tumut tunnel (DCPS), downstream of the dump (DCDO) and in a small tributary near the toe of the dump on the opposite side of Deep Creek (DCT). The characteristics and locations of the sampling sites are listed in Table 4.1. The streamflow downstream of the dump was monitored continuously before, during and after the irrigation experiments using a natural rock weir with a graduated stake and data logger. The pipeflow supply was kept constant and monitored during the experiments. Streamflow at the upstream and tributary sites was measured only once or twice during each experiment using a pygmy flow meter and cross-sectional areas. Precipitation was measured using a rain gauge on top of the dump.

The chemistry of the water at several sites was measured in the field and the laboratory, also in cooperation with others. Temperature, pH, dissolved oxygen (DO) and electrical conductivity (EC) were monitored using HydroLab

Table 4.1. Deep Creek Adit Spoil Dump sites sampled in April 2001, and October and December 2002

Site label	Site name	Relationship to dump and adit	Latitude longitude
DCUS	Deep Creek Upstream	Approximately 30 m upstream of the dump. Not influenced by dump or adit waters. Indicates base flow of Deep Creek 200 m downstream of the Deep Creek Dam.	Not available (na)
DCPS	Deep Creek Pipe Supply	Approximately 30 m upstream of the dump and 10 m downstream of the adit. Water was seepage from the adit tunnel (probably locally-derived groundwater) and was used for the irrigation experiments.	36°00'42.2''S 148°20'07''E
DCT	Deep Creek Tributary	Located approximately 420 m from the adit, and on the opposite side of Deep Creek to the dump. Supplies surface flow adjacent to the toe of the dump and dilutes discharges from the dump.	na
DCDO	Deep Creek Dump Outflow	Located at the toe of the dump, approximately 500 m downstream of the adit. Water at this point consisted of water discharge from the dump and tributary waters.	36°00'32.2''S 148°20'00.2''E
DCDS	Deep Creek Downstream	Located approximately 260 m downstream from the toe of the dump and 750 m from the adit. Chosen by the Snowy Scheme hydrologists to monitor streamflow downstream of the dump using a natural rock weir.	36°00'25.1''S 148°19'55.4''E

DataSonde sensors installed in Deep Creek upstream of the dump, at the toe of the dump (dump outflow) and 200–300 m downstream of the dump. Water was sampled automatically at half-hour time increments at the dump outflow and downstream of the dump, before, during and after the irrigation experiments. Dissolved element concentrations were measured to assess the possible contribution of materials from the dump to downstream contamination. According to ANZECC guidelines for freshwater quality (ANZECC 1992), the dissolved elements that would be of the most concern were aluminium, copper and possibly cadmium. Concentrations of dissolved major elements (calcium, iron, sodium, magnesium, potassium, silicon and aluminium), minor elements and some trace elements (strontium, barium, copper, manganese, cadmium, scandium, titanium and rubidium) were measured in all water samples (filtered in the field and un-acidified at site but acidified at the lab) by Inductively Coupled Plasma Emission Spectroscopy (ICP-ES) by the New South Wales Environmental Protection Authority (NSW-EPA). Concentrations of dissolved anions (chloride, nitrite, nitrate and sulfate) were measured by ion chromatography (IC) in all water samples (filtered in the field and un-acidified) by the Department of Land and Water Conservation (DLWC) of NSW. Selected samples (approximately 20 filtered and acidified in the EPA lab) were measured for trace element concentrations by High Resolution Inductively Coupled Plasma Mass Spectrometry (HR-ICP-MS) at Monash University.

Rock samples representative of those observed on the top and side of the dump were characterised for their type and mineralogy.

A summary of results for the streamflow, chemistry and mineralogy is given below.

4.1. Streamflow

Streamflow in Deep Creek downstream of the dump increased during irrigation and during rainfall (Figure 4.2). Water from the Tooma–Tumut tunnel, mixed with groundwater discharging from the adit, was pumped onto

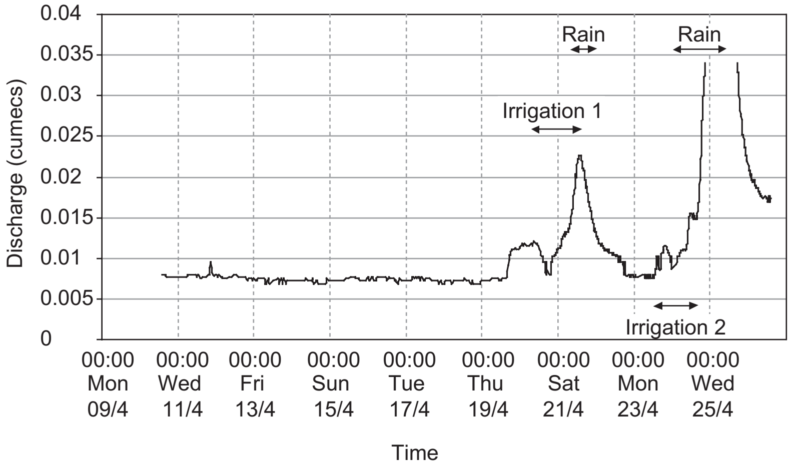

Figure 4.2. Stream discharge in Deep Creek measured at the downstream site several hundred metres downstream of the toe of the waste-rock dump. Cumecs are m^3/s.

the dump in two experiments: Irrigation 1 (Friday 20 April 2001 to Saturday 21 April 2001), and; Irrigation 2 (Monday 23 April 2001 to Tuesday 24 April 2001).

The time lag between the start of irrigation and observed increase in the streamflow downstream of the dump was 18 hours for Irrigation 1 and 24.5 hours for Irrigation 2. The greater time lag for Irrigation 2 could have been because the irrigation area was further away from the toe of the dump, or the dump material had a lower permeability there.

Rainfall during the experiments is shown in Figure 4.3.

4.2. Hydrologic budget

A hydrologic budget calculation was made for the one time when there were measurements for all sites (Table 4.2).

The sum of the water input into Deep Creek from upstream of the dump, the one tributary to the creek on the opposite side of the dump, irrigation and precipitation is 0.032 m^3/s. The measured value downstream of the dump is 0.023 m^3/s, lower than predicted from the other values. Although the runoff is unknown, the difference suggests that water was being retained in the dump

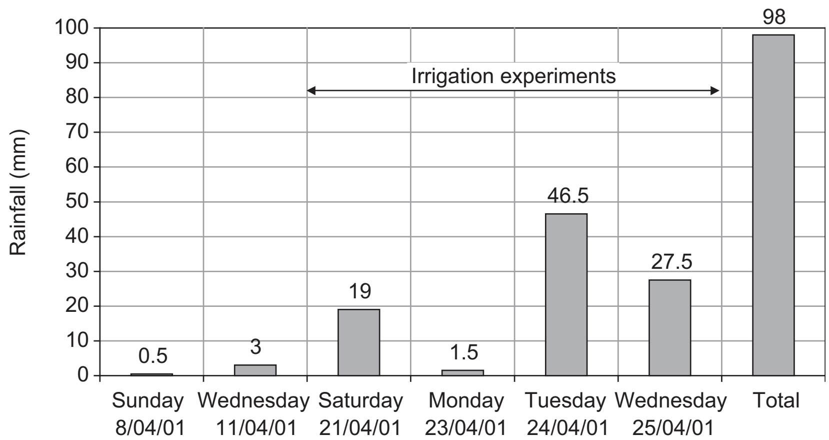

Figure 4.3. Rainfall on Deep Creek waste-rock dump during irrigation experiments

Table 4.2. Measured and calculated streamflow values for Saturday 21 April 2001. Site locations are given in Table 4.1 and Figure 4.1.

Measurement site	Streamflow (m^3/s)
Upstream (DCUS)	0.019
Tributary (DCT; opposite toe of dump)	0.0047
Irrigation	0.0078
Precipitation	0.00081
Runoff	Unknown
TOTAL (calculated)	0.032 + unknown runoff
Downstream of dump (DCDS)	0.023

or was recharging the deeper groundwater system under the dump. The result is uncertain, but might indicate that, if there is any contamination from the dump, it could be entering the deeper groundwater system and we could not observe it at the sites we monitored.

4.3. Water chemistry

pH

pH values in all samples were between approximately 6.2 and 7.2, well within the range typical of natural waters (5 < pH < 9). The measured pH of water right at the toe of the dump was somewhat lower than that upstream, i.e. 6.2–6.3 versus 6.6–6.7. Some of the variation between sites could be due to calibration error in the Hydrolab instruments. pH variations with time during the irrigation experiments and rainfall events were small, much less than 1 pH unit, and no differences related to any of the irrigation experiments or precipitation were noted. The lower pH values recorded at the top of the dump may indicate a small amount of acid was being generated in at least some parts of the dump, but the results are not conclusive.

Electrical conductivity (EC)

Figure 4.4 shows the results of EC measurements at the monitored sites around the dump and in the Tooma River. There was a small increase in EC from the dump after the first experiment but not the second. Small increases in EC were also observed following the rainfall event. These results indicate that small amounts of dissolved elements were flushed from the dump during the first experiment and the rainfall event, but the EC values are very low and indicate little, if any, contamination.

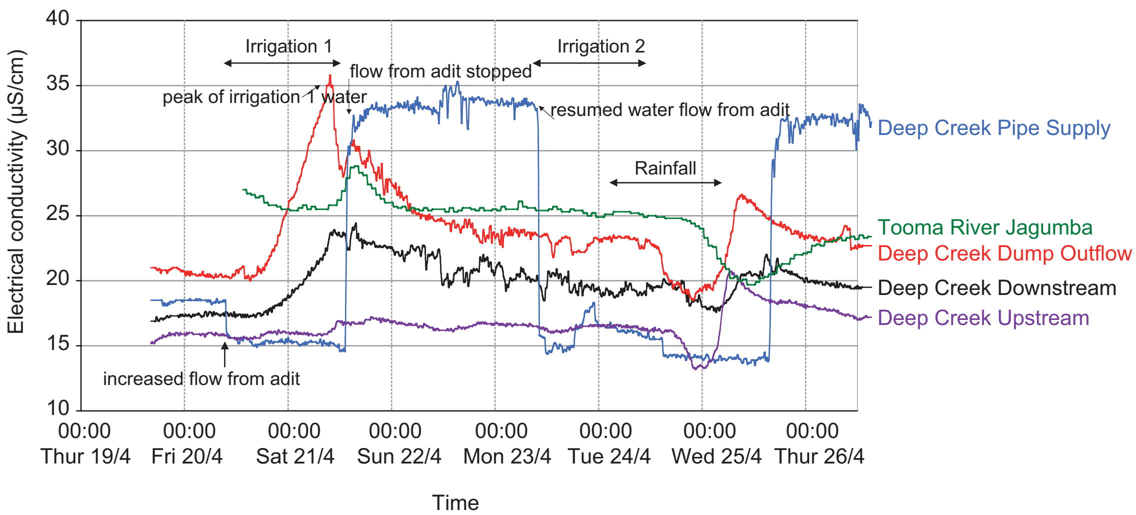

Figure 4.4. Electrical conductivity in water during the Deep Creek dump irrigation experiment

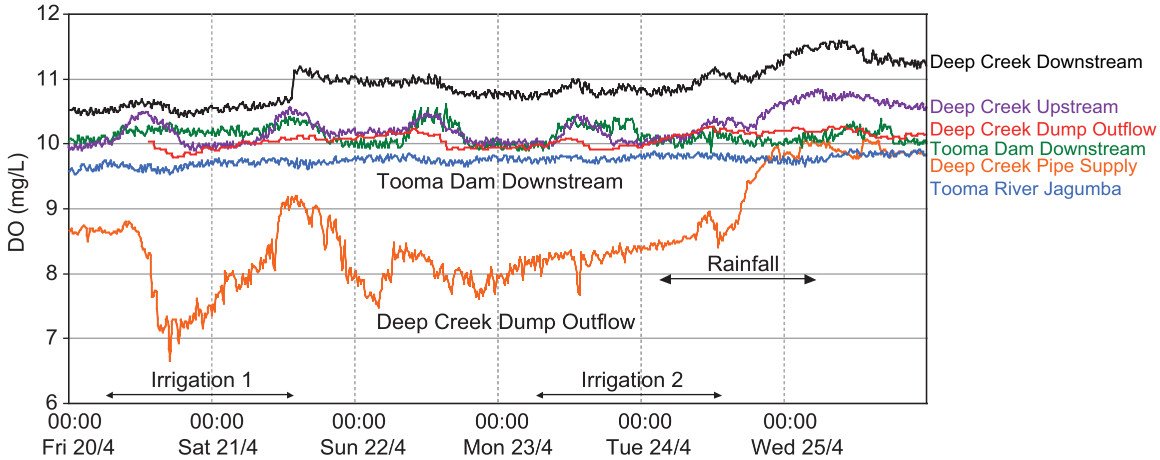

Figure 4.5. Dissolved oxygen patterns during the Deep Creek dump irrigation experiments

Dissolved oxygen (DO)

The accuracy of the DO measurements is uncertain because no calibrations were done; however, relative changes are informative. Diurnal variations in DO were noticed at all sites (Figure 4.5), as expected from daily biotic activity in the waters. There may have been a decrease in DO in the water flowing at the toe of the dump after the first irrigation, which would be consistent with many groundwaters being less oxidised than surface waters. Increases in DO were observed at most sites during and following the rainfall event (Figure 4.5), a result of increased turbulence and the probably higher DO content of the rainfall.

Anions

Most anions (e.g. chloride, nitrite, nitrate) did not show systematic variations. Sulfate increased to 2.5 mg/L at the dump outflow site compared to around 1 mg/L at the upstream site. The source of the sulfate could be the weathering of iron sulfide minerals observed in a few rock samples on the dump and recorded during the digging of the tunnel. Although slightly elevated iron concentrations were also observed in water samples from the toe of the dump during the experiment, there was no decrease in pH, so it is unlikely that acid drainage was a problem at the dump at the time. Under different conditions, e.g. long periods of no or low rainfall, any iron sulfide minerals in the dump would have time to oxidise more, and there might be some acid drainage. Note that no iron staining, typical of acid drainage environments, was observed in Deep Creek other than on very small areas on the surface of the dump near its toe.

Major elements

Of the major elements, calcium exhibited the highest concentrations: 1–3 mg/L before the irrigation experiments and in waters upstream of the dump. Peaks of up to 4.7 mg/L occurred during the Irrigation 1 and the main rainfall event. Sodium, magnesium, potassium and silicon were in low concentrations and showed only minor variations during the experiment. The sources of these elements are the minerals in the granitic rock that appears to make up most of the rock in the dump. They are being released as part of normal weathering of ferro-magnesium and potassium-aluminium silicate minerals observed in the rocks (see below). Dissolved iron concentrations increased following irrigation experiments and the rainfall event. These could be due to the weathering of silicate minerals or iron sulfide minerals.

Dissolved aluminium at the Deep Creek Dump Outflow site may be of some concern, as concentrations reached up to 0.046 mg/L on Saturday 21 April following Irrigation 1; however the natural variations may show concentrations this high, based on increased aluminium concentrations in waters upstream of the dump during the rainfall event.

Trace elements

Trace elements strontium, barium, copper, manganese, scandium, titanium and rubidium were found in the greatest concentrations, relative to other trace elements. Increased strontium, copper and barium concentrations occur at the downstream site, compared to upstream, indicating those elements are sourced from the waste-rock dump. Copper and cadmium concentrations in the water reached the limits recommended at that time (ANZECC 1992) for freshwater systems (2–5 μg/L for copper; 0.2–2 μg/L for cadmium; however, they did not exceed the limits during or after the experiments.

4.4. Minerals in the waste-rock pile

To investigate whether possible sources of contamination were present, conventional petrographic methods were used to identify minerals present in the rocks of the dump. Traces of sulfide minerals (pyrite and chalcopyrite) were present; however, there was little evidence of contamination (e.g. acid drainage, heavy metals) from their weathering. Other minerals (e.g. quartz, plagioclase, biotite, muscovite and clinopyroxene) that were identified are typical of granitic rocks and are unlikely to result in any contamination. Plagioclase, biotite, muscovite and clinopyroxene are the probable sources of aluminium in the Deep Creek water as part of natural weathering processes.

4.5. Summary

- The impact of the dump on the water quality in Deep Creek and hence the Tooma River is small, based on the results of our experiments. However, only two 50 m × 30 m sections were irrigated and it is likely that the impact of the whole dump is greater than we were able to detect.
- According to ANZECC guidelines for freshwater quality (1992), the dissolved elements that would be of the most concern were aluminium, copper and possibly cadmium, although they were not in particularly high concentrations.

- The preliminary hydrologic budget calculations suggest that water percolating through the dump may have entered the groundwater system and flowed beneath our monitoring point furthest downstream on Deep Creek. If that is true, then it is possible that some contamination could have reached Deep Creek or the Tooma River directly, but most likely at levels low enough to be effectively diluted by the streamflow in the Tooma River.
- The possibility remains that a rainfall event bigger than we could simulate or observe during our experiments could flush higher levels of contamination from the dump. In addition, potential contamination within the dump could accumulate during periods of low rainfall and then be flushed out of the dump during a rainfall event. The rocks and minerals that could be observed at the surface of the dump are likely to be benign, so if there is any contamination from the dump, it would be from rocks or other materials that are buried within the dump.

5. Statistical analyses of water-quality data in the Tooma River study

Lee Bowling[1] and Hugh Jones[1]

5.1. Introduction

This section of the Tooma River project report describes the outcomes of some of the water-quality investigations in Deep Creek and Tooma River during the irrigation experiment described in Section 3, as well as the analysis of the major anions.

5.2. Experimental design

The null hypothesis to be tested was that there would be no change in the concentrations of water-quality variables in Deep Creek downstream of the waste-rock dump, compared with concentrations in the creek upstream, following irrigation of portions of the waste-rock dump. The alternative hypothesis was that the concentrations of water-quality variables in Deep Creek upstream of the waste-rock dump would differ from the concentrations of these variables in the creek downstream.

Water-quality sampling was split into two time periods, before and after irrigation, at two sites, one upstream of the rock dump and the second downstream. These periods were divided into blocks of 12-hourly periods, with three blocks before the start of irrigation, and three following the start. Four subsamples were to be taken at randomly selected times during each block. It was planned to analyse the data by Analysis of Variance (ANOVA). The variables analysed to detect contamination leaching from the rock dump were potassium, sodium, magnesium, calcium, silicon, fluoride, chloride, sulfate and nitrate.

5.3. Materials and methods

The water-quality fieldwork involved the collection of samples at several sampling sites around the Deep Creek study location, and the collection of *in situ* data at these sites. Fieldwork was undertaken from 18 to 28 April 2001. Although water-quality sampling was undertaken at the site throughout the fieldwork program, the planned experimental approach to testing for changes in water quality was run for only part of the period, i.e. from the 18 to 22 April. This coincided with the first irrigation period, during which the rock dump was irrigated from 08:00 on 20 April to 12:00 on 21 April.

Water samples were collected from sites both upstream and downstream of the rock dump before, during, and after irrigation. These sites were Deep Creek Pipe Supply (DCPS) and Deep Creek downstream (DCDS) (see Figures 4.1 and 4.2 and Table 4.1). Samples were collected in 250 mL or 1 L

[1]Centre for Natural Resources, NSW Department of Land and Water Conservation

polyethylene bottles and chilled prior to analysis for anions by ion chromatography at the DLWC laboratory, and for cations by inductively coupled plasma (ICP) spectroscopy at the Environment Protection Authority (EPA) laboratory. Water temperature, dissolved oxygen, pH and electrical conductivity (EC) were measured *in situ* at these sites, using Hydrolab data-logging equipment. Snowy Hydro staff measured stream flow in Deep Creek.

Practical problems with the water-sampling program for this component of the study were experienced in the field, which meant the data collected did not meet the assumptions of ANOVA. These problems included:

1. The source of irrigation water was originally intended to come from a temporary weir on Deep Creek upstream of the rock dump. Because of low-flow conditions in the creek, however, water was instead released from the Tooma–Tumut tunnel via the Deep Creek adit. Too few data were collected from Deep Creek upstream to allow comparison with water quality in the creek downstream of the rock dump.

2. Water flowing from the tunnel adit at DCPS and used for the irrigation experiment had a different water-quality signature compared to the small amounts of groundwater seepage that flows from the adit under normal conditions. Water quality at DCPS therefore varied markedly during the course of the experiment, according to whether the water supply from the tunnel was switched on or off, making it unsuitable for use as an upstream control site for the ANOVA.

3. A number of samples within several of the 12-hour blocks were not collected at either DCPS or downstream site, or both, resulting in missing data.

Nevertheless, there were still sufficient data obtained from the water-quality sampling program for some analyses. The data from DCDS were split into two series — those collected before any impact of the irrigation experiment on flows was noticeable at the downstream site, and those collected afterwards. The time between the start of irrigation and an observed increase in stream flow downstream of the dump was 18 hours (see Section 4). Electrical conductivity data collected by a Hydrolab sonde positioned at this site indicates the EC had started to increase by this time as well. Therefore, for the statistical analysis, all water-quality data collected prior to 02:00 on 21 April were assigned as 'before' impact data, and all data after this time were considered to be 'after' data. Because the 'before' sampling had actually commenced at 21:00 on 18 April, this cut-off time is actually 53 hours after the commencement of sampling for the experiment.

A multivariate statistical method, Hotelling's T^2 test, was used to test for joint differences in mean ionic concentrations between the 'before' and 'after' periods. This is the multivariate equivalent of a t-test (Wichern and Johnson 1988). The Wilcoxon rank sum test (Conover 1986) was used to compare 'before' and 'after' periods for each ion. These tests were undertaken on data collected for both the Pipe Supply (DCPS) site and the downstream (DCDS) site.

More detailed modelling was undertaken to explore the nature of changes in ionic concentrations over time at DCDS, particularly in relation to irrigation releases. Piecewise polynomial regression (Montgomery and Peck 1992) was used because this allowed the inclusion of 'knots' and discontinuities at specific times.

5.4. Results and discussion

Summary statistics are provided in Table 5.1 for the water-quality variables measured at the Deep Creek Pipe Supply (DCPS) and Deep Creek Downstream (DCDS) sites. Additionally, time-series plots with loess smoothers fitted to the data are shown for the cation (Figure 5.1) and anion (Figure 5.2) concentrations that were measured at both sites.

Table 5.1 reveals that concentrations of potassium, sodium, magnesium, calcium, chloride, sulfate, fluoride and nitrate at DCDS all increased during the course of the irrigation experiment, while concentrations of silicon decreased. Concentrations of all variables except sulfate also increased at DCPS. The standard errors indicate a much larger variability in the ionic concentrations measured for DCPS compared to DCDS. This would result from the changing source of water at DCPS during the experiment (i.e. local groundwater or water from the Tooma–Tumut tunnel).

A major confounding effect observed in the experiment was the considerable increase in the concentrations of most of the cations at DCPS after 50 hours (Table 5.1, Figures 5.1 and 5.2). This was due to the change in the source of water at DCPS following the cessation of irrigation at this time (midday on 21 April), when flow from the Tooma–Tumut tunnel adit was switched off. However the concentrations of most of the ions at the downstream site (DCDS) had started to increase several hours earlier than the occurrence of the step change at DCPS. This indicates that the changes in ionic concentrations at DCDS were not due to the change in source water at DCPS once irrigation ceased.

The increase in the mean concentrations at the DCDS site can be attributed to the irrigation experiment. Concentrations of water-quality indicators in the water from the Tooma–Tumut tunnel (DCPS) used for irrigation were actually similar to, and in some cases slightly less than the concentrations in the water at DCDS prior to irrigation (Table 5.1). The increased concentrations at DCDS thus cannot be attributed to the source of irrigation water. Likewise,

Table 5.1. Mean values (mg/L) and ±1 standard error (in brackets) for various water-quality variables measured at the Deep Creek Pipe Supply (DCPS) and Deep Creek Downstream (DCDS) sites before and after the irrigation experiment. (n = 17 for both cation and anion 'before' data.)

Variable	DCPS		DCDS	
	Before	After	Before	After
Potassium	0.39 (0.02)	0.51 (0.10)	0.47 (0.02)	0.57 (0.03)
Sodium	2.88 (0.23)	3.97 (0.45)	3.20 (0.03)	3.30 (0.03)
Magnesium	0.91 (0.08)	1.23 (0.11)	0.82 (0.01)	1.07 (0.01)
Calcium	4.17 (0.37)	5.52 (0.54)	3.36 (0.03)	4.37 (0.03)
Silicon	5.94 (0.48)	7.50 (0.66)	6.80 (0.04)	6.10 (0.04)
Fluoride	0.07 (0.008)	0.09 (0.011)	0.04 (0.005)	0.06 (0.006)
Chloride	1.17 (0.10)	1.24 (0.10)	1.04 (0.06)	1.30 (0.05)
Sulfate	0.79 (0.08)	0.73 (0.05)	0.80 (0.12)	2.13 (0.03)
Nitrite	—	—	0.12 (0.005)	0.30 (0.01)

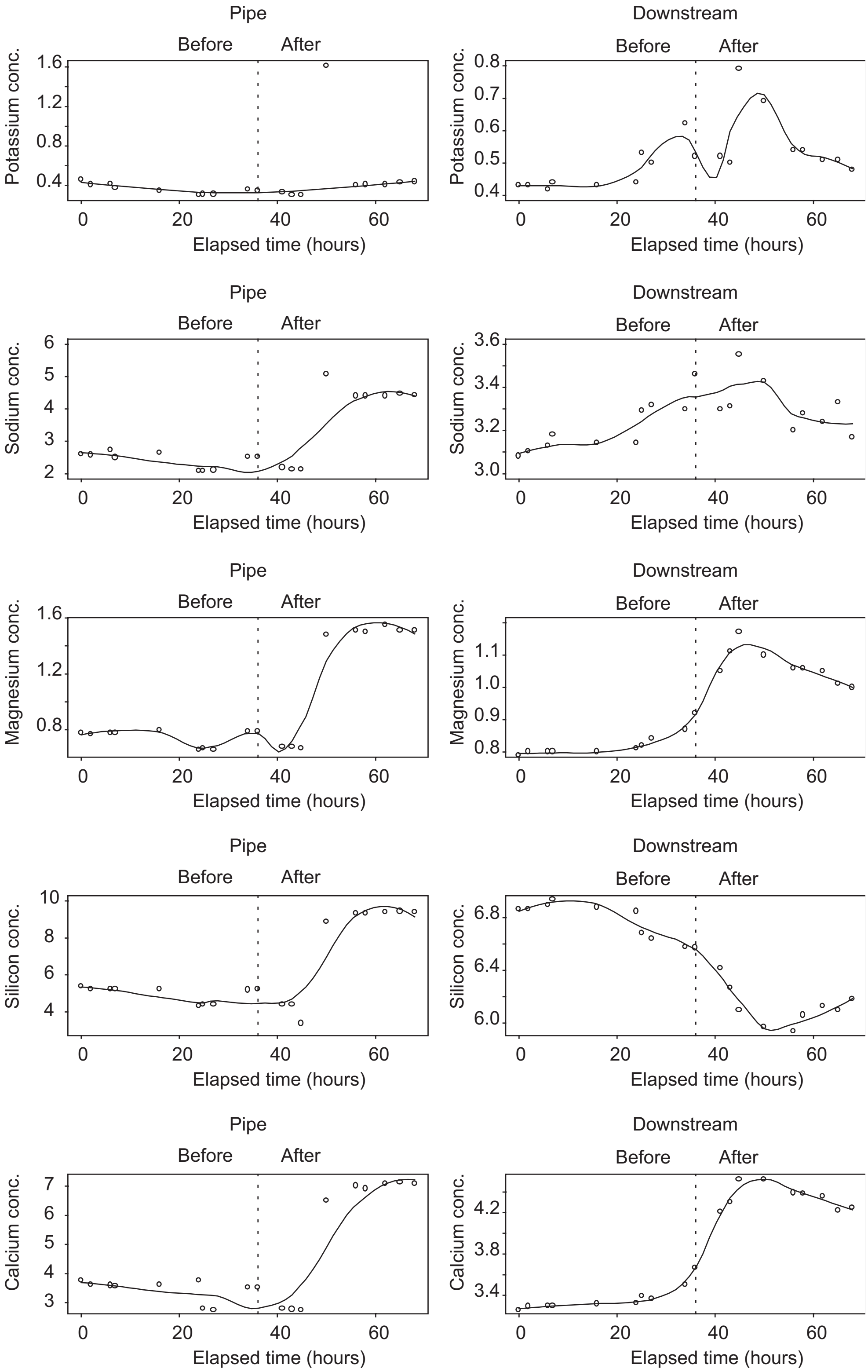

Figure 5.1. Time series plots of cation concentrations at the DCPS and the DCDS sites. The curves are loess smoothers fitted to the data. Collection of cation data (elapsed time = 0 hours) commenced at midday on 19 April. Irrigation commenced at 08:00 on 20 April (elapsed time = 20 hours). The designated cut-off time (vertical dotted line) was 02:00 on 21 April (elapsed time = 38 hours).

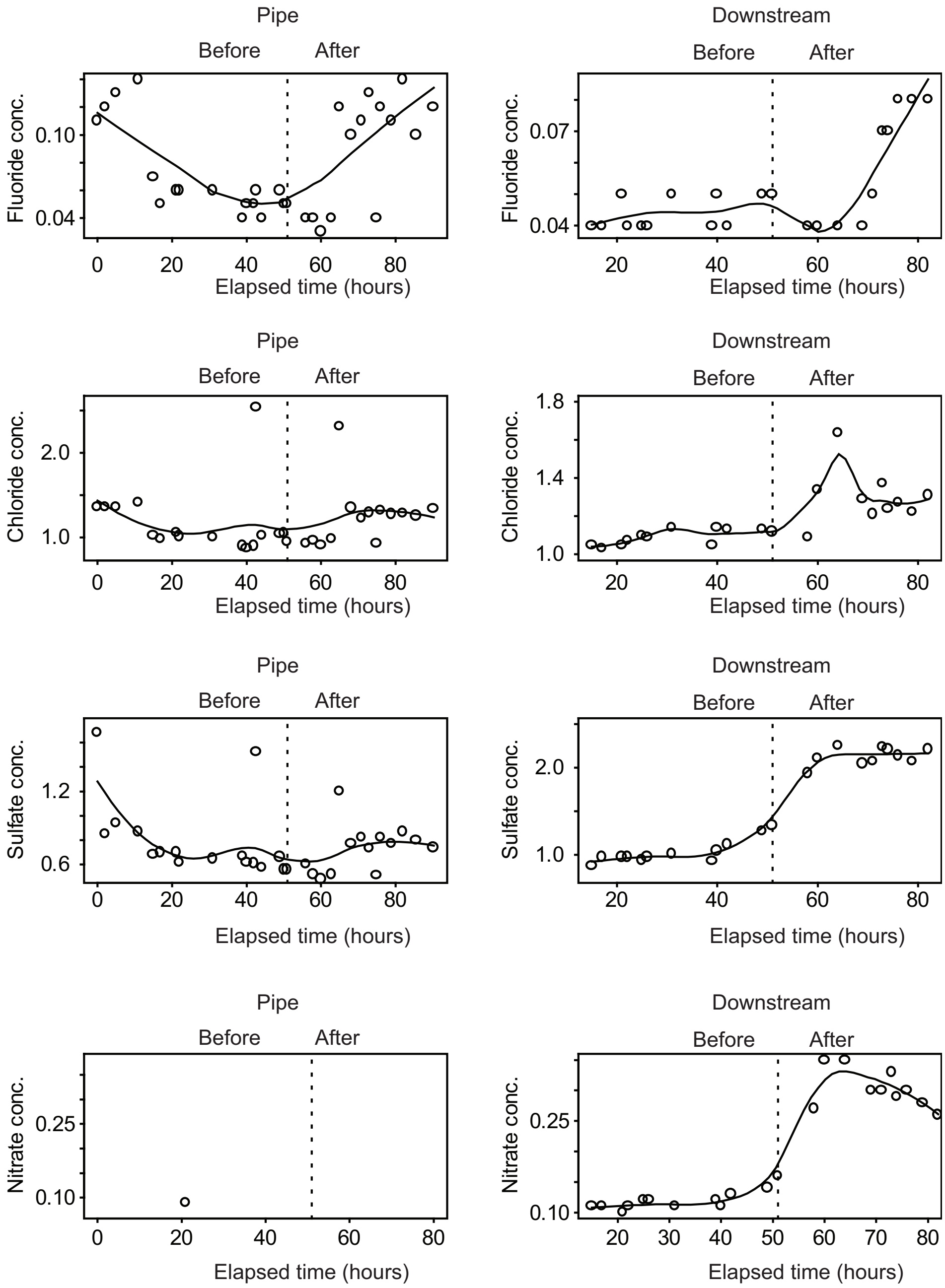

Figure 5.2. Time series plots of anion concentrations at the DCPS and the DCDS sites. The curves are loess smoothers fitted to the data. Note that the elapsed time on these figures differs from those in Figure 5.1. Collection of anion data commenced at 21:00 on 18 April (elapsed time = 0 hours). Irrigation commenced at 08:00 on 20 April (elapsed time = 35 hours). The designated cut-off time (vertical dotted line) was 02:00 on 21 April (elapsed time = 53 hours).

the few data collected for Deep Creek upstream of the study site, and for the tributary stream on the left bank opposite the rock dump (Section 4), also indicate lower concentrations at these sites. Therefore the increased solutes at DCDS are unlikely to have come from the creek upstream of the rock dump (DCUS), or from the tributary stream. The only other source would be from the rock dump itself.

Statistical analysis was then undertaken on the data from the DCDS site, comparing ionic concentrations measured before the irrigation commenced with those following irrigation. Hotelling's T^2 test indicated that the two sets of multivariate means for cations and anions, 'before' and 'after' irrigation, were highly significantly different ($T^2 = 1514$, $F_{9,12} = 101$, $p \leq 0.001$). All ion concentrations, with the exception of fluoride, varied significantly between the 'before' and 'after' periods (Table 5.2). Of these, only silicon significantly decreased in concentration (Table 5.1).

The conclusions from these analyses are that these increases in the ionic concentrations at DCDS were a result of the irrigation of the rock dump.

Statistical analysis was also conducted on the 'before' and 'after' data sets from DCPS. Despite the apparent increases in concentrations of most variables between these sampling periods (Table 5.1), only magnesium indicated a statistically significant change (Table 5.3). The lack of significance can be attributed to the large variation within the data sets for the variables, as indicated by the large standard error of the means presented in Table 5.1.

The response of sodium at DCDS to irrigation was equivocal. Figure 5.1 shows that sodium concentrations began increasing after 24 hours had elapsed (but only four hours after the start of irrigation), and had returned to be close to pre-intervention concentrations after approximately 50 hours (30 hours after the start of irrigation). The plots in Figure 5.1 also show that the response to irrigation is more complex than a simple step change. Potassium, sodium, magnesium and calcium all exhibited a pulse response to irrigation, whereby concentrations increased then decayed towards their former concentrations. Concentrations of all cations began to increase

Table 5.2. Summary of Wilcoxon rank-sum tests of ionic concentrations for the 'before' and 'after' periods for the downstream site, DCDS. (n.s. = not significant.)

Variable	z-statistic	p-value
Potassium	–2.99	< 0.01
Sodium	–2.11	< 0.05
Magnesium	–4.17	< 0.001
Calcium	–4.14	< 0.001
Silica	4.13	< 0.001
Fluoride	–1.76	n.s.
Chloride	–3.73	< 0.001
Sulfate	–4.21	< 0.001
Nitrate	–3.96	< 0.001

Table 5.3. Summary of Wilcoxon rank-sum tests of ionic concentrations for the 'before' and 'after' periods for the Pipe Supply site, DCPS. (n.s. = not significant.)

Variable	z-statistic	p-value
Potassium	–0.597	n.s.
Sodium	–1.51	n.s.
Magnesium	–2.09	< 0.05
Calcium	–1.49	n.s.
Silicon	–1.39	n.s.
Fluoride	–0.52	n.s.
Chloride	–0.40	n.s.
Sulfate	–0.12	n.s.
Nitrate	—	—

24 hours after the initial samples were collected, which was four hours after the commencement of irrigation. This was also 14 hours before the designated cut-off time between the 'before' and 'after' phases of the experiment, which was 02:00 on 21 April (i.e. 38 hours from the start of the sampling). Concentrations peaked after approximately 43 hours (i.e. 23 hours after the start of irrigation) before decreasing once more.

The gradual changes in the concentrations of these water-quality variables at DCDS were most likely due to the gradual mobilisation of soluble salts as the irrigation water started to percolate slowly through the rock dump. Over time, as the rock dump became more and more saturated, more salts were mobilised, and greater volumes of water with higher ionic concentrations seeped out into Deep Creek downstream, gradually increasing the concentrations within the creek.

The behaviour of silicon at DCDS was very different, showing an opposite response to that of the other cations (Figure 5.1). Concentrations steadily decreased after 24 hours (four hours after irrigation commenced), dipped sharply after 36 hours (16 hours after the start of irrigation) and bottomed out at 56 hours (36 hours from the start of irrigation).

The anion data, and in particular sulfate and nitrate show similar patterns of temporal change in their concentrations at DCDS (Figure 5.2). Concentrations of these two anions commence around 40 hours after the commencement of sampling (five hours after the start of irrigation), and peak around 62 hours (27 hours after the start of irrigation). In comparison, chlorine and fluorine concentrations only appear to increase towards the latter stages of the sampling period.

The cation and anion data are also consistent with the electrical conductivity data collected *in situ* at DCDS using the Hydrolab equipment during the course of the experiment. Electrical conductivity began to increase around 10 hours after the start of the irrigation, and well before the nominated cut-off time between the 'before' and 'after' sampling periods (02:00 on 21 April). Electrical conductivity continued to increase after this time, and began to plateau around 26 hours after the start of irrigation, at 24 mS cm^{-1}.

The cation and anion data for DCPS (Figures 5.1 and 5.2) also show the marked variation that occurred in the concentrations of a number of these variables at this site during the course of the experiment. Particularly marked was a sudden step-like increase during the 'after' period that corresponds with the change in source water from the Tooma–Tumut tunnel to locally derived groundwater, once water from the tunnel adit was turned off. This was also shown by the electrical conductivity measured *in situ* with a Hydrolab at DCPS. Decreases in the concentrations of some ions (Figures 5.1 and 5.2) and electrical conductivity were also noticeable at DCPS during the 'before' sampling period, and are considered to correspond with the release of water from the tunnel at the commencement of the irrigation experiment.

Piecewise linear regression of log-transformed cation concentrations from DCDS, with knots at 24 hours and 43 hours (four hours and 23 hours after the start of irrigation, respectively), provided good descriptions of the changes in cation concentrations at this site over time. The modelling of the concentrations on a log scale indicated that cations increased and decayed exponentially.

5.5. Conclusions

Although water-quality data collection for the Deep Creek irrigation experiment was not undertaken according to the original experimental design, due to on-site logistical difficulties, sufficient data were obtained to assess the success of the experiment in terms of water quality. These data have shown, not surprisingly, that the irrigation of the rock dump did in fact result in an increase in electrical conductivity and in the concentrations of most of the cations and anions measured at the Deep Creek site immediately downstream of the rock dump. The irrigation also caused a decrease in silicon concentrations at the site. It is therefore possible that heavy rainfall on the rock dump can also cause the leaching of these ions from the dump, which if associated with more toxic leachate, may cause contamination and the depauperate fish and macroinvertebrate fauna downstream. However while these water-quality results provide supporting data for this hypothesis, it is not possible to actually conclude that this is occurring from the results detailed in this report.

Some future work would be desirable to measure the impact caused by a heavy rainfall event to provide conclusive evidence to support or reject the hypothesis. Given the remote location and the infrequent nature of the fish kills in the Tooma River, this will prove difficult. But some consideration should be given to the possibility of remote sensing of water-quality conditions in Deep Creek upstream and downstream of the rock dump. Additionally, potential management actions need to be investigated to prevent leachate from the dump impacting on the fauna of Deep Creek and the Tooma River, in order to provide better and more stable habitat, and in particular to protect threatened species of native fish.

6. A survey of waste-rock dumps In the Murray-Darling Basin: summary report

Jessica Kress[1]

6.1. Introduction

One of the objectives of the Tooma River Project was to identify streams that may be at risk from metal or acid contamination at waste-rock dumps associated with mines or tunnels in the Murray-Darling Basin (MDB). The Survey of Waste-rock Dumps in the MDB, conducted between 11 March 2002 and 11 July 2002, identified waste-rock dumps and streams below them. It characterised the documented dumps in terms of their size, volume, and composition and listed known environmental impacts of the waste-rock dumps, especially those resulting from mineral oxidation.

6.2. Methods

Waste-rock dumps in the MDB were located by searching available literature across the Basin, and by correspondence and interviews with key regulatory government departments especially NSW Mineral Resources and the Victorian Department of Natural Resources and Environment (NRE). Excavations that have, or are likely to have, produced waste-rock dumps across the basin were identified, with emphasis on mines as the main source of dumps. Once identified, each dump was further researched from the available literature, such as reports or environmental studies, and by interviews and correspondence.

6.3. Sources of information

There are limited data in available literature on waste-rock dumps in MDB and no listings or databases containing information regarding waste-rock dumps in any of the states (Doug Sceney, Victorian Department of Natural Resources and Environment, pers. comm., April 2002; James Brisebois, NSW Department of Mineral Resources, pers. comm., April 2002).

Metallogenic maps and environmental studies (including environmental impact statements) give an indication of the extent of waste-rock dumps in the MDB by providing information on historic mines. This study has not included all mines, for example the occasionally mined sites or the small mines, due to time restrictions and the lower probability of those mines producing enough waste rock to cause severe environmental impacts to the surrounding area.

A significant portion of the information is based on anecdotal evidence from local councils or on the presumption that waste-rock dumps would be present at any large historical or current mining site. Where previous

[1]School of Geosciences, Monash University

environmental assessment work has been conducted at the sites, information is available, although limited in view of the vast number of waste-rock dumps in the MDB. The information is available through the mineral resources departments, either at their libraries or at specialised sections within the department, such as the Derelict Mines Section of NSW Mineral Resources.

6.4. The spreadsheet

Information was collated in a spreadsheet with the aim of documenting and characterising waste-rock dumps in the MDB. The spreadsheet has been designed to be expanded to incorporate future research into waste-rock dumps in the MDB as information becomes available.

The spreadsheet lists information on waste-rock dumps under four main headings (each with subsidiary sections), i.e.

- location (state, grid references, nature of dump, location of dump);
- catchment characteristics (catchment, nearby watercourses, geology of area, primary and secondary mineralisation, occurrences, gangue, climate);
- dump characteristics (volume of material in dump, composition of material in dump, size of dump material, vegetation cover on dump); and
- environmental aspects (aesthetic quality, degradation of downstream environment).

The data recorded in these sections are outlined below.

General location: State

NSW has the greatest landmass in the MDB and also the greatest concentration of waste-rock dumps. Good records of historic and current mining practices in NSW and in South Australia have made it relatively easy to locate mines and hence waste-rock dumps in those states' portions of the basin. There are few waste-rock dumps in the Queensland portion of the MDB, and many of the mineral deposits there are simply prospects. Most of the remainder are historic mines such as the Warwick arsenic and coal mines, and the Silver Spur gold, silver and copper mine. Victoria has many small historic mines that were active in the 18th century and early 19th century during the gold-rush era. Mines currently operating are located in central Victoria, such as the Bendigo, Fosterville and the Stawell gold mines. South Australia's comparatively few mines in the MDB are situated in the Kanmantoo block, including the Burra, Brukunga, Radium Hill and Kanmantoo mines. These all are historic or abandoned mines with documented waste-rock dumps (Ray Cox, Primary Industries Research SA, pers. comm., 2002).

Location: grid references

Many of the grid references to the mines listed in the spreadsheet were identified using metallogenic maps and studies conducted by the Geological Survey of New South Wales over the past few decades. Until recently, the Australian Map Grid system 1966/1984 was used as the standard grid referencing system. The Map Grid of Australia replaced the old system in 1994 to become directly compatible with the Global Positioning System (GPS) (Geoscience Australia, National Mapping Division website <www.ga.gov.au>). Where possible the grid references have been converted to the Map Grid of Australia using Redfearn's formula as provided by the National Mapping Division. However, both grid references are included in the spreadsheet in case of any errors in the conversion between the two systems.

Location: nature of dump

Waste-rock dumps can result from any excavation process, including the mineral extractive industry for both metallogenic and industrial rock sources, and excavations for dams or tunnels. There is a strong correlation between the existence of waste-rock dumps and mining excavation. This is due to the number of mines currently or historically operating, the large scale of excavation required to extract minerals, and the amount of waste rock produced when extracting minerals that have low concentrations per tonnage. For instance, mining involves recovering a selected portion of the ore, often material that is above the cut-off grade, and discarding the rest for waste (Paithankar 1994). As an example, gold ores can have a concentration of anywhere between 1 and 70 g gold/tonne of rock.

The mining extractive industry includes the extraction of metals such as gold, lead, and copper and the extraction of industrial minerals including slate and clay. This study has focussed on the extraction of metals from goldfields and from major mining centres because of the potentially degrading impacts the extraction may have on the surrounding environment.

A goldfield is an area with numerous small mining claims, with workings mainly on the surface or in shallow shafts and adits. Waste rock produced on the gold fields was therefore minimal when compared to major mining centres, and is not expected to produce large amounts of rock that would have any serious impacts on the environment. Dunolly, Bendigo and the Murrumbateman District, located in central Victoria, are typical examples of goldfields in the MDB. These waste-rock dumps, or 'mullock heaps', are likely to be small (usually being only a few cubic metres), and located around old pits, shafts and adits. However there have been references to mullock heaps on the goldfields containing high levels of arsenic and mercury (K. Jones, Indigo Shire Council, Victoria, pers. comm., 2002) and therefore goldfields have been included in this study.

Major mining areas in the MDB include the Lachlan Fold Belt (NSW), the New England Fold Belt (NSW), the Broken Hill area (NSW) and the Kanmantoo group (SA). Large mineral deposits are found in these geological regions, including gold, copper, tin, and the platinum group elements. These mineral deposits are commercially developed and produce large waste-rock dumps that are likely to have the potential for serious impacts on the local environment.

The construction of the Snowy Mountains Hydro-electric Scheme, located in the Kosciuszko National Park NSW, involved the excavation of large interbasin tunnels which connect dams for water storage and hydro-electrical purposes. Rock dumps produced in the Snowy Scheme are mainly from the excavation of these inter-basin tunnels and are peculiar to the scheme. Most dams, especially in NSW, are constructed across the river, with borrow pits for the construction located within the dam area, and they are unlikely to produce large amounts of waste rock. Spillways however, may involve some waste-rock dumps, although the material excavated in their construction is likely to be non-mineralised, and may therefore pose little threat to the surrounding environment (Abel Immaraj, NSW Department of Land and Water Conservation, pers. comm., July 2002).

Location of dump

Where information is available, the nearest township is indicated to show the location of the waste-rock dump. Most dumps are located in the Lachlan Fold Belt, the New England Fold Belt, and the Kanmantoo and Broken Hill blocks. Geologically, most of the MDB has Phanerozoic Basin cover, in which few mineral deposits have been identified, and therefore few waste-rock dumps were identified in that region.

6.5. Catchment characteristics

Catchment

The MDB is divided into 26 sub-catchments. Where possible, the sub-catchment is noted for each waste-rock dump, to identify catchments that may be potentially affected if the dumps produce contamination.

Nearby watercourses

'Nearby watercourses' are streams that could be at risk from any leachates produced from the waste-rock dump. Because of their relatively small volumes and proximity, streams close to dumps would have higher risk of serious contamination if any were to be produced. With increasing volume of water downstream, from tributaries and groundwater discharge, contaminant concentrations would decrease, therefore lowering any threat to water quality.

Geology of area

The geology of the area is directly related to the geochemistry of the water through the ongoing process of weathering of the country rocks, and the subsequent dissolution of weathered minerals into the water systems. In unpolluted catchments, chemical weathering of rocks is the dominant source of solutes in the water (Drever 1997).

Primary minerals and secondary mineralisation

By identifying minerals present in a waste-rock dump, possible contaminants can be identified that may have consequences for environmental quality in the area. Primary minerals are those that have formed at the same time as the surrounding rock (Kearey 1996); they are often in a reduced state due to anoxic conditions belowground. Of particular environmental concern are the sulfide minerals, including pyrite and pyrrhotite. These minerals naturally weather at slow rates when exposed to the surface, with erosional processes normally taking thousands of years. The small quantities of minerals usually exposed, and these slow weathering rates, generally ensure low environmental impact. But after mining, large quantities of minerals may oxidise when brought to the surface and exposed to air and water (Jambor 1994). With large quantities of sulfide minerals exposed in crushed form, and thus with a high surface area, and with the aid of bacterial catalysts, environmental problems can occur including acidification and heavy metal contamination with metals such as lead, copper, aluminium or cadmium. This process results in deteriorating surface and groundwater water quality, with threats to fish and invertebrate populations. This is a well-documented problem in the mining industry and is referred to as Acid Mine/Rock Drainage (Jambor 1994; Drever 1997; Harries 1997; Craw 2000; Banwart 2001).

Secondary minerals are those that have formed after the formation of the enclosing rock, usually by the alteration of a primary mineral (Kearey 1996). These minerals have already been oxidised and include malachite and azurite (copper ores). They are often associated with sulfide ores and therefore acidification and heavy metal contamination may occur in waste-rock dumps that contain these minerals.

Occurrence

The 'occurrence' of the ore body — whether it is a vein or a placer deposit — may indicate the type of rock or other minerals that may be present in the waste-rock dump. The sulfide content can be estimated, knowing the type of deposit (Cox and Singer 1986; Harries 1997): it may be a high (>5% total sulfide), medium (2–5%) or low-sulfide deposit (<2%).

The 'occurrence' section of the spreadsheet also indicates the grainsize of the minerals in the ore being mined and whether the ore is massive or disseminated (i.e. occurring sporadically through the ore body). This may have implications for the extent of acid rock drainage in a rock dump, including whether the mineralised rock is contained within one section of the waste-rock dump in a particular rock type, with overburden material constituting the remainder of the waste rock, or is distributed unevenly throughout the entire dump. It may also indicate the rate of oxidation through the surface area of mineralised rock that is exposed to the atmosphere. Smaller grainsize minerals have higher surface area exposed, and hence more of the mineral is available for oxidation (Jambor 1994; Stromberg 1999).

Gangue

Gangue minerals are those associated with the ore mineral, and can include quartz and calcite. Gangue minerals have different weathering rates and to some degree can counter the effects of acid rock drainage, depending on the amount of gangue present compared to sulfide minerals. For example calcite can produce alkaline conditions capable of neutralising acidity caused by sulfide oxidation (Stromberg 1999; Craw 2000).

Climate

Temperature and rainfall have roles in oxidation rates and in the transportation of sulfide minerals and their products. Important factors include rainfall duration and quantity, evaporation and storm intensity (Harries 1997). Where there is little rainfall and high evaporation, sulfide minerals are seldom exposed to water, thus reducing oxidation within the dump, and providing no extensive transport mechanism for dissolution products. An example of a low rainfall environment is at Broken Hill along the dump known as the Line of Lode located in the centre of the city. Even though the Broken Hill Mine exposes large quantities of sulfide minerals to the atmosphere, acid mine drainage is not known to pose any problems because of the arid climate (G. Scott, Environmental Services, Broken Hill, pers. comm., March 2002).

6.6. Dump characteristics

Volume of material in dump

There is little direct information on the volumes of material in dumps. Most information relates to the weight of ore that has been mined. The amount of material remaining in a dump can be inferred from this information by subtracting the amount of product produced from the total amount of ore mined. But this does not account for any backfilling of shafts or pits that may have occurred during rehabilitation. Many mines, however, have not been backfilled because of the potential for re-opening the mine.

Composition of material in dump

There is little direct information on the composition of dumps, but it can be inferred from the geology of the ore deposit, information that is commonly available.

Size of dump material

Information on the size of particles in the dump material is scarce but, where available, it can indicate the surface area of the rock fragments and hence the exposure of sulfide minerals to atmospheric conditions.

Vegetation cover on dumps

Information on the vegetation cover of dumps is also scarce, but is sometimes mentioned, more as an after-thought in available sources of information. The presence of vegetation on the dump's surface promotes stabilisation of the dump and reduces runoff. Vegetation also may represent rehabilitation works that have been conducted on the dump. The absence of vegetation however, may sometimes be an indication of the toxicity of the dump, especially where vegetation is unable to sustain itself due to high levels of contaminants.

6.7. Environmental aspects

Waste-rock dumps may cause a range of impacts on the environment, including acid mine drainage, heavy-metal contamination, erosion of sediments from the dump into water systems and erosion of dust particles from the dump into the atmosphere (Harries 1997; Riley 1998; Craw 2000; Myung Chae Jung 2001; G. Scott, Environmental Services, Broken Hill, pers.

comm., March 2002). Where information is available for dumps in the MDB, these problems have been documented. However the information is scattered and often difficult to access.

Aesthetic quality

Whether the dump site imposes visually on the surrounding environment is an environmental consideration. Where a rehabilitation program exists, it usually aims to rehabilitate the dump to mimic the surrounding environment's relief and vegetation. In some instances, for example around Lightning Ridge in NSW, waste-rock dumps produced from opal mining are considered a tourist attraction (M. Goodwin, Walgett Shire Council, pers. comm., 2002).

Degradation of downstream environment

With rainfall and subsequent leaching of materials in water percolating through the dump, contaminated flows into surrounding water systems is a common problem associated with waste-rock dumps (Harries 1997). Acid mine drainage causes acidification and the release of heavy metals into waters contained within the dump through oxidation of sulfide minerals, and is associated with dumps produced from mining sulfide ores (Drever 1997), for example at Captains Flat Mine on the Molonglo River (Joint Government Technical Committee on Mine Waste Contamination of the Molonglo River 1974). Heavy metals may include copper, lead, zinc, cadmium, nickel, chromium, mercury, vanadium, beryllium and other elements (Muthregja 1994).

6.8. Results and recommendations

A total of 153 sites were identified across the MDB and their characteristics are recorded in relevant sections of the survey spreadsheet. The spreadsheet is available on the Web site of the Cooperative Research Centre for Freshwater Ecology (http://freshwater.canberra.edu.au). The great majority of waste-rock dumps listed are associated with substantial mines located in the main geological regions: the Lachlan Fold Belt, the New England Fold Belt, and the Kanmantoo and Broken Hill blocks.

The survey shows that it is important to establish more clearly the extent and environmental consequences of contamination arising from waste-rock dumps in the MDB. It is recommended that the current survey data should be used as a basis for improving detailed knowledge and to guide remedial work to remove potential and existing threats to the health of streams and rivers in the basin.

Additional studies on particular waste-rock dumps in the basin could include a more intensive examination of the available literature and mining records, with visits to the particular sites for direct study. This additional work would establish dump characteristics more clearly and identify any environmental impacts present at the many potentially contaminating sites where little research has so far been done.

6.9. Acknowledgements

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The success of this project depended on the information gathered from various libraries around the MDB and from correspondence and interviews with government departments and local councils. I thank the staff at the libraries of Geoscience Australia, the Snowy Mountains Hydro–Electric Authority, the NSW Department of Land and Water Conservation, the NSW and Victorian Environment Protection Authorities, Primary Industries and Resources, SA and the Victorian Department of Natural Resources and Environment for their help in identifying and gathering sources of information. I also thank Barry Dunn and Marianne Weaver of the Snowy Mountains Hydro–Electric Authority, and James Brisebois and the staff at the Derelict Mines Section of NSW Mineral Resources.

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