Technical Memorandum 31

Investigation of the erosional stability of waste rock dumps under simulated rainfall

A proposal

S. J. Riley and T. J. East

Supervising Scientist for
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INVESTIGATION OF THE EROSIONAL STABILITY OF WASTE ROCK DUMPS UNDER SIMULATED RAINFALL

A PROPOSAL

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ABSTRACT

S.J. Riley & T.J. East (1990). Investigation of the erosional stability of waste rock dumps under simulated rainfall: a proposal. Technical Memorandum 31, Supervising Scientist for the Alligator Rivers Region.

The Guidelines to The Code of Practice on the Management of Radioactive Wastes from the Mining and Milling of Radioactive Ores (1982) specify structural lives for rehabilitated tailings structures of the order of 1000 years, i.e. the design is in a geological time frame and not a secular one. There are large volumes of material involved in the structures at Ranger and the areas of disturbance are extensive e.g. approximately 5 km^2 for the final rehabilitation landforms.

The major agent of erosion of the rehabilitation structures will be water, either as concentrated or distributed flow across the surface of the structure or as soilwater and groundwater flow. Estimated peak discharge for the 100 year event from the batter slopes is 0.5 to 5 L/s/(m.width). Peak discharge from the surface of the proposed rehabilitation structure (~ 5 km^2) to Magela Creek is calculated to be approximately 70 cumecs. The potential for drainage network development with extensive rilling and gullying is high. Rapid weathering of the chlorite rich rocks, which break down into expansive clay smectite, will significantly alter the infiltration capacity and erodibility of the surface.

It is not possible to rely on the results of monitoring under existing climates as these may not be typical of future climatic regimes. The only cost-effective method of testing long-term stability under different climatic scenarios is by the use of computer modeling of the erosional characteristics of rehabilitation structures.

It is proposed to use simulated rainfall and concentrated surface flow to study the erodibility characteristics of the surface materials and to assess the impact on erosion rates of different surface materials, slope geometries (gradients, shapes and lengths) and ground covers (vegetation and rock material). Artificial rainfall, produced by rainfall simulators, has an advantage over natural rainfall in that experimental conditions concerning rainfall intensity, duration and energy can be controlled. Concentrated flow will be produced by discharging water through a flume siting on the slopes. The experiment will enable existing hydrological and erosion models to be tested and will allow new models to be developed (if there is a need).

1 INTRODUCTION

1.1 Aim and objectives

The aim of the proposed investigation is to validate and develop (where necessary) computer-based models of erosion by water that apply to waste rock and below-ore-grade uranium material (BOGUM) piles at Ranger uranium mine (RUM) in order to provide cost-effective and rapid methods of testing the erosional stability of design options for the rehabilitation of mine structures.

There are two facets to this study: the hydrological study of the hill-slopes and the erodibility-erosivity study of slopes and channels. Together these will lead to a computer-based erosional model.

Specifically, the objectives of the study are:

1. To quantify the relation between the erodibility[1] of batters and covers and the erosivity[2] of the hydraulic forces that cause their erosion by:

   a) identifying, for the slopes and channels at RUM, relationships between the hydraulic forces of erosion and slope angle, slope length, material, and vegetation cover;

   b) evaluating the hydraulic force parameters which determine sediment transport, namely, the shear stress, velocity and power required to entrain sediment, maintain transport, and below which deposition occurs on slopes and in channels;

   c) determining the texture of material transported by flows;

   d) determining the nature of armouring and its effect on erodibility of slope material;

   e) developing relations between sediment transport rate and hydraulic parameters of shear stress, velocity, and stream power.

2. To determine the hydrological characteristics of the slopes by:

   a) describing the infiltration characteristics of the batters and covers by evaluating saturated hydraulic conductivity, time to ponding, infiltrability rates and parameters of the Philips and Horton infiltration equations;

   b) determining the hydraulic parameters required for hydrologic models, namely, roughness characteristics (Manning n, Darcy Weisbach f) of surface materials on the slopes and in the channels;

   c) determining the influence of vegetation on the effects of rainfall and on slope hydrology.

3. To validate computer-based hydrologic and erosion models suitable for use in optimising the rehabilitation design.

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[1]Erodibility is a measure of the soil's susceptibility to detachment and transport by the agents of erosion (Lal 1988). It is often measured in terms of the weight of sediment/soil that is removed by the action of one or more erosion processes from a unit area.

[2]The driving force of erosion that causes soil detachment and transport (Lal 1988).

4. To determine short and long-term erosion rates and rates of surface lowering for a range of slope and channel materials, geometry and vegetation covers.

The aim and objectives accord with the objectives of the Alligator Rivers Region Research Institute of the Office of the Supervising Scientist, namely:

> To provide a scientific basis for the development of standards and measures for the protection and restoration of the environment and for assessing the actual and potential effects of mining operations in the Alligator Rivers Region. (Supervising Scientist 1987, p. 15)

2 BACKGROUND

The Ranger uranium mine is located approximately 260 km east of Darwin and is surrounded by the Kakadu National Park, which is included in the World Heritage List. Ranger Uranium Mines Pty Ltd operates within the 78 km^2 Ranger Project Area, which is located near Jabiru on the Magela Creek system (Fig. 1). The rates of weathering and erosion of the natural landsurface appear to be low, assisted by rock carapaces which armour the surface against the action of rainsplash and overland flow (Cull & East 1987). Rocks are deeply weathered and the surface material is largely indurated ironstone (laterite).

By the time Orebody No. 1 is mined out, at the end of 1991, approximately 10 million tonnes of tailings and 28 million tonnes of waste rock and BOGUM will require containment. The stabilised waste rock, low-grade ore dumps, and tailings impoundment (either above or below grade) could form an artificial landform some 5 km^2 in area and perhaps 20 m high (Unger et al. 1989).

A capping on the tailings impoundment (either above or below grade) will be required to afford long-term protection from loss of tailings by weathering, erosion and mass movement as required by the Code of Practice on the Management of Radioactive Wastes from the Mining and Milling of Radioactive Ores (1982). Guidelines to the Code of Practice define 'long term' in terms of a 'design life' of at least 200 years and a 'structural life' of about 1000 years. Current engineering design for rehabilitated mine structures are unlikely to be able to meet these specifications - particularly in light of the climatic extremes of the wet-dry tropics (Ryan 1987). There appears to have been no testing of the long-term stability of artificial landforms designed under existing engineering-based guidelines for either Ranger or any other Australian mine site.

Ranger has prepared a conceptual plan for final rehabilitation of the site which is regularly updated and reviewed by the regulatory authorities. In this, Ranger has proposed that the tailings from No. 1 orebody be stabilised in the present tailings dam, and that the tailings from No. 3 orebody be deposited in the mined-out No. 1 pit during milling; the mined-out No. 3 pit would be allowed to fill with water to become a lake. This proposal is at variance with Ranger's present authorisation which requires that all tailings be transferred to the mined-out pits (Section 41 Authority, Environmental Requirement 29; Uranium Task Group, 1979) and it will require detailed assessment before it could be recommended for approval.

The decommissioned and rehabilitated Ranger Project Area will be included in Kakadu National Park. Therefore, rehabilitation of the waste rock dumps and the tailings impoundment should include, as a major objective, the minimisation of sediment yields, with a primary goal being the attainment of yields from the mine site that do not biologically, radiologically or geomorphologically degrade the receiving ecosystems.

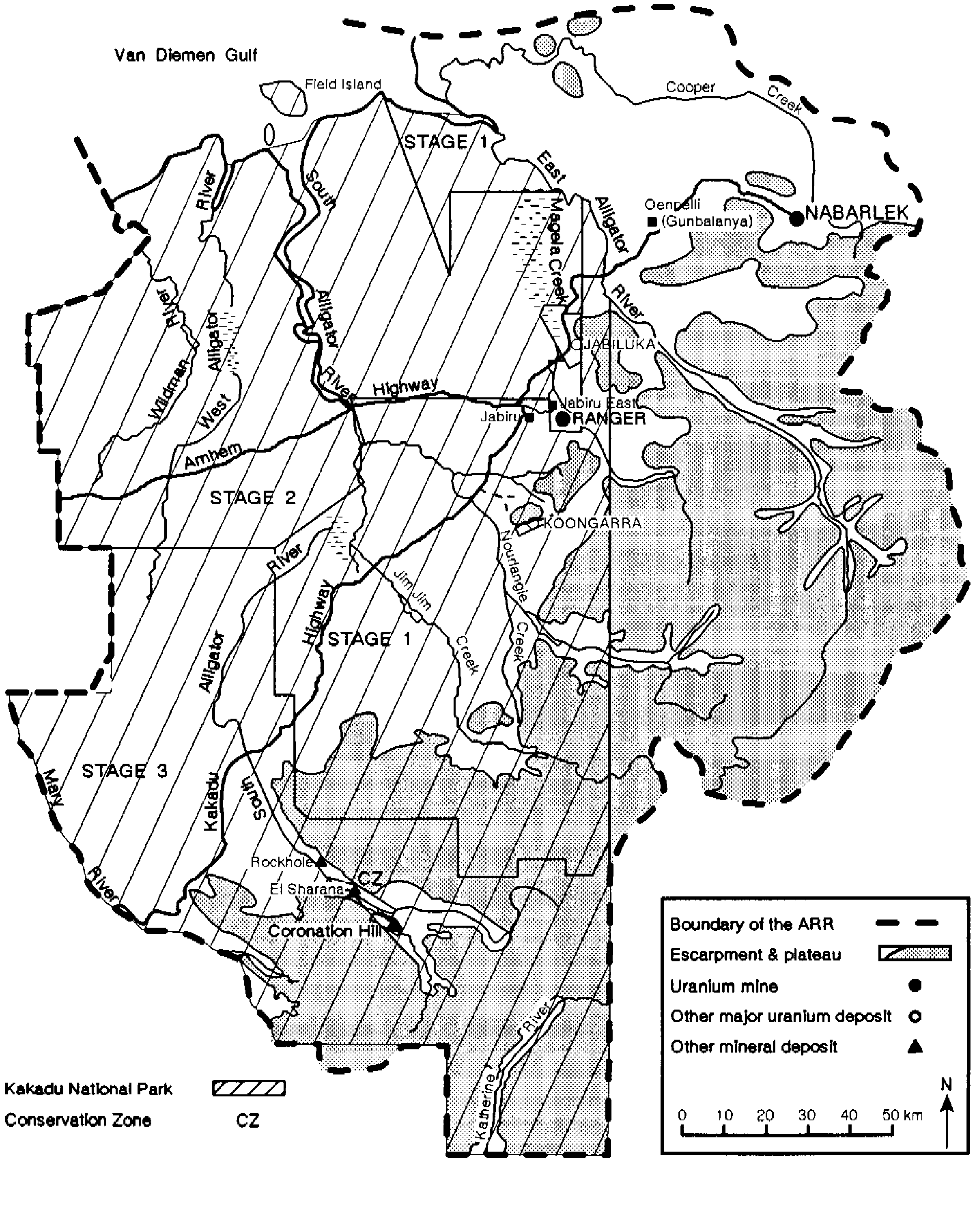

Figure 1. The Alligator Rivers Region

2.1 Erosional processes

The geomorphic agent responsible for most of the degradation and instability of both natural and engineered slopes in the ARR is water, acting upon slopes in several ways (Fig. 2):

1. Through raindrop impact, which is a net downslope transporting process in its own right. Rainsplash also prepares surface material for transport, seals surfaces and reduces infiltration, and increases turbulence in thin film overland flow (Moss et al. 1979; Moss 1979). A suitable surface cover, including vegetation or a placed or naturally formed rock cover, is able to reduce the potential erosivity of raindrop impact, although not always (Poesen 1986).

2. In concentrated (rill)[3] and unconcentrated (inter-rill)[4] flows it gives rise to erosion by slopewash and gullying (Loch 1979; Soulliere & Toy 1986);

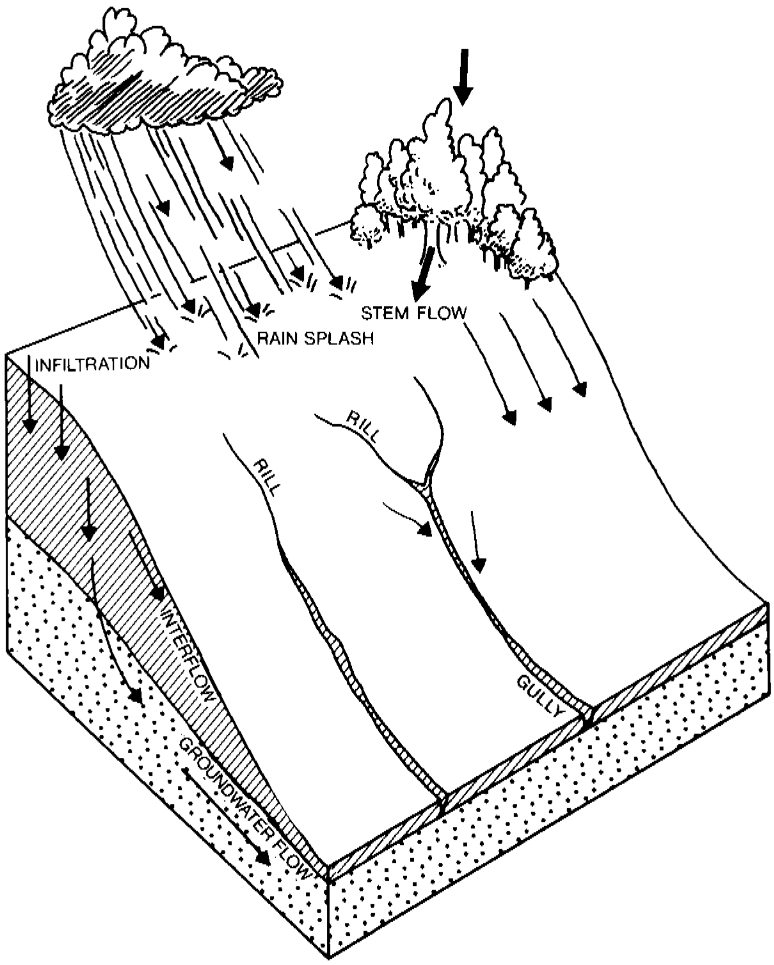

Figure 2. Schematic diagram of the action of water on slopes

[3] Small, concentrated channel flow. On the waste rock slopes of Ranger the rills are approximately 10 to 30 cm wide and 5 cm deep, but these dimensions vary considerably.

[4] Shallow water (sheet flow) erosion that occurs between the rills. Depths of flow usually less than 1 cm. Several processes of erosion and transport may take place in this zone.

3. In soilwater flow, which may constitute a significant proportion of the quickflow[5] of a catchment. This flow may concentrate to develop pipes, and through a complex set of actions and interaction may either increase or decrease the erodibility of material (Pilgrim & Huff 1983);

4. Through groundwater flow, which may produce positive pore water pressures as well as promote the chemical disintegration of slope material. A combination of these processes may increase shear stress and reduce shear strength, resulting in the mass failure of the slope.

Initial studies of the erosional stability of waste rock batters show sediment concentrations of storm runoff in excess of 100 times that from the undisturbed Magela Creek catchment (East, unpublished data, 1987). It is recognised by the CSIRO (1986) that there is a high potential for gully erosion in the artificial landforms.

Other erosional processes have been noted, particularly those of the biosphere, as detailed in Ryan (1987) and East (1986). Of particular interest is the action of termites and windthrow in overturning the soil to depths of at least 1 to 2 metres.

2.2 Soil stability

Critical to a consideration of the stability of the artificial landform is the nature of the rocks of which it is composed. 'The mine contains dark coloured metasedimentary rocks of the Lower Proterozoic age (Lower Cahill Formation) unconformably overlying light coloured gneisses of the Nanambu Complex basement' (CSIRO 1986, p. 1.4). The major rock types are gneisses, marbles and calc-silicates, porphyroblastic schist, chloritic and carbonaceous schists, mica and amphibole schists, dolerites, pegmatites, massive chlorite, and a ferricrete capping. 'The whole rock sequence is irregularly but extensively weathered, bleached and iron-mottled to depths between 20-30 m' (CSIRO 1986, p. 1.5). The major minerals of the rocks are quartz, chlorite and muscovite whilst the major clays are illite, kaolinite and smectite, which are dispersive. Except for the quartz rich rocks, weathering takes place rapidly in 'response to the alteration of the ubiquitous chlorite' (CSIRO 1986, p. 1.11) and contributes to the susceptibility of the waste rock material to water erosion (CSIRO 1986, p. 1.12). The smectitic clay lattice expands and contracts significantly as a result of moisture changes and thus is a major factor in the rapid breakdown of the rocks.

Seven soils were recognised by the CSIRO (1986), representing either a gradation in weathering of the waste rock material or the influence of groundwater and associated geochemical reactions. Infiltration rates in waste rock material with four-year-old trees were of the order of 0.01 mm/h. Weathered waste rock developed a crust during rainfall simulation experiments. Even if dispersion and crusting of the soil could be overcome the infiltration rate would only increase to 10 mm/h (CSIRO 1986, p. 4.11). Thus the runoff during major storms (where rainfall intensities are commonly in excess of 50 mm/h) would still be greater than 80% of incident rainfall.

Armouring of the waste rock dump surfaces by the most commonly available material is not permanent because the armour breaks down by weathering and can be readily breached during large events. The CSIRO (1986) report concludes that the breakdown process may exacerbate the erosion problem, because the clays reduce infiltration, thus increasing runoff and hence increasing the erosive capacity of rainstorms. Vegetation does not appear to prevent crusting (as indicated by the CSIRO study in the area of four-year-old trees), it simply covers it with litter. Bioturbation appears to maintain the infiltrability

[5]Flow which rapidly runs off a slope during and immediately after a rainstorm. Quickflow may occur as overland flow (on the surface) or as shallow subsurface flow (interflow or throughflow) (Crouch et al. 1986).

of the surface. There is clearly need for additional study of the effect of vegetation and fauna on slope material, particularly on the hydrological properties of the soil.

Armouring by quartz dominant rocks may be possible for some areas, but there is doubt that sufficient quartz rock would be available to cover the whole of the artificial landform. Questions also need to be answered concerning its suitability when revegetation criteria are considered.

2.3 Erosion potential of runoff

Estimates of the magnitude of runoff from the rehabilitation structure can be obtained from application of the Rational Method (Institution of Engineers Australia 1987). The following analysis must be viewed as giving estimates of peak discharges and not as an accurate prediction of runoff. The waste rock dump slopes, which will have gradients of approximately 1:5 under the proposed rehabilitation plan (Unger et al. 1989), are between 20 and 100 m long. For the longest of these slopes the time of concentration[6] is between 5 to 10 minutes. The rainfall intensity of a 100-year 10-minute storm is approximately 250 mm/h. The peak runoff discharge at the base of a 100 m long slope, assuming a loss coefficient of 0.8 (Ryan [1987] used a value of 0.75), will be 5 L/s/(m width). For 20 m long slopes the runoff peak is approximately 0.5 L/s/(m width). The shallow, amphitheatre shaped surface of the engineered landform has an area of ~5 km^2 and, assuming a one hour time of concentration, the peak discharge will be of the order of 70 000 L/s (70 cumecs). It is highly likely that flow down the steep batters and flow over the cap will concentrate and form rills and gullies. Ranger's proposed landform assumes that flow will not concentrate. However, surface preparation by bulldosers cannot produce perfectly plane surfaces and the discharges indicated above will have a significant erosional force. Dendritic rill and gully networks can be expected to develop.

2.4 Design strategy for rehabilitation

Such highly erodible soils, high rates of rainfall, and potential for high runoff discharges, suggest a need to design the engineered landforms with considerable attention to minimising the erosion risk. The large volumes of material to be moved and the large area to be rehabilitated suggest that considerable cost savings will be made if the design for minimising erosion can be demonstrated to be optimal before rehabilitation. Potential environmental degradation will also be minimised with this approach.

The most appropriate design should:

a) minimise the engineering costs of rehabilitation by maximising stable batter angles;

b) optimise the placement and remoulding of dumped materials;

c) minimise post-rehabilitation maintenance costs; and

d) satisfy regulatory requirements for the long-term protection of humans and the environment.

In order for rational design options to be considered it will be necessary to provide details on the complex relationship between slope, drainage, material type, vegetation cover, age of structure and erosion hazard. These complex relationships will be best described in terms of process-response models of erosion of the slopes and channels and models of the

[6]The time of concentration is the time that it takes for water to move from the most distant part of the catchment to the outlet.

hydrologic behaviour of the artificial slopes. These models will need to be numerical so that they can be interfaced with each other and with other models (e.g. Digital Terrain Models of design options). It is difficult to envisage how quantitative estimates of the erosion hazard of the proposed rehabilitation structures and strategies can be made without such models.

3 REHABILITATION

The rehabilitation of the mine site has several aspects, including aesthetic and cultural considerations. This proposal is concerned with the biophysical environment. The proposed research project will produce models that will allow the environmental impact of other aspects of rehabilitation, when translated into design options, to be assessed.

3.1 Problems of rehabilitation

The expected design life of the engineered landforms is such that a number of factors will operate that are not normally considered in traditional engineering considerations of material stability. Biological activity will be a factor that will need to be considered (East 1986; Ryan 1987). It is also highly likely that materials will not last for the design period, e.g. the wire cages of gabbions and the fabric filter mats used for the protection of surfaces will most likely deteriorate in periods much less than 200 years. Within this period even the rock material protecting the surfaces may undergo significant weathering (CSIRO 1986). There are no long-term test results that can be used to assess the viability of the materials and structures.

Tatzenko (1985) of the Conservation Commission of the NT, after reviewing the various options for stabilising the batters, noted that:

> Up until recent years, stabilisation of mine sites has relied primarily on the provision of a stable surface cover. In the future, in order to optimise the stabilisation of artificial landforms, it will be in the industry's best interest to research, plan and design for the modification and optimisation of all factors that affect overall stability of a landform and not only manipulate one or two after the landform exists (p. 228).

It would be better to design using geomorphic principles, rather than engineering ones, for there are ample opportunities within the ARR to assess the suitability of different geomorphic designs, e.g. the optimum drainage density for the channel system of the rehabilitated waste rock dump may be determined from examination of drainage densities in appropriate areas in the immediate vicinity of the mine. The channel geometry for drainage ways and channel morphology-catchment area relations should be determined by examining these relations in the immediate area.

It is highly likely that during the expected structural life of the structures, events will occur with recurrence intervals of the order of 1000 years, approaching probable maximum values of rainfall and runoff. It is an ethical responsibility assumed by this generation that structures will be designed and built to ensure as far as is reasonably practical that their integrity will not depend upon continuing surveillance and maintenance by communities that may not be able to do so. To ensure that structures will withstand the resultant hydraulic forces, the design will have to incorporate tests of the stability of materials under these extreme conditions. The proposed research will develop relationships between the hydraulic forces and slope material erodibility, enabling the impact of extreme conditions to be assessed.

Climatic change is a possibility within the structural life of 1000 years. Climatic change as a result of the 'Greenhouse effect' (Pearman 1988) and changes that would normally occur within such a period are expected. In fact, there may be several 'climatic changes' in a 1000-year period. The exact nature of these changes is uncertain and there is a range of possibilities for future climatic trends. It is not possible to set up monitoring experiments to test the integrity of the rehabilitation structure for climatic regimes that are not precisely predictable. Simulation of the effect of different climatic scenarios is the only way that the integrity of the rehabilitation strategy can be tested. This testing must involve numerical modelling.

3.2 Rehabilitation costs

It is in the interest of the mining company to develop a rehabilitation strategy that is both demonstrably viable and cost effective. Data available from a number of mine rehabilitation projects suggest that costs can be high. Ryan (1987) has analysed rehabilitation costs from a number of sites (Table 1).

Table 1. Costs of rehabilitation of mine sites in Australia

Site	Cost $/ha (in 1986 $)
Weipa (direct costs)	4 565
Captains Flat (total cost)	220 000
Rum Jungle (total cost, excluding water treatment)	150 000
Hunter Valley Coal mine (direct cost)	16 000

Table 2 Per hectare summary costs of rehabilitation at Rum Jungle
Source: Ryan (1987); does not include design or monitoring costs

Component	Vegetated surfaces	Rock mulched surfaces
Reshaping	$A500	$A500
Ripping	400	400
Clay sealing (1A clay)	6750	6750
Water retention layer (1B soil)	6750	6750
Surface soil layer (2A soil)	4050	-
Rock mulch (3A cover)	-	41500
Drainage		
- Erosion control banks	1060	-[a]
- Rip rap, matressing and gabions	8175	
Revegetation[b]	625	498
Maintenance	875	-
TOTAL	29185	56398

[a] Add $11 500 ha^{-1} for rock batter drainage (1/2) round RCP, Armnco chutes and subsoil toe drains
[b] Add $7130 for bituminious hay mulching.

Direct comparison with Ranger is difficult because of the obvious differences in the size of the operations, the materials available for rehabilitation and climatic conditions. However, it is clear that Ranger's rehabilitation costs will be at least of the order of several million dollars for a waste rock dump with an area of approximately 5 km^2.

The component cost of rehabilitation at Rum Jungle (Table 2) indicates that failure of specific items of the engineered landform would involve considerable expense in repair. For example, failure of the erosion control could cost millions of dollars to rectify. If the capping has to be hydromulched the cost of treatment may be in excess of $4 000 000. It is clearly in the interest of Ranger to be sure of the erosional stability of their rehabilitation structures before construction. The only way to ensure the success of the rehabilitation design is to test it, and the only feasible method of testing is by simulation, as described below.

The above analysis has considered the monetary aspects of the on-site rehabilitation costs. There are environmental costs of a failure. These costs are less easy to quantify. If there is an increase in erosion then more clay will enter the Magela Creek system. Since clays commonly carry potential pollutants, and because the clays and larger sediments of the mine site weather rapidly, there will probably be environmental disruption, if not degradation, in the receiving water system.

Exposure of the tailings by erosion of the cap and the transport of tailings to the streams would also create environmental problems, not the least of which will be release of radioactive materials.

Whilst the above analysis has considered the costs to Ranger of the failure of a strategy for rehabilitation, the proposal presented here could result in a considerable cost saving. A number of potentially successful rehabilitation designs are proposed, and there will be substantial differences in their cost. It is in the interest of Ranger to optimise the design in terms of costs, taking into account the constraints of aesthetics, culture etc. Physical testing of different design options will not be possible in most cases. Simulation with computer-based models provides the best and cheapest way of testing each proposal.

The benefit to the environment and the cost savings to Ranger Uranium Mines Pty Ltd of a successful rehabilitation cannot be underestimated.

The cost of rehabilitation can be reduced by developing a strategy that minimises or eliminates maintenance and by adopting a design that is not only environmentally effective but also cost effective in terms of materials used, movement of materials for shaping structures, and surface preparation.

The first step in reducing the costs of rehabilitation involves testing design options. There are three methods that can be used to test designs, namely trialling, simulation and modelling. These are not necessarily alternative approaches; they may complement each other in the testing process.

Trialling

Trialling (monitoring) involves building structures or slopes with the suggested design characteristics and monitoring the effect of natural processes on the these features.

A first step in developing and testing models is to establish monitoring programs on existing natural and artificial slopes under the natural rainfall regime. An OSS/RUM joint project was commenced in 1987 with the aim of comparing the erosional stability (hydrology, erosion rates and water quality of storm runoff) of four batter designs on the Ranger waste rock dumps. Two of the batters incorporated selected characteristics of natural stable hillslopes and their erosional stability was measured and compared with batters constructed according to more conventional engineering designs during the 1987-88 Wet season. Preliminary results showed that peak discharges for the 'natural', concave slopes were lower than the conventional, rectilinear slopes by about a factor of two. Suspended sediment concentrations and yields from the concave slopes were lower than for the rectilinear slopes, reflecting the lower erosivity of runoff from the concave batters. Further monitoring of these batters is planned for the 1988-89 Wet season. However, these types of programs are insufficient in themselves for the purposes of optimising the rehabilitation design, for the following reasons:

1. They produce empirical models which are sufficient only if the range of designs is limited to what is monitored.

2. They are unable to take account of major environmental changes that may be important in determining the long-term stability of slopes. It is now well established that there are major secular changes in climate in some areas of Australia which, depending on the nature of the shift, may induce changes in the stability of slopes. There is also considerable evidence that world climates and ecosystems will be modified as a result of increased CO_2 levels in the atmosphere. It is generally considered that these changes will take place over the next 100 years and that they may impose rainfall regimes different from those presently experienced (Pearman 1988; see articles by Robinson and Wasson et al. in the volume).

Process-based models of the interaction of slope and water are better able to predict the impact of these new regimes.

3. They may not take account of extreme events;[7] recent, below average Wet seasons in the ARR highlight this possible deficiency.

Simulation

The monitoring program can be accelerated by the use of field-based simulation. With a simulation experiment it is possible to control variables that are important in assessing the erosion hazard. The greatest control can be exercised on the shape of the ground surface, on the nature of the material initially laid at the surface, and on the rainfall and surface flow.

This second approach involves simulation of rainfall and runoff on test plots with materials and structures of the type to be incorporated into proposed designs. Simulation in this proposal involves the use of rainfall simulators and the discharge of large flows through a flume in drainage lines and over slopes. The magnitude of the rainfall intensity and discharge must be of the order of the largest expected event.

One of the major advantages of simulation, apart from the control of some of the variables, is its cost effectiveness. Whilst there are costs involved in setting up simulation equipment, the short period of testing and the speed with which results are obtained make the simulation experiment much less expensive than the monitoring experiment (Meyer 1988; Hossain 1983, p. 155).

Another advantage of simulation is the possibility of varying the experimental design whilst the program is in progress in response to data obtained in early phases of the experiment. It is not uncommon for analysis of initial experimental results to suggest improvements.

Simulation results also form a data bank for the development of important relations between the erosivity and erodibility processes operating on the slopes. These relationships are then incorporated into computer-based process-response models of hydrology and erosion.

Computer-based models

The third method of testing design options is to use computer-based hydrology and erosion models.

Computer-based modelling, while one of several types of modelling approaches that can be used to test rehabilitation options, is preferred for several reasons:

a) most hydrologic and erosion models are computer-based;

b) computer testing is cost effective and rapid once model parameters are established and a model is verified;

c) computer models of erosion commonly have a number of modules simulating different aspects of the erosion process, and it is possible to vary these modules to suit the local conditions; and

[7]The probability of one or more of the 1-in-50-year rainfall events occurring in a 5-year monitoring period is 9.6%. The probability is 4.9% for the 1-in-100-year event. The 5-year event only has a 63% chance of occurring in the 5-year period.

d) there are a number of computer-based hydrologic and erosion models available with different assumptions concerning process-response interaction.[8] Thus it is possible to test assumptions concerning the significance of different processes.

The best models are process-response models. These attempt to model the actual processes and predict responses in terms of changes in the character of the system being modelled. For Ranger the model would show how slopes, drainage lines and sedimentation basins respond to given rainfall, runoff and soilwater conditions.

Basic to process-response models are relationships describing the interaction of the components of the system (e.g. vegetation, soil type) and the forces operating within the system (e.g. stream power, flow velocity). For example, the relationship between rainfall energy and rainsplash erosion rate will have to be developed for the Ranger site. While a number of rainsplash transport models are available (Yamamoto & Anderson 1973; Bryan 1974; Poesen 1985, 1986) they will have to be tested.

Complications arise because of interactions. The rainfall-energy/rainsplash-erosion relationship will have to be adjusted to account for depth of overland flow, material type and geometry of the slope (Quansah 1981, 1985; Moss & Green 1983; Torri et al. 1987; Moss 1988).

It will be necessary to test/develop the relationships for the Ranger mine site because they are either not available or have not been verified in any comparable situation within Australia.

There is little information on the erosional and hydrologic characteristics of mine and rehabilitated mine sites. One of the largest studies conducted up to this time, that of the Soil Conservation Service of NSW in the Hunter Valley of NSW, used plot areas less than 4 m^2 to assess erosion (Elliott & Dight 1987). These plot areas are completely inappropriate for developing relationships when the interaction of overland flow and rainsplash, the development of rills, and the effect of concentrated flow are to be considered. Even the design criteria and relationships between processes and slope geometry and materials outlined by Hannan (1984) in his handbook are empirical and untested for the Ranger situation.

The input to computer-based models is commonly the physical characteristics of the area being modelled. In the case of the rehabilitation of Ranger, the inputs would be digital terrain models (DTMs are computer representations of the shape of the structures), descriptions of the materials of the surface and subsurface, and a simulated climatic regime (including rainfall, and evaporation where necessary). In the early stages of the proposed project the erosivity-erodibility relationships that the models use to predict the outcome of the interaction of process and materials will be developed. In the latter stages simulation studies using the computer-based models will be undertaken.

The designer needs to define the geometry and materials of the structures before running the model. There are many approaches to the description of the geometry and materials of the site for the model. These approaches are dependent on the type of model used. In this proposal a distributed model approach will be used, i.e. the geometry and materials of the rehabilitation site are described for a number of small areas that together make-up the whole rehabilitation structure. The size of these small areas is determined by the degree of spatial variability of the processes operating in the rehabilitated area and the number of geometric and material components needed to define the biophysical character of

[8]Process-response systems are defined by Chorley & Kennedy (1971, p. 8) as: consisting of cascading (chains of subsystems dynamically linked by a cascade of mass or energy) and morphological (formal instantaneous physical properties) components which mutually adjust themselves to changing input-output relationships...the emphasis is placed on identifying the relationships between a process and the forms resulting from it.

the area to be rehabilitated. The rainfall-channel flow simulation study proposed herein defines these spatial patterns and their erosional significance.

The only other input to the erosion model is a simulated climatic regime. There are a number of techniques for simulating a climatic time series suitable for input to a computer simulation of long-term erosion (e.g. Srikanthan & McMahon 1985). The series will consist of rainfall data of events for periods of the order of 1000 years. The actual character of the series will be determined by the particular climatic scenario used. For example, it is possible to generate a series typical of the present rainfall regime or one which has a higher number of cycles and higher average annual rainfall (as suggested by some of the Greenhouse scenarios).

Ideally, any model should not only give a result in terms of the predicted response of the system to the climatic regime but it should express this result in terms of a confidence limit, i.e. a prediction of the sediment yield should be expressed in terms of a confidence level. No models do this at present, although it is possible to either modify them to produce the confidence estimates or to run the computer based simulation in such a way that a range of results is produced from which a confidence limit can be established.

An example of a modelling approach the work of Smith (1984). His model, KINEROS, has limitations, and while it will be tested it will not necessarily be that finally selected as best representing the erosional processes of the mine site. However, it does illustrate the potential of modelling erosion processes in mine sites. The model incorporates modules describing the detachment of material, its transport and deposition through drainage lines, the action of sedimentation ponds, and the hydraulic and hydrologic characteristics of the site.

The key to any successful modelling is the identification of the main factors in the system that is to be modelled. Thus, the first section of this study is an investigation of the processes of erosion as observed during natural rainstorms and in simulated rainfall (unconcentrated flow) and gullying (concentrated flow) experiments.

The procedure for developing an erosion model suitable for Ranger involves a study of the following factors of the erosion process:

- hydraulics
- hydrology
- slope material

and the interaction of these factors in the erosion processes on slopes and in gullies/channels.

The sequence of the study is one in which several factors are studied at the same time (Fig. 3):

1. An erosion model of a distributed type will require a distributed hydrologic model so this must be developed early in the project.

2. The hydraulic, geometric and material characteristics of the slopes and channels have to be included in the hydrologic model hence it is necessary to describe them and their interactions in ways that can be incorporated into computer-based models.

3. It is necessary to describe the erosive action of the water on the slopes and in the channels for the different processes of erosion, hence a study of erosivity and erodibility is necessary.

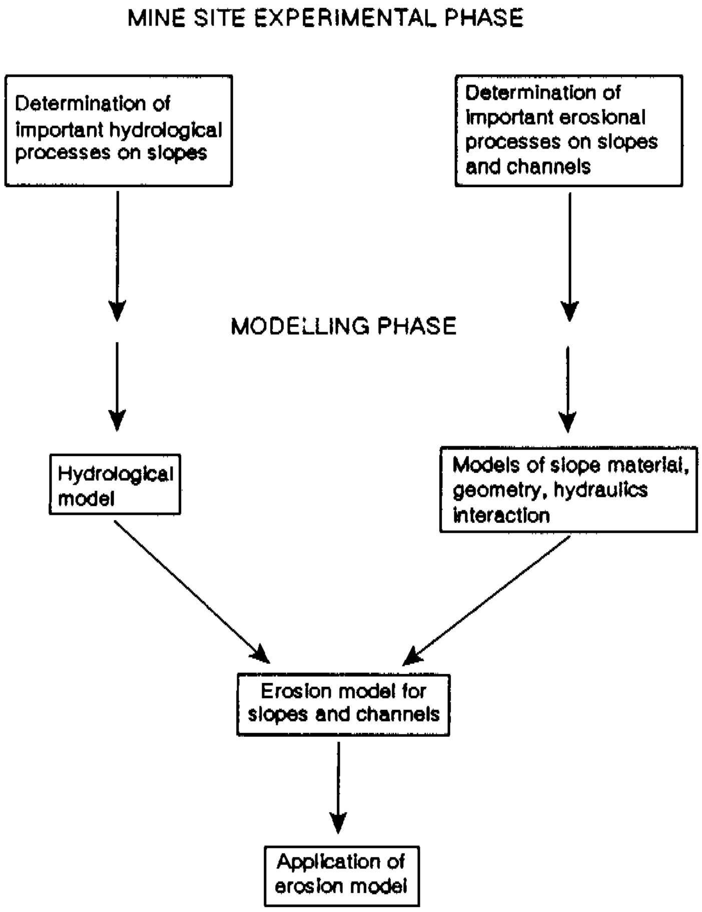

Figure 3. Stages in the proposal to develop an erosion model suitable for RUM

4. Finally, the erosion model has to be tested to ensure that its predictions are within the limits of accuracy set by the problem.

3.3 Factors in modelling erosion at the Ranger mine site

The major components that need to be evaluated for a model that will simulate the long-term behaviour of the engineered landforms at Ranger are:

- the hydro-geomorphic characteristics of the natural drainage system: topography, drainage network pattern, channel morphology and sedimentology, catchment hydrology and sediment yield, source areas of sediment and runoff;

- the biological interaction in soil erosion and slope hydrology: vegetation canopy cover and seasonal changes, stemflow, throughfall energy, root mat distribution, soil fauna;

- the hydrological characteristics of the natural and artificial slopes: rainfall erosivity, soil moisture, infiltration characteristics, surface roughness, shear strength of soil surface;

- the hydraulic characteristics of flow over slopes, in drainage lines, and through the soil: depth and velocity of flow, roughness coefficient, stream power and shear stress; and

- the interaction of materials, rainfall and runoff: relationships among parameters listed above.

Hydro-geomorphology of the natural drainage system

The hydro-geomorphic characteristics of the natural drainage system are:

- topography - the geometry of the landsurface, i.e. slope geometry, length, height, drainage basin areas;

- drainage network patterns - the planimetric arrangement of channels in a catchment;

- channel morphology and sedimentology - the width, depth, slope and meander wavelength of channels and the composition of their bed and banks with special attention to armouring features;

- catchment hydrology and sediment yield - hydrograph and sedigraph characteristics, significance of groundwater and throughflow, magnitude of baseflow component of runoff, character of sediment load (texture and type), role of vegetation in runoff and erosion processes;

- source areas of runoff and sediment - the areas within a catchment from which sediment and water is derived (essential if an appropriate conceptual model of catchment hydrology and erosion is to be selected) and the way in which this water and sediment reaches the catchment outlet.

These characteristics need to be described because they will enable the long-term (stable) relations between catchment slopes, materials and drainage to be defined. The data will also allow the erosion models to be evaluated.

Some of the information has already been collected (Duggan 1984; Cull & East 1987). Additional information will be required and can be obtained from aerial photograph interpretation, limited sampling in a number of select catchments, and rainfall and runoff simulation in a small number of catchments.

The advantages of having this information are:

- it provides a quick method of testing erosion models.

- will provide information on the natural sediment losses from the area and input to model parameters for modelling of erosion from natural catchments. Comparison of sediment yields from modelled natural and mine-site catchments will allow assessment of the significance of predicted sediment yields from the mine site. The natural drainage system data and relationships are base-line data against which the results obtained from the mining site can be evaluated.

- provides information for design of channel networks and slopes which minimise erosion.

- furnishes information on the nature of processes operating within the area and the processes that may be omitted from the modelling. This is particularly important when assessing the biological components of a model. If they can be omitted or simplified, savings of effort will be made in the study, particularly in model development.

Biological action

The biological factors that may be important in erosion processes are:

- vegetation canopy cover and seasonal change - the height and extent of the cover and the protection it affords to the ground surface against raindrop impact throughout the year;

- stemflow - the flow of water down the stem of plants, particularly large shrubs and trees;

- throughfall - the rainfall patterns and energy underneath the vegetation;

- root mat distribution - the density and depth of roots and their contributions to slope stability and to the soil water and groundwater components of the hydrologic cycle; and

- soil fauna - the activities of animals in relation to their modification of the hydrologic cycle and erodibility of surface and subsurface material.

The role of the biosphere in the stability of the rehabilitation structures is unclear at present. The biosphere can interact with the erosion processes in a number of ways. Tree and shrub canopies intercept rainfall and redirect it or change its energy before it reaches the mineral surface. Litter layers may protect the surface from rainsplash activity and also increase the resistance of the ground surface to overland flow. Termites, which turn-over soil at high rates (Williams 1978), may significantly alter the erodibility of surface materials. The depth to which they penetrate the soil may have significant effects on the stability of some structures (e.g. contour banks) and the hydrology of the slopes. There are a large number of other ways in which the biosphere could significantly influence the stability of artificial landforms.

The important biological questions that need to be answered to provide input to computer-based erosion models are:

a) The depth of tree roots of different species and the density of these roots. This information will:

   - enable the stabilising effect on soil of different species to be determined; and

   - allow assessment of the impact of trees on groundwater hydrology (through transpiration) and the depth to which it extends.

b) The effect of canopy and ground cover on rainfall. The interception of rainfall by vegetation can result in its redirection, e.g. stemflow, and the reduction of rainfall energy and hence splash erosion below the tree canopy. It is possible that vegetation may interfere in the hydrological cycle in such a way as to promote erosion. Stemflow concentrated at the base of trees and shrubs may lead to rill development (de Ploey 1984; Moss & Green 1987; Herwitz 1986). Particular species may 'soften' or 'harden' soils to erosion by a number of chemical and physical means.

c) The significance of tree fall in the mobilisation of soil and its preparation for water erosion. Ryan (1987) noted that windthrow of *Eucalyptus* spp. overturned soil to a depth of 200 mm. Windthrown trees may turn-over a large amount of soil when their roots are pulled from the ground. Some trees are more prone to windthrow than others and some, when they are thrown, have minimal effect on the soil from which they are pulled.

d) The rate of construction and destruction of termite nests and the depth to which the galleries extend. Nests erode and provide subsurface material for entrainment (Hooff 1983; Bonell et al. 1986). The termites also change the hydrological characteristics of the soil, although the exact nature of this change needs to be established for the ARR. Some preliminary work has been carried out at the Alligator Rivers Region Research Institute (ARRRI) on the quantities of soil materials transported by termites in the Region. That work will be assessed as part of the proposed study.

The biosphere has a significant impact on slope hydrology, as explained above, and this needs to be determined before a hydrological model can be applied.

The role of vegetation in the rehabilitation of uranium mines is currently being assessed at the ARRRI, and a program of research is being developed to address questions of vegetation at the Ranger mine. The relationship between vegetation and erosion form part of the assessment. It is proposed (by ARRRI Geomorphology and Plant Ecology staff, in consultation with the authors of this proposal) to develop a project to investigate those vegetation factors relevant to the erosional stability of rehabilitation of the Ranger mne. The results of this proposed study will provide input into the erosion model, supplementing the vegetation treatments addressed in the simulation field experiments.

Hydrological characteristics of slopes

The hydrology of slopes is a key aspect of any erosion model because flowing water is the agent of erosion. Hydrologic models require:

- parameters describing flow through the soil and overland (infiltration and hydraulic conductivity);
- parameters that describe flow characteristics of concentrated and unconcentrated flow on the slopes and in the channels; and
- relationships between the parameters that describe the spatial and temporal interaction of the different components of the hydrologic cycle with each other and with the slope material.

Most of the information on the hydrology of slopes can be gained by rainfall, overland and channel flow simulation studies and long-term monitoring is not required. The simulation studies would have to cover a range of rainfall intensity and concentrated flow discharge (per unit width). The upper limits of these ranges can be gained from estimates of the probable maximum rainfalls and discharges under given climatic scenarios. The lower limits are largely determined by the rainfall and discharge thresholds that are important in erosion. Practical aspects of simulator design in terms of achievable rainfall intensities and discharges and area covered in individual experiments also limit the range.

Hydraulic characteristics of flow

Continuing-on and overlapping the hydrologic study is a study of the hydraulics of the flow on slopes, through slope material and in channels. Hydraulic information concerns the physics of flow of water over the slopes and through the slope materials. It is the hydraulic parameters that enable estimation of velocity and depth of flows and the hydraulic forces acting on the slopes. Erosion modelling requires estimates of the hydraulic conductivity of the soil material; these allow prediction of rates of groundwater and soilwater flow, base flow contribution to runoff, and the erosive effect of soil water flow. A number of other hydraulic parameters have to be evaluated (as described in subsequent sections).

The hydraulic parameters are estimated by measuring the depths and velocities of flow on slopes and in channels and the changes in soil moisture content and groundwater table levels during the simulation studies. These measurements are then related to slope material and geometric conditions and these relationships are incorporated into the hydrologic models.

Relations between flow and slope materials

At the heart of all erosion models are relationships, usually empirically based, describing the interaction of slope materials and hydraulic (erosive) forces. For example, Moore & Burch (1986) use the simplified version of the unit stream power approach to predict sediment concentration, namely:

$$C = \gamma P^{\beta}$$

where: C = transport capacity (g/m^3)
P = the unit stream power, and
γ and β are 'functions of the median sediment size, the kinematic viscosity of the water, and the terminal fall velocity of sediment particles in water'. Moore & Burch (1986, p. 1624) note that 'for finer grained material they must be calibrated to field conditions'.

Rose's (1985) model of sediment concentration at the base of a planar slope is:

$$c(L,t) = (aC_eP^2/QI) \sum_{i=1}^{I} \{1/\gamma_i + \delta gSKC_r(1 - x_*/L) \qquad (L > x_*)$$

where: c(L,t) = sediment concentration
L = length of slope (plane)
t = time
a = detachability of soil by rainfall
C_e = fraction of soil surface unprotected from raindrop detachment
P = rainfall rate
Q = runoff rate per unit plane area
I = infiltration rate/number of sediment size ranges
γ = function of settling velocity of particles and Q
δ = density of water
g = acceleration due to gravity
S = slope of surface
K = 0.27η, where η is the efficiency of entrainment by overland flow
C_r = fraction of soil surface unprotected from entrainment by overland flow
x_* = value of x, distance down-slope from top of plane, below which sediment entrainment rate > 0

This equation has been simplified and there are models for slopes with channel systems at their base and for slopes with complex geometries. Rose indicates that the model needs to be calibrated for i, a, and threshold of stream power.

Most soil erosion models have been developed for agricultural areas and cannot be directly applied to a mine site. There appears to be no database within Australia against which the empirical models can be tested and developed, and even if there were such a database, there is no guarantee that it would apply to the Ranger area. Calibration of the relationships is required before the models can be used.

The simplest way to determine and test these relationships is by simulation study of the slope hydrology and erosion, selecting a range of slopes that covers, as much as possible, the likely range to be found in the rehabilitated area.

4 PROPOSAL

It is not possible to define the erosion-response characteristics of the engineered landform prior to its construction. Simulation studies coupled with computer modelling of the responses are the only methods available to predict the erosion characteristics of planned structures. None of the presently available hydrologic and erosion process-response models can be used in this environment (Ranger) without calibration and testing with site specific data.

The proposed study aims to use simulated rainfall, surface and channel flow to:

- identify the key processes of erosion on the natural and artificial slopes of the mine and;
- to collect data for calibration of numerical hydrologic and erosion process-response models.

This proposal extends the work of the OSS and RUM on the monitoring of slope processes.

4.1 Rainfall and flow simulation

Rainfall simulation is a technique that has been adopted in a number of research areas, most notably in agriculture (Meyer 1988). There are a number of studies assessing the erosion hazard in mining areas that have used rainfall simulators. Neff (1979) lists the advantages of rainfall simulators as:

- cost effective; and
- providing maximum control over when and where data are to be collected; plot conditions at test time; and rates and amounts of rain to be applied.

Amongst the disadvantages are:

- their cost of construction and number of operators required;
- size of the treated site may be small and the site may be unrepresentative of the area under investigation; and
- simulated rainfall may be unrepresentative of natural rainfall.

The cost aspect has to be examined in terms of the time required to run a field monitoring project. The cost of a 10- to 20-year monitoring program may greatly exceed that of a two-year simulation project. Furthermore, there is no guarantee that at the end of the 20 years the monitored events are sufficiently varied to give a comprehensive view of the process-response. With the simulation experiment the results are available for immediate analysis and may be used in refining the experimental technique in order to improve the quality of information and understanding of the processes.

An important consideration in simulation is the size of the rainfall simulator: large units are expensive to construct and run but are necessary if the spatial heterogeneity of small areas is to be reduced (Williams & Bonell 1988). Small simulators are easy to use but cannot reproduce many of the processes that develop as inter-rill flow develops into rill flow. A compromise has to be developed, usually in terms of those processes that are considered significant in measuring the erosion hazard of an area.

The relationship between simulated rainfall and natural rainfall is a complex one, and comparison involves studying the intensity and the kinetic energy of the two types of rainfall. Compromises have to be determined on the basis of assessment of critical factors in the processes of runoff and erosion when selecting simulated rainfall characteristics. In monitoring programs there is no control and the variability in rainfall energy and intensity, even during short period storms, is such as to make interpretation of the data difficult.

In this proposed experiment a combination of rainfall, surface flow and channel simulators will be used to measure the erosion hazard of the materials on slopes of different geometries, of different ages and with different vegetation covers. Data collected from these simulation experiments will then be used to test existing hydrologic and erosion models and, if necessary, modify or develop models.

4.2 Modelling

The design of artificial slopes requiring long-term stability needs to assess the hydrologic and hydraulic properties of the slope and will have to use process-response models of hydrology and erosion. Process-response models describe the interaction between water and the materials, geometry and vegetation cover of hillslopes. Calibrated numerical models may be used to predict the sediment yields of catchments without the need to undertake costly and time consuming monitoring. They are a cost-effective method of predicting the sediment yield and erosion hazard of design options.

The advantage of numerical models is that they may be incorporated into computer-aided rehabilitation designs. Design then becomes cost effective because several computer-generated design alternatives can be assessed not only in terms of aesthetics and geometry but also in terms of structural stability over the 1000-year structural period. It then becomes possible to start early construction of the final structures with a high degree of confidence that the design will be optimal in terms of reducing the erosion hazard and satisfying the relevant regulatory requirements. The need to design and then test the design with monitored plots and catchments may be significantly reduced. The models also allow determination of confidence estimates of the predicted erosion hazard.

Input to process-response models consists of:

- topographic information (the Digital Terrain Models - the numerical definition of the rehabilitation structures);
- hydrologic, hydraulic and material characteristics of the slopes and channels of the designed structure; and
- the climatic regime.

Hydrologic model

In this project a distributed or network modelling approach will be used to predict the movement of water over the structure. Examples of these models are ANSWERS (Beasley et al. 1980), Kinematic wave models (Kibler & Woolhiser 1970), Watershed bounded network model of Boyd et al. (1979, 1987), the three-dimensional topographic models of O'Loughlin (1986) and Moore et al. (1988).

The model will produce hydrographs (flow discharge vs time) of flow in the channel and on slopes and provide the information required to calculate the hydraulic conditions of the flow as an input into an erosion model.

It is not possible to select the most suitable hydrologic model before undertaking the experiment. Each model has inbuilt assumptions concerning the nature of hydrologic processes and these have to be confirmed for Ranger. Analysis of data obtained in the early stages of the simulation project and observations on the waste rock dumps during the first Wet season (of this project) will allow selection and testing of the best hydrologic model. However, the best options at this stage appear to be the hydrological models imbedded in ANSWERS, KINEROS, Rose's model and the three-dimensional topographic model of O'Loughlin.

Erosion models

Relations between the hydraulics of overland and channel flow and the erodibility of material are basic to erosion models. The erodibility of material depends on its texture, chemistry, fabric and vegetation cover. The hydraulics of flow depend on discharge and surface geometry and material composition of slopes and channels. A number of models are available. The erosion process is complex and not easily modelled. The complexity is partly related to the variety of erosion processes and partly to the multi-phased nature of the process, e.g. the relationships that govern detachment are not the same as those that govern transport and deposition. Spatial heterogeneity of process and materials further complicates the modelling.

As in the case of hydrologic modelling it would be unwise to accept an erosion model without testing it. Furthermore, the performance of the model should be checked against that of other models which on theoretical grounds may appear to be suitable. Both erosion and sediment transport models need to be tested.

Experience within Australia suggests considerable uncertainty about the usefulness of most commonly available erosion models. Freebairn et al. (1988) suggest that the USLE and two models that incorporate it may be suitable, whilst Edwards (1988, pers. comm.) shows that the USLE based models are often poor predictors. The USLE itself will be of little use in predicting erosion because it gives a gross estimate of sediment yield and does not have the capacity to define erosion at specific sites, which is important when the consequences of breaching the cover of the tailings dam are considered. It does not have the ability to predict the effect of sedimentation ponds and to be useful must be integrated into an event-based model, which immediately violates the nature of the assumptions used in constructing the USLE. Models, such ANSWERS, KINEROS and those of Rose and O'Loughlin, will be examined in detail and evaluated for testing.

The most suitable models appear to be ANSWERS, and of Rose et al. (1983, 1985) and Rose (1985) (Fig. 4), Smith (1981), and Moore et al. (1988), which require material erodibility, slope angle, slope length and overland flow power. These models estimate sediment transport and deposition rates, information required to predict sediment yields and erosion rates.

There are several stages in the development of an erosion model which, for this study, have been separated into investigations of the erosivity of flows in channels and flows and rainfall on slopes and the erodibility of the materials that composed these channels and slopes (Fig. 5).

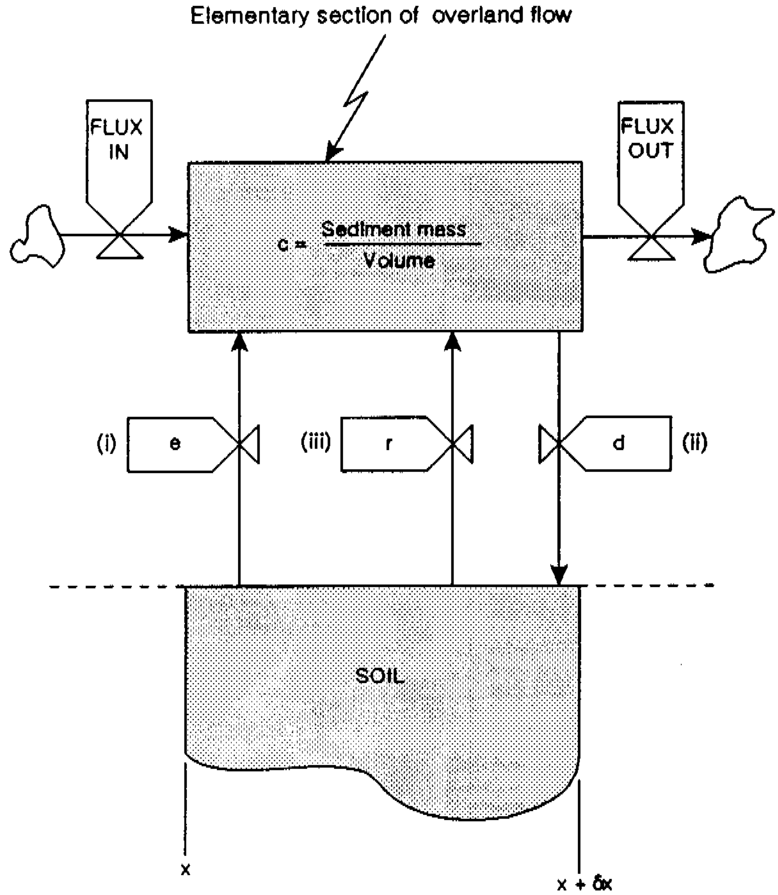

Figure 4. Rose's conceptual model of erosion

Sediment transport, degradation and aggradation models will be an integral part of the erosion model eventually selected and will need to be tested. Yang's (1976) sediment transport model, shown by Maroulis et al. (1988) to be suitable in agricultural areas, will be tested for the Ranger site. Stream power in both concentrated and unconcentrated flow appears to be a good predictor of sediment concentrations (Gover & Rauws 1986).

Simulation models will need to assess the significance of armouring. The techniques of Lee & Odgaard (1986) may be of use here, integrated into an existing erosion model or as part of a new model. Armouring is important because it will influence the erodibility of material. Because the rocks weather rapidly the armouring will have to have a time dependent factor in it - this may require a sub-project in itself in order to develop the relationships between particle size and period of weathering.

5 EXPERIMENTAL DESIGN

The proposed program comprises five projects as outlined below. The objectives and methodologies of the five phases are different, but all the phases are essential contributions to the central aim and objectives of the proposed program.

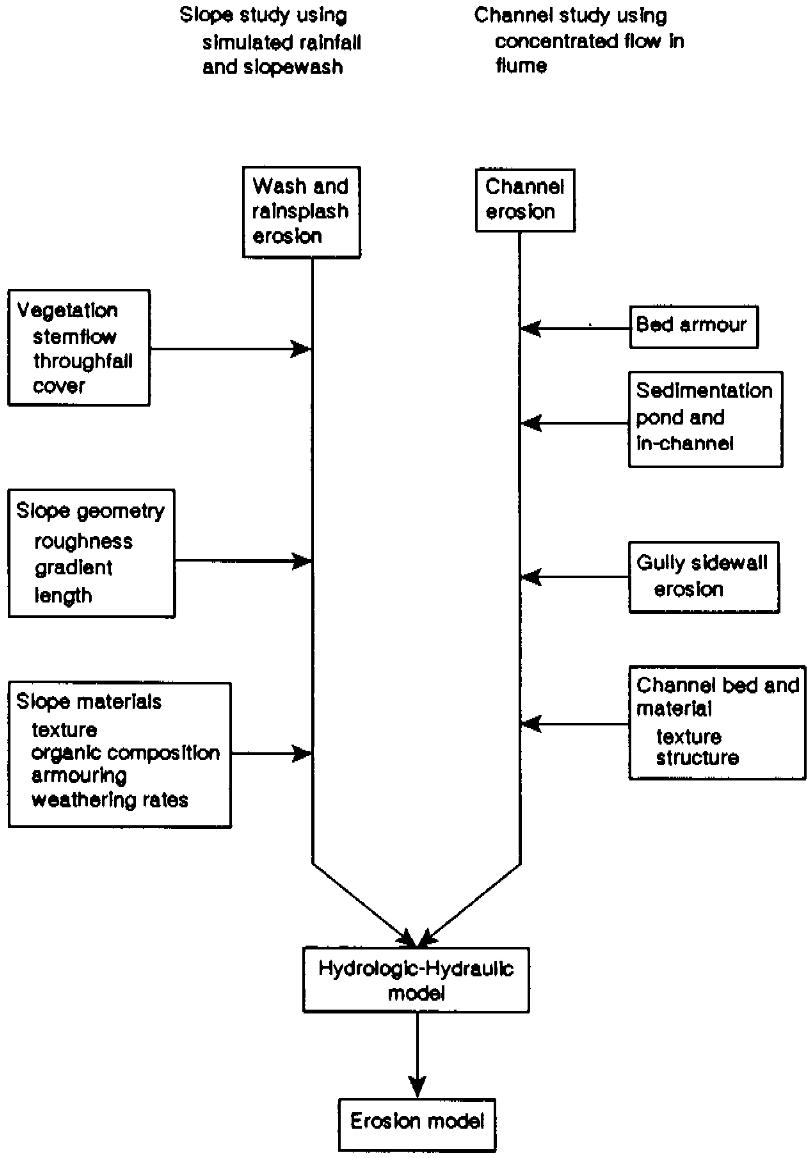

Figure 5. Stages in the development of an erosional model

Project 1 is the preliminary testing of two models. Project 1 is designed to establish, on theoretical grounds, the significance of key variables in the erosion process and important aspects of the modelling program.

Project 2 is the construction and testing of the concentrated flow flume and rainfall simulator for use in Projects 3 and 4. Project 2 is essential to the proposal for it involves the development and testing of the equipment to be used in the simulation experiments at Ranger.

Projects 1 and 2 will be undertaken first, during 1989 (Fig. 6).

Project 3 is concerned with the erodibility of material under concentrated (channel) flow, i.e. rilling and gullying. The concentrated or channel flow experiment is designed to examine the impact of rill and gully systems on the stability of the rehabilitation structure. The key objectives of this experiment are:

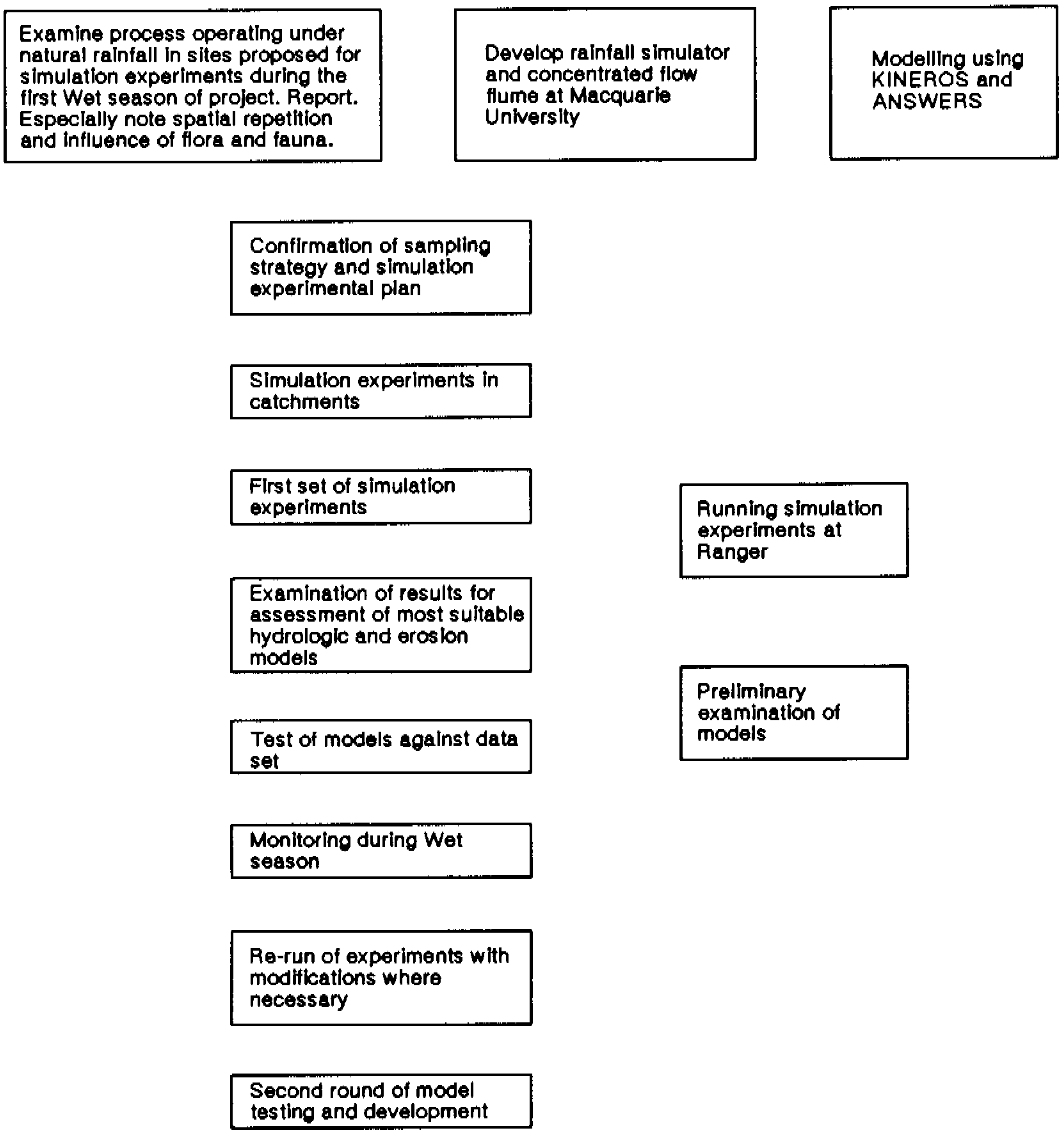

Figure 6. Outline of proposed projects

- the development of erosion-transport-deposition models that will apply to channel flow for the range of materials found at the site;
- an assessment of the critical hydraulic conditions at which significant erosion takes place; and
- hydraulic conditions of concentrated flow.

Project 4, the rainfall simulation and slope wash experiment, is designed to assess the impact of rainfall and the complex of processes associated with inter-rill flow, on the erosion of the rehabilitation structure. In this experiment information will be collected to determine:

- whether rainsplash is a significant phenomenon;
- the hydraulic conditions of overland flow at which significant erosion takes place;

- hydrologic conditions of different slopes including infiltration and soil water properties; and

- hydraulic conditions of surface and subsurface flow.

The experiments of Projects 3 and 4 will give the following:

1. Infiltration characteristics of the waste rock material under different covers at different stages of weathering, defined by:

    - infiltrability rate,
    - hydraulic conductivity and sorptivity,
    - soil moisture content,
    - parameters of the Philips and Horton equations.

2. Hydraulic conditions of surface material, defined by:

    - Manning n and Darcy-Weisbach f,
    - Surface geometry.

3. Erodibility of surface materials:

    - texture, and
    - shear strength.

4. Thresholds of entrainment and deposition for different slope geometries, cover and materials, extracting

    - relationships between entrainment and shear stress, velocity and stream power for flow on the slopes and in channels, including the effect of rainsplash energy.

5. Influence of vegetation on hydrology and erosion using vegetation covers presently available at the Ranger Mine (a further study is being developed to determine more precisely the role of vegetation in the erosion process), including:

    - pattern of rainfall under different species of tree and shrubs,
    - rainfall energy underneath the vegetation canopy,
    - ground cover (litter and canopy) variations during the year,
    - stemflow volumes and rate standardised to unit rainfall,
    - root density and distribution through the soil column, and
    - variations in the shear strength of soil under different species.

6. Hydrology of surface and subsurface runoff:

    - throughflow and surface flow rates and volumes (hydrographs),
    - sources of runoff within catchments,
    - the velocity, shear strength and stream power of surface flow,
    - spatial distribution of flow, and
    - relative significance of surface wash and rill flow.

7. Sediment transport rates for overland flow and channel flow, deriving:

    - sediment concentration and sedigraphs, and
    - relations between sediment discharge (load) and the velocity, shear stress and power of the flow,

for different slope and channel geometries and materials and including the effect of rainsplash energy.

Project 5 is the development of the erosion model; it uses the information gained in the other four parts.

Project 5 will involve testing and validation/calibration of erosion and hydrologic models for natural catchments and for the mine site.

This information and the resultant models will allow prediction of the erosion hazard, of different rehabilitation strategies expressed in terms of:

- sediment yield
- erosion rates
- depths of erosion-sedimentation in different areas of the simulated catchment, and
- stability of component landforms.

Projects 3 and 4 will run concurrently since equipment is common to both and the sampling sites and sampling strategy will be the same. It is proposed to undertake the first set of experiments of Projects 3 and 4 in the 1990 Dry season and to repeat the study during the 1991 Dry on sites that have had one year to 'mature'. The hydrologic and erosion model validation will take place concurrently with Projects 3 and 4, the majority of the work being undertaken during the 1990-91 and 1991-92 Wet seasons. During the 1989-90 Wet season observations will be made of the hydrologic and erosion processes on natural slopes and artificial slopes at Ranger and the sampling strategy will be reviewed in the light of the observations.

6 PROJECT ONE: PRELIMINARY MODELLING

Objectives

The aim of Project 1 is to test the performance of two erosion models on the waste rock dumps of RUM to:

- compare the predicted erosion rates of the two models;
- define the sensitivity of the model parameters and compare the parameters of one model with those of the other;
- assess the effect of spatial variability on the predicted erosion rate; and
- assess the limitations of the models in terms of expected processes.

The results will:

- enable the limitations of the models to be assessed;
- allow the magnitude of the erosion problem to be defined;
- pin-point the degree of detail required for calibration of the models;
- allow assessment of the sampling strategy for the monitoring and simulation experiments;

- establish the usefulness of modelling early in the experiment; and

- identify key parameters in the modelling program.

Background

There is no rational way of assessing the most suitable erosion model before data are collected and evaluated. However, some benefit can be gained by applying two well-known models that have been used on mine rehabilitation sites. The benefits are:

- experience is gained in running the model for the specific site conditions. This experience may indicate weaknesses in experimental design.

- the significance of key parameters that are common to many models is tested through sensitivity analysis. If models are 'robust' to variations in certain parameters then these need not be studied in great detail, unless it is shown that in other models they are important or that their interaction with other parameters is important.

- preliminary estimates of the parameters are gained from various sources, and these estimates can be compared with those derived in the simulation and monitoring experiments.

- the significance of the spatial resolution can be assessed at this stage in a preliminary way. The spatial detail required for estimating model parameters and the sensitivity of the model to this detail will guide future experiments.

- by varying key parameters best and worse case situations in terms of erosion of the rehabilitation structure can be gained. These estimates of erosion will confirm the significance of the study, within the obvious limitations of the unproven validity of the models used.

7 PROJECT TWO:
DEVELOPMENT OF RAINFALL AND FLUME SIMULATORS

This project involves the development of the flume and rainfall simulators and their testing and calibration. The project will be undertaken at Macquarie University in the School of Earth Sciences, in order to reduce travelling and accommodation costs and because of the availability of specialist workshop staff. When the system is ready it will be shipped to Jabiru for the next stage of local field tests.

The design for the flume is detailed in Project 3 and that of the rainfall simulator in Project 4.

8 PROJECT THREE: CONCENTRATED FLOW EXPERIMENT

8.1 Objectives

The aim of Project 3 is to assess the erodibility of surface materials when subject to concentrated or channelised flow to:

- define the influence of highly concentrated flows in the development of surface lag (rock armour);
- define the threshold conditions of rock movement;
- test sediment transport models for rills/gullies (these models will incorporate degradation and aggradation components and a module to account for armouring); and
- define the depositional regime of sediment moved from the concentrated flow region.

The results will enable:

- the incorporation of a module for channelised flow into the erosion models;
- estimation of the maximum discharges that will not cause erosion and deterioration of the main drainage lines or initiation of rilling/gullying on planar slopes; and
- evaluation of the erosional stability of those covers and batters in Ranger's proposed rehabilitation designs which may carry concentrated flows.

8.2 Background

Whilst it is not proposed in the existing Ranger rehabilitation design (Unger et al. 1989) to have concentrated drainage it is highly probable that it will develop with the consequent formation of rills and gullies that could easily breach the cap protecting the tailings. There have been no tests by Ranger to validate the assumption of unconcentrated flow and the calculations presented in Section 2.3 suggest a peak discharge of the order of 70 cumecs from the main artificial landform.

Recent laboratory and field research suggests that parameters used in standard engineering approaches for estimating the size of material to stabilise drainage lines are not good predictors of threshold movement of gravels in rills and gullies and that movement of large particles (gravels and cobbles) may take place at shear stresses less than those predicted (Torri & Poesen 1988; Abrahams et al. 1988). Standard engineering approaches may result in erosion of drainage lines (Ryan [1987] noted this in the Rum Jungle rehabilitation).

There are two classes of channels in the mine:

- Designed channel systems carry sediment loads and discharges which are not supposed to degrade them. There is a need to check that degradation will not result by conducting the experiments indicated below. It should be noted that sedimentation is just as large a problem as in-channel erosion. Sedimentation reduces the capacity of the channel and may trigger avulsion with consequent serious erosion.
- Rill and gully erosion may develop extensive, unplanned, channels on slopes. It is necessary to measure the hydraulic thresholds under which these channels develop in order that slopes are designed which do not have the propensity to gully.

A flume, placed on slopes typical of those to be established in the mine site, will enable the effect of concentrated flow to be measured directly. The effect is measured by observing the stream power (also velocity and shear stress) at which erosion of the slope commences and the nature of the erosion. The magnitude of the erosion is the sediment concentration in the water at the outlet of the flume. The results of the experiment are directly transferable to both the concentrated flow situation on batter slopes and channelised flow in gullies. In the experiment described here the conditions that promote sedimentation may also be assessed.

The experiment is conducted on a range of slope geometries and batter materials. The range will encompass those found in the mine rehabilitation structures. From the data the relations needed to predict erosion, sedimentation and transport rates can be derived. The effect of armouring can also be predicted.

8.3 Sampling design

Batter materials

The batter materials range from fresh rock to highly weathered, clay rich, compacted soils. The range of rock types can be reduced to two basic types, adopting the CSIRO (1986) classification, namely, those that weather as a result of chlorite and those that don't (the minority quartz rich rocks). There is a gradation in the chlorite rich rock, from the fresh rock material through to the highly weathered material that is essentially clay size. Between these two extremes of weathering is the partly weathered rock, which contains both clay and larger particles. Thus, four essentially different types of material can be identified:

- resistant quartz rich rocks which do not weather,
- fresh chloritic waste rock,
- weathered waste rock, and
- highly weathered waste rock.

Ideally it would be desirable to conduct experiments over this range of material with one set of measurements (incorporating several replicates) undertaken on each. The oldest, most highly weathered slopes within the mine site are approximately 8-years-old and it will be difficult to obtain a site that can confidently be claimed to be the most likely end-point type in terms of weathering. Advice from those pedologists from CSIRO who have worked on the weathering of the rocks at Ranger will be sought concerning the best sites. However, the weathering process rates are reputed to be very high and the grain size analysis undertaken by CSIRO (1986) of the oldest waste rock dump slopes show that very little cobble or boulder material remains, the majority of the material has broken down in the 8-year period to particles less than 2 mm in diameter.

It is planned to conduct some experiments on natural slopes in the area adjacent to the mine. It will be assumed that these slopes represent the end-point of a long period of weathering (whether 1000 years, the structural life, is sufficiently long for the slopes to reach a similar condition is unknown) and that the hydraulic response of the natural slopes is equivalent to that of the mine slopes after a long period of weathering.

Batter geometry

The two aspects of batter geometry that will influence the selection of sampling sites are the length and slope of the batter, and the shape of the batter.

Length and slope

The length of the batter is of less concern in the proposed experiment because it is clear from observations of existing batters of RUM that rill systems develop within batter lengths of 10 m. Since most of the batters will be at least this length and since this is a length that can be accommodated with the rainfall and concentrated flow simulators, plots will have lengths of the order of 10 to 20 metres.

The proposed batters and cap of the waste rock dump have a variety of slopes, which range from 1-in-3 for the steepest batters to 1-in-20 for the cap surface. It is axiomatic that the greatest erosion potential will be in the steeper slopes so the experiment will concentrate on these slopes. It is proposed by Ranger that the largest area of the planned rehabilitation, the cap, which is composed of the gentlest slopes, will carry discharge of ~70 cumecs in the downslope end of the structure (towards RP2, Pit 3). Because there is no information on the critical slope angles for erosion a stratified sampling design of batter slopes cannot be rationally developed at this stage. Preliminary tests with the flume will give details on the important slope angles. The site selection may have to be modified as the experiment proceeds.

For the time being slopes will be grouped within the following ranges:

- batter slopes > 1:4 (the steepest)
- batter slopes 1:10-1:4 (intermediate)
- cap surface slopes ~1:20 (the gentlest)

Shape

Complications arise in analysis of the role of slope geometry in the erosion process when the shape of the batter is a consideration. Planar slopes behave differently from concave, convex, diverging and converging slopes. Converging and diverging slopes are eliminated from the proposed experimental design because it would not be practical to run a simulation experiment to cover an area large enough to examine the convergence/divergence factor. The information obtained from simulation experiments on planar elements will be readily adapted to different shape geometries, as can be seen in the erosion model approaches of O'Loughlin and Rose, because smaller planar elements can be combined to represent complex slope geometries.

The preliminary information obtained from the four runoff plots established by OSS and Ranger (East, pers. comm. 1988) suggests that there are significant differences between the rectilinear and concave slopes; it would thus be advisable to study both types of slope.

The results of the simulation studies on the existing rectilinear slopes will establish whether slope curvature is sufficiently critical to require inclusion.

Hydrologic and erosion models will be tested to ensure that complex slopes can be modelled using information derived from planar slope elements. Tests will include data from the four plots established by OSS and Ranger.

Vegetation cover

The vegetation cover factor is the most difficult of the factors to simulate and to replicate in the experimental design. However, the range of vegetation covers can be limited by considering best and worse case extremes.

At one extreme are bare slopes with unweathered material. This material may or may not be hydromulched and fertilised as part of the rehabilitation. It is possible that the batters will be fertilized and hydromulched but not so likely that the 5 km^2 cap surface will be so covered (Ranger environmental staff, pers. comm.).

At the other extreme are the older, highly weathered slopes, which for most of the time will be covered with vegetation and have a cover of litter. During the Wet season these older slopes will have maximum vegetation cover but in the Dry season there will be little or no vegetation cover, particularly if slopes are burnt. The Dry season condition is of little concern because there is unlikely to be any major rainfall event in this season. However, there is a time in the early part of the Wet season when the vegetation cover is not established and slopes will be most vulnerable to intense rainfall (Williams 1978).

It needs to be confirmed that the dense vegetation cover of the Wet season significantly reduces the erosion hazard. For the initial stages of the experiment four major types of vegetation cover can be identified which will result in a significant erosion hazard:

- new slopes with no vegetation cover;
- new slopes with hydromulching and fertiliser;
- older slopes with burnt vegetation; and
- older slopes with reduced vegetation cover at the end of the Dry season.

The ageing factor

Slopes 'age' as a result of two factors. Firstly, the rapid breakdown of rocks by chemical and physical weathering. Secondly, the stripping of surfaces by erosion events and the exposure of new material. The CSIRO noted that consecutive erosion events make fresh material available to weathering and erosion. This aspect of the 'ageing' of the surface can be studied by repeating simulation experiments on plots over a period of two years. The intervening year will give the site time to 'mature' after the simulation, and the significance of maturing will be assessed by repeating the simulation for both concentrated and unconcentrated flow.

It is proposed to maintain the plot boundaries so that the experiment can be repeated at each site. Furthermore, during the 1990-91 Wet season the sites will be monitored for runoff and sediment loss in order to assess the impact of natural rainfall on the plots and to compare the results with those obtained from the simulation experiments. Monitoring will improve the confidence in the simulation experiments and add to the data store on the nature of processes significant to erosion.

Total sampling design

The sampling options are set out in the following table:

Materials	Slope	Shape	Vegetation cover
quartz-rich	> 1:4	rectilinear	new slope, no vegetation
fresh waste rock	1:10-1:4	concave	new slope, hydromulched
slightly weathered	~1:20		burnt older slope
highly weathered			Dry season older slope

If all combinations were required then a total of 96 sites would have to be chosen which, with duplication, would require 192 tests to be conducted. This is not feasible within the time constraints. Furthermore, it is not necessary to conduct experiments to cover all combinations.

Only two materials are critical in the early stages of the experiment, the fresh waste rock and the highly weathered waste rock. The quartz-rich material should be more stable than these two and the slightly weathered waste rock is an intermediate stage between the two. If it becomes necessary to examine the other two materials then experiments can be undertaken based on experiences in the early part of the testing program. Early testing will define the important factors in the erosion processes and thus enable a more sophisticated (and reduced) sampling program.

As indicated in previous discussion, the rectilinear slopes are all that need to be studied in the first instance. However all three slope classes should be examined if the relationships between erosion and slope gradient and length are non-linear.

Three vegetation cover conditions are important: the new slopes with no vegetation, the new slopes with hydromulching and the burnt older slopes or older slopes with reduced vegetation cover.

Thus, the total number of combinations that need to be studied initially is 18, or 36 runs with replication. Thirty-six runs can be accomplished in 4 to 5 months, allowing 3 to 4 days for each experiment, including setting-up time. The sampling combinations are:

Materials	Slope	Shape	Vegetation cover
fresh waste rock	> 1:4	rectilinear	new slope, no vegetation
highly weathered	1:10-1:4		new slope, hydromulching
waste rock	~1:20		burnt older slope

The sampling strategy will depend on the availability of suitable sites. It will be necessary to collaborate with Ranger in order to obtain the necessary sites, e.g. hydromulching and burning of slopes.

In addition to the sites within the mine, sites in the natural, undisturbed areas will be required. These sites will provide the baseline information for the project.

Erosion will be greatest in the early stages of decommissioning while the structure and the hydrologic-erosion processes interact. In the long-term the erosion hazard will reduce as a result of dynamic equilibrium being reached. The problem is one of predicting the long-term equilibrium erosion rate and the time taken to reach this equilibrium. It is also possible that the rehabilitation structure will undergo significant morphological change if the initial erosion rate is greater than the equilibrium erosion rate. Furthermore, the equilibrium erosion rate may not be acceptable.

The models developed in this study will enable short-term and long-term erosion rates to be determined for particular rehabilitation strategies.

In the long-term the slope condition that is most important is one of highly weathered rock with burnt vegetation. This will be the worst case condition for erosion (this statement will be confirmed in the early study of the hydrology-erosion potential of vegetation). Three experiments are thus critical, i.e. the three slope gradients for the highly weathered rock with burnt vegetation.

It is assumed that the 'mature' slopes included in this sample will have representative assemblages of flora and fauna. Some confirmation of this assumption will be gained by comparing the 'mature' slopes in RUM with those used in the simulation study on natural slopes.

For the short-term, initial, erosion condition 18 experiments, as outlined above, are necessary within the mine site. Outside the mine site, two experiments should suffice.

Experimental design

The experiment consists of discharging water through an open-bottom flume sitting on the slope and collecting sediment that is washed out. The flume has a diverging downstream structure to assess the effect of dissipating flow on sediment deposition. A range of discharges, as specified below, will be used on a range of slope materials, ground covers and slope angles, in order to develop the following relations, which will be incorporated into erosion models:

- stream power (a function of discharge per unit width and slope), shear stress and velocity versus sediment loss rate;
- stream power, shear stress, velocity versus threshold of erosion for different size particles (threshold is defined in terms of sediment concentrations of discharges that are considered acceptable); and
- stream power, shear stress, velocity versus temporal variation in sediment load (a measure of the increasing efficiency of armouring in the plot).

These relations are the essential components of a model of the erosion, transport and deposition of sediment in concentrated flow, and will be related to the nature of surface material by parameters which describe the texture, fabric, shear strength, litter cover and root density.

Important hydraulic parameters

Hydrologic and erosion models include hydraulic parameters, usually incorporated in relations that describe the process-response of slopes and channels. The hydraulic variables needed to define the concentrated flow condition and its erosivity are:

Flow velocity. There are a number of ways that this can be measured. Because of shallow flow depths (< 1 cm on inter-rill areas and < 10 cm in the concentrated flow experiment) current meters are not a viable option. The three methods that appear to be best suited are dye gauging, Sharps strain gauge system, and sonic probes.

Depth of flow. This can be recorded either manually or with some sensor linked to a datalogger. The latter is preferred because it will reduce data handling and accelerate analysis of results. The same techniques are used to measure depth of overland flow and piezometer levels.

Slope angle and energy gradient. These can be determined with conventional surveying techniques.

Discharge will be measured using calibrated weirs. In the unconcentrated flow experiment a portable weir will used to determine discharge from subplot areas, thus allowing partial area contributions to flow to be assessed.

Water temperature. Needed for viscosity and will be measured by a sensor connected to the datalogger.

Initiation of erosion and deposition. The time at which these occur and their location will be easily observed from the videotape record of each experiment.

From these key measurements the following hydraulic parameters of the sediment transport and hydraulic modules of the concentrated flow component of the erosion models will be determined:

- Mannings n or Darcy-Weisbach f;
- shear stress;
- shear velocity;
- stream power; and
- average velocity.

A number of related parameters will also be determined, e.g. Reynolds and Froude numbers.

In addition to these hydraulic parameters it will be necessary to sample surface materials using the techniques of photosieving (Ibbeken & Schleyer 1986) and spatula sampling of the upper surface (Loch et al. 1988). Textural analysis will identify both the changes in surface material that take place during concentrated flow and the threshold size of material entrained under the particular hydraulic conditions. The spatial distribution of sediment in the diverging flow section of the flume and its textural characteristics will enable the depositional threshold (the hydraulic condition at which material ceases to be transported) and depositional forms to be determined. These threshold values and forms will be integrated into hydraulic models of entrainment, transport and deposition. Textural and shear strength studies of the surface material will also enable prediction of erodibility through relations that will be developed between the geomechanic parameters and erodibility. Shear strength will be determined by tore-vane and dynamic penetrometer (Rose, pers comm., 1988). Samples of runoff will be handed to OSS should they require detailed chemical analysis of solutes.

8.4 Methodology

Description of the flume

The flume consists of a 0.5-1-metre wide race with an inlet at the upslope end, a sampling station at the down hill end of the parallel walls, and diverging walls below the sampling station (Fig. 7). The bed of the flume is the natural slope material, which will be exposed to the direct action of the water in the race. The flume will be designed to enable width to be varied.

The race is approximately 5 metres long and the diverging section will be of approximately the same length. Both lengths are adjustable to suit slope conditions. Walls will be constructed of steel sheeting that will be bolted together in the field. It may be possible to reduce this length and preliminary experiments will be conducted using a prefabricated plywood structure.

The inlet will consist of a large diameter PVC pipe with holes jetting down onto a steel plate. For very large discharges it will be necessary to use a trough which overflows onto the steel plate. The steel plate, which extends across the width of the flume, will be 30 cm wide, and covered with roughness elements whose characteristics will be similar to those on the slope. Water is pumped into the PVC pipe or trough from a reservoir, using a pump with a maximum capacity of approximately 40 L/s. Flow is controlled by a regulator. A small, easily installed swimming pool will be used for water storage.

Flume width will be reduced to approximately 0.3 m where it is necessary to obtain high shear stresses and stream powers. The experiment will run for at least 10 minutes before the reservoir runs dry. The pump will need a maximum capacity of 20 to 40 L/s to maintain flow. Average velocities in the flume will be approximately 1 m/s.

The sampling point (Fig. 7) is a site for hand sampling of suspended load, bedload and solution load (water chemistry) and also a control structure for assessing discharge from the flume.

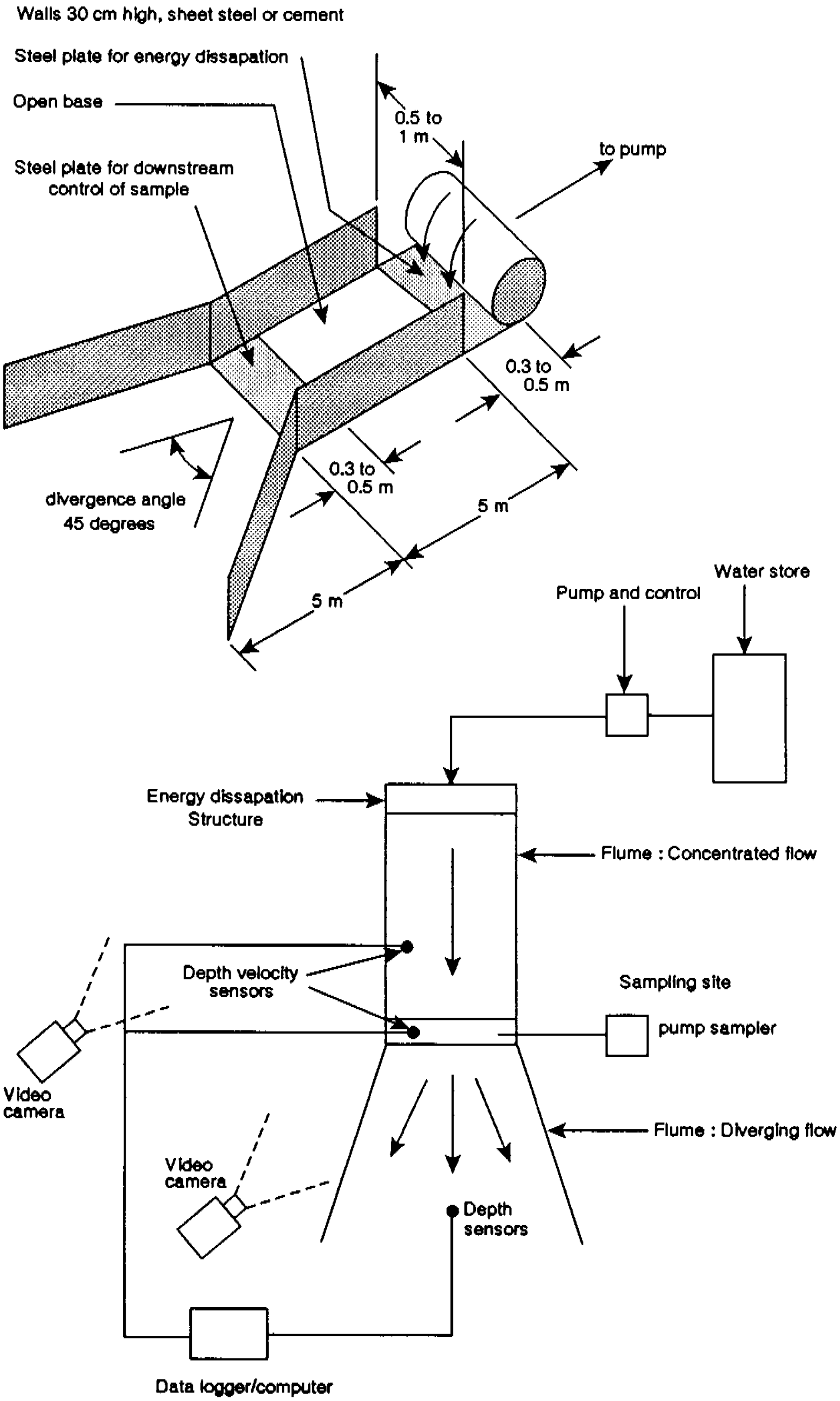

Figure 7. Schematic sketch of flume for simulating concentrated flow on a slope

The divergence area will be visually examined for sites of deposition and a number of depth gauges installed to monitor the reduction in water level as the flow diverges.

After the attainment of steady or near steady sediment discharge from the flume the plot will be subject to simulated rainfall whilst the discharge continues. This combination will allow assessment of the interaction between rainfall, runoff and erosivity of the flow, which should be particularly significant at the lower flows (Moss & Green 1983). The experiment will be run until a new equilibrium is attained.

Discharge is measured at two points - the first is at the pump, the second is at the sampling point. Infiltration/leakage losses may then be determined by the difference. Water depth is measured using staff gauges. It will be necessary to measure velocity in the flume using either small current meters, or a system developed in Melbourne by Sharp (1981) which uses strain gauges, or a sonic (acoustic) probe.

As described below, considerable effort is required to collect data, limiting time for observation of events in the flume and maintaining performance of the pumps etc. Since the second phase (Project 4) of the experiment will require datalogging equipment and a variety of sensors, a datalogger will be used on the concentrated flow experiment in the following way:

- instead of manually reading depth at a number of gauges, depth sensors, such as capacitance rods, will be attached to the walls of the flume and throughout the site;

- to continuously log velocity in the flume; and

- to control the sampling of the flow for determination of suspended and chemical loads using a Gamet automatic water sampler.

An additional observation instrument is the video camera. Two should be used to record changes in the bed configuration within the flume and the divergence zone.

Significance of methodology

The system of measurement described here has several advantages over other systems described in the literature (Roels 1984; Maroulis et al. 1988). There is greater control on the stream power concentrated on a unit area of the slope and high stream powers can be obtained.

The concept of a diverging section downstream of the race appears to be innovative and will allow assessment of the depositional process that take place with the decay of surface flow.

Conduct of the experiment

The basic procedure is as follows:

1. The flume is positioned randomly within a selected area of batter or cover.

2. The flume is set in position and pumping equipment in stalled.

3. Stream power is preset by defining the relevant inlet discharge for the slope angle of the flume. The pump is adjusted to deliver this discharge. The experiment is first run at a low stream power. The power is then increased and the experiment run again at the same site. The procedure is repeat twice, up to the maximum stream power

considered important (typical or extreme) in the investigation area. The upper limit of stream power will also be governed by the pump capacity.

4. Each run has a duration of at least 10 minutes, at which time a visual assessment is made of the stability of the bed material. If erosion has ceased as a result of armouring the experiment is terminated. If the loss of sediment is high the experiment is run for 1 hour (subject to available water), a time probably typical of the base period of the hydrograph for short duration storms within the area. The experiment is then repeated with simulated rainfall for at least 10 minutes.

5. Sampling of flow takes place at 1-minute intervals in the first 5 minutes of the run, then every 2 minutes up to 20 minutes, thence every 5 minutes up to 1 hour. Notes are also made at these times of the erosional characteristics (forms) in the bed of the flume and of the depositional characteristics in the diverging section.

6. Sediment sampling of bed material is conducted in two ways. For coarse grained materials stereo-photographs will be taken. For fine grained material samples will be taken from the flume and divergence zone at the end of the run. Samples from the divergence zone will be collected in a line from the end of the parallel walls downhill, in order to define the textural trends in this zone. Samples are collected prior to the experiment from the outside flanks of the flume.

7. Stereo photographs are taken of the site using the Macquarie University P32 metric camera before and after each run. These stereo models are then available for topographic analysis using the SD4 analytical stereo-digitiser in the School of Earth Sciences.

8. Standard particle size and sediment concentration analysis techniques are used in the laboratory. Textural analysis will discriminate material into the following classes; silt/clay, fine, medium and coarse sand, gravels and larger. Tore-vane and dynamic penetrometer tests will be undertaken before and after the experiment. Moisture content samples of the soil will be taken at the beginning and end of each experiment from within the flume.

9 PROJECT FOUR: ERODIBILITY OF SURFACE MATERIALS UNDER SIMULATED RAINFALL AND DISTRIBUTED FLOW

9.1 Objectives

The aim of Project 4 is to assess the erodibility of slope materials when subject to distributed flow (surface wash or interrill flow) and rainfall to:

- define the relations between stream power, velocity, shear stress and erosion for shallow flows;
- examine the width, depth and pattern of scour and rill development as a result of overland flow;
- determine the infiltration characteristics of a range of slope conditions;
- assess the significance of splash erosion on infiltration, runoff and erosion;

- assess the significance of splash erosion on infiltration, runoff and erosion;
- assess the impact of different slope covers, geometries and material composition on runoff and splash erosion;
- evaluate parameters of slope hydrology and erosion models;
- identify those slope conditions that will not erode under given hydraulic stresses (the threshold conditions); and
- characterise material eroded from the slope under different hydraulic stresses in terms of its texture.

9.2 Background

The majority of the area of the engineered landform will be subject to overland flow and raindrop impact. The surface can withstand the erosive effect of flow up to a certain threshold, beyond this threshold excess stream power and shear stress result in erosion. Thresholds vary among the batters and covers because of different materials, slope geometries and vegetation. In addition, thresholds at a given site vary over time with the weathering of materials and the development of a vegetation cover. Concentration of flow and the development of a dendritic network of rills on the slopes is a possibility. It is essential for erosion modelling that the nature of the hydrology of the slopes be described and that numerical models of the erosion processes be included in the complete erosion model of the rehabilitation structure.

Details of the processes of erosion have been given in the preceding discussion. Project 4 is designed to provide the information on these processes in a form that can be incorporated into a numerical model of erosion. The study involves the use of a rainfall simulator which has the option to distribute a sheet of water onto the plot. In this way the individual and combined action of rainfall and sheetwash can be studied. The simulation is carried out on a defined plot, a section of slope in which the experiment is performed.

Plot size is dependent on the spatial replication of processes and erosion features. Plots cannot be smaller than the minimum size of erosion feature and should be large enough to allow erosional features to fully develop (Williams & Bonell 1989). The plot size for the RUM will be estimated from the 1989-90 Wet season study of erosion on the slopes and from the early stages of the simulation experiment.

This experiment differs from the concentrated flow experiment: there is no deliberate attempt to develop concentrated flow. However, rill networks are likely to develop in the plot and these may grow to the size of small gullies. The plot must be large enough to allow this growth to develop, at least to the stage where the gully processes are similar or overlap those studied in the concentrated flow experiment of Project 3. There is a continuity in the nature of the experiments of Projects 3 and 4, the unconcentrated experiments overlapping the concentrated flow experiments at the lower range of shear stress and stream power.

Project 4 is primarily concerned with processes operating on the slope whereas Project 3 is concerned with the concentrated flow effects and directly with processes of erosion, transportation and sedimentation in channel systems.

Interflow experiments will be undertaken at the same time. Interceptor pits at the downslope end of the plots will monitor the throughflow component and hydrographs and sedigraphs of flow through the slope material will be derived. The deeper groundwater flow on the slopes will be studied using piezometers.

9.3 Methodology

Sampling design

The sampling design will be the same as for Project 3, the logic behind the selection of sites and materials, and experimental replication being discussed in that section of the proposal.

Experimental design

The essential element of this experiment is the discharge of a thin film of water over a slope segment (plot), with the option to generate surface runoff by rainfall and to study the interaction of rainfall and surface wash. The experiment resembles that described by Abrahams et al. (1988).

The significance of rainfall simulation to the experiment is two-fold. Firstly, surface runoff is rainfall generated on most slopes and rainfall simulation will reproduce this aspect of the runoff process. Secondly, there are interaction effects between thin film runoff and rainfall (Moss 1979) which may increase the erosive capacity of the flow.

The size of the plot is determined by the downslope distance required to establish steady state conditions of scour, rill formation and flow. The width of the plot is determined by lateral migration of flow and spacing of scour features. Preliminary examination of batters at RUM suggests that downslope distances of the order of 5 to 10 m are required and that scour features are spaced 2 to 4 metres across the slope. Rills are spaced 1 to 2 m apart and distances from the batter crest to initiation of rills are of the order of 2 m. The rill networks appear to stabilise after a distance of 5 to 10 metres. Wet season monitoring (1989-90) will confirm these Dry season observations. It appears that the minimum size of plot required for the study is 4 m wide by 10 m long.

Description of the experiment

In the natural environment the onset of overland flow is preceded by rainfall and it is planned to follow that sequence in running this experiment. The sequence for each experimental run will consist of:

- a period of rainfall simulation up to the time of initiation of runoff;

- a period of runoff production by rainfall alone; then

- a period of runoff production combined with overland flow generated from the headwater region of the catchment. At each stage the characteristics of surface flow and erosion will be monitored with video cameras.

Rainfall will be generated with sprinkler rainfall simulators of a type to be determined. High rainfall intensities will be used since slope geometry will be most strongly influenced by the less frequent events of high intensity rather than the more frequent events of low intensity. Rosewell (1985) gives the rainfall energy attained for particular rainfall intensities. Design of the sprinkler system will aim for these energies. The intensities will be estimated from Jabiru intensity-frequency-duration (IFD) data. The selection of rainfall simulator is the subject of Project 2.

The preferred rainfall simulator consists of a series of vertical tubular poles and on top of each is a sprinkler head. At the base of each pole is a pressure gauge to control flow; all the poles are connected by flexible pressure tubing to a pump. A water store of approximately 4000 L capacity is required for a 100 mm/h rainfall on a 40 m^2 plot lasting for one hour.

Placement of sprinkler poles is a function of the shape of the plot and the spray characteristics of the sprinklers. This will be determined in preliminary experiments.

The choice of sprinkler is a function of the design specifications of rainfall intensity and rainfall energy. A large number of alternatives are commercially available and each has specified drop sizes and discharge rates as well as spray patterns. Calibration of drop sizes will be undertaken using filter paper techniques.

Within the plot it will be necessary to establish two 0.2 mm tipping bucket raingauges and a number of manual raingauges. The tipping bucket raingauge information will be logged continuously, the manual raingauge information is recorded at the end of the experiment as a check on spatial uniformity of rainfall.

The system should be capable of operating in wind speeds up to 10 km/h. Beyond that speed there is potential for distortion of the flow patterns. Wind speed data for Jabiru suggest that optimal wind conditions for the experiment will be experienced for the majority of the time during the Dry season.

Moisture conditions of the slope material before and after the simulation runs will be determined by gravimetric sampling techniques. Sampling of interflow rates and water quality will take place with the use of interflow interception pits at the downslope end of the plots.

Discharge at the outlet of the plots will be monitored with an H-flume. Water level will be continuously recorded using a capacitance rod depth gauge, linked to the datalogger. A pump sampler located at the outlet will take the necessary sediment samples. This sampler will be located above a bedload trap that can be replaced in order to assess bedload variations during the experiment.

Within the plot a combination of tensiometers and piezometers will be located to monitor the soilwater movement. Tensiometers will be connected via pressure transducers to the dataloggers. Piezometers will use capacitance rod depth gauges and be connected to the datalogger. Throughflow will be measured by H-flumes if rates are high, otherwise with tipping buckets. Samples for particulate and chemical analysis will be taken by hand.

During the experiment the observer will use a small portable H-flume to monitor the discharge of small rills within the plot. The observer will also take suspended sediment samples from these sites. The distributed character of the erosion and source areas of erosion will thus be defined.

The introduction of overland flow at the top of the plot will be via a 50 mm diameter PVC pipe, connected by pressure hose to the pump. A flow regulator will be inserted in the line. The PVC pipe will have a number of small diameter holes jetting down onto a steel plate.

Two video cameras will be installed on the margins of the plot to record all events during each run. Two are necessary because of the detail required. Four splash boards will be installed within the plot as a means of assessing the significance of splash transport of sediment as a component of the total sediment yield from the site.

Sediment samples from the ground surface will be collected in the manner described for the concentrated flow experiment in Project 3. Samples for the determination of moisture content will also be taken before and after the experiment since this is an important parameter in the application of some infiltration equations.

Sediment analysis will follow standard procedures. The data from each run will enable infiltration characteristics of the material to be determined. Scour patterns and magnitude of scour sites will be mapped and analysed for spatial distribution. Hydrographs and sedigraphs will be analysed in terms of spatial and temporal patterns of erosion and also for purposes of calibrating erosion models. Soilwater flow will be assessed in terms of its significance to the erosion events. Suspended sediment samples will also be available for chemical analysis should OSS require them.

Important hydraulic parameters

These are the same as those detailed in Project 3 together with the following:

Discharge within the plot. A portable weir will used to deter mine discharge from subplot areas, thus allowing partial area contributions to flow to be assessed.

Time to commencement of runoff. This can be determined by stop-watch. However, since a video camera with a recording timer will be monitoring events, the time to ponding and to commencement of runoff of different sections of the plot can be readily determined by viewing the tape.

Piezometer level. This will be determined by manual observations or by a depth sensor connected to the datalogger.

Matrix potential. Either gypsum blocks or tensiometers with pressure transducers will be used. Some difficulty may be experienced in installing the tensiometers, particularly in rubble, where the contact with the cups will be poor.

Infiltration rate. Assessed from the hydrograph and tensiometer data.

Saturated hydraulic conductivity. This will be determined from the advance of the wetting front, hydrograph and tensiometer data.

Sorptivity. Determined from analysis of the hydrograph and tensiometers.

Replication

It is desirable to replicate all experiments in order to estimate the degree of variability within sites. If there are indications of high variability then the experiments will be repeated within the constraints of time, cost and improvement in prediction accuracy. At this stage duplication is considered sufficient.

10 PROJECT FIVE: MODELLING EROSION PROCESSES

10.1 Objectives

The aim of Project 5 is to validate numerical models of the hydrologic and erosion processes operating within the Ranger uranium mine to:

- develop models that relate the hydraulic characteristics of flow in channels and on slopes to erosion, sediment transport, and deposition;
- describe the hydrologic system of RUM with a numerical model that is process based;
- develop an erosion model that incorporates channel and slope components and that can be applied to RUM as well as natural catchments in the area; and

- produce an erosion model that may be used by Ranger to predict the long-term rates of erosion and sediment yield in RUM when assessing the erosional characteristics of their rehabilitation strategies.

10.2 Background

The rationale for the major aim of this project, as stated in the introduction, is to provide a numerical or computer-based model that may be used by RUM to predict the erosional characteristics of its proposed rehabilitation structures. This approach is necessitated by the cost of long-term monitoring, by the potential for a changing climate in the area (making interpretation of monitoring results difficult), and by the economic and environmental necessity to be as sure as possible of the success of a proposal before construction begins.

There are no data available within Australia against which a model could be tested prior to its adoption for Ranger. Hence the need to collect the data, as outlined in Projects 3 and 4. There appears to be no previous experience in Australia in the application of erosion models to a mine site like Ranger at the degree of detail required. Thus, while there are a number of erosion models that may appear to be suitable, they need to be validated (tested), and in all probability modified, for application to Ranger.

The basis of an erosion model in a regime which is dominated by water erosion is a hydrologic model. At this stage it appears that the model developed by CSIRO under the direction of O'Loughlin would be suitable, although others are available (see KINEROS, Rose's model, and the hydrological model embedded in ANSWERS). The first stage of this Project is to select a suitable hydrologic model.

Once a suitable hydrologic model is selected then an erosion model will be validated. Because so many of the existing erosion models are tied to hydrologic models it is highly likely that rejection of a hydrologic model will result in rejection of the associated erosion model. However, many models are in modular form, each module describing a certain aspect of the erosion process in a catchment. It is not inconceivable that the final model will incorporate modules from a number of different sources and that model finally selected is composed of the better parts of several erosion models.

10.3 Methodology

It would be logical to begin the modelling work by enlisting the aid of research groups that have potentially useful models. Thus, the groups led Dr O'Loughlin of CSIRO and Professor Rose of Griffith University will be asked to collaborate in the testing of their models on the data generated by the experiments of Projects 3 and 4.

ANSWERS and KINEROS will be tested at Macquarie University by the research fellow employed for this study. The results of each of the tests will then be compared and a final decision made on the best model or the best modules of each model. The next step is one of fine-tuning the final model, testing it against available catchment and plot data.

Selection of most suitable model will be on the basis of simplicity within the constraints of accuracy of representation of the hydrologic and erosion processes and accuracy of prediction of erosion rates, sediment yields, sedigraphs and hydrographs. An attempt will be made to provide a model that can be used on a PC, although this may be difficult with the need to incorporate a DTM.

Once this model is developed it may then be handed to Ranger for assessing the erosional characteristics of their proposed rehabilitation structures.

11 SUMMARY

The primary aim of this project is to validate and develop (where necessary) computer-based models of erosion by water that apply to waste rock and BOGUM piles of RUM; and to use these models to test the erosional stability of design options for the rehabilitation of the mine structures.

Erosion modelling in this context is innovative and considerable effort will be needed to validate the models and establish their reliabilities. The modeling is innovative and important because:

- event-based modelling of a waste rock dump in a tropical environment with extremely high rainfall intensities has not been attempted before;
- modelling for prediction of erosion over a long time period (geomorphic time) has not been attempted before;
- significance of the erosional integrity of the artificial landforms to the health and well-being of humans and the environment;
- lack of *a priori* information on the significant short-term and long-term erosional processes; and
- likely non-stationary behaviour of the erosional system over the design life of the structures.

A keynote of the proposed research project is its flexibility; it is not possible to predict the significance of certain processes until initial tests are conducted. After initial tests, the important processes will be further investigated and integrated into the erosion model, the insignificant ones ignored and removed from the model.

The principal erosional processes that will need to be investigated in order to establish their short-term and long-term significance are: sheet wash, rainsplash, rilling, gullying, tunnelling (piping) and chemical disintegration (weathering).

The erosional processes are driven by the hydrological processes, hence it will be necessary to investigate the following and establish their nature and significance in both the short term and long term: infiltration, throughflow (interflow), rainfall spatial and temporal variability, overland flow, concentrated flow (in gullies and rills) and sources of runoff.

A number of parameters will be used to describe these erosional and hydrological processes, amongst which will be those that describe the entrainment, transport and deposition of material.

The interaction of the biosphere with the erosional and hydrological processes will be investigated. Most particularly, the following will be investigated: termite activity, interception and stemflow, windthrow and ground cover.

Baseline information on hydrological and erosional processes in the natural environment will be obtained from existing data, supplemented by limited monitoring and experimentation where necessary.

Material characteristics and rates of breakdown of rocks will be investigated, using (wherever possible) the data collected by Ranger's consultants.

Research will proceed in the following manner:

1. Construction of rainfall and concentrated flow simulators and their testing at Macquarie University - these simulators will be used in experiments to derive the parameters that describe the erosion and hydrology of the waste rock dumps. Specifically, this aspect of the project will:

   - design a simulator which can produce rainfall intensities between 60 and 300 mm/h;
   - produce a simulator that can be used on a variety of slopes and plots of different areas;
   - aim to reproduce rainfall energies; and
   - develop necessary monitoring instrumentation, with emphasis on electronic data-logging.

2. Testing of two erosion models (ANSWERS and KINEROS) to establish the magnitude of predicted erosion rates; to test the sensitivity of parameters incorporated into these models; to provide a benchmark for the wet season monitoring; and to assess the suitability of sampling strategies for the simulator experiments. In this component of the project:

   - best estimates of the parameters of the models will be derived from the literature, from data available within the area, and from best judgments;
   - parameters will be varied to assess their significance in the models;
   - spatial variability and its influence on predicted erosion will be assessed using Monte Carlo techniques;
   - grid cell and sub-catchment sizes assessed for their influence on the predicted erosion; and
   - work will start on developing climatic time-series of rainfall events for simulation runs.

3. Monitoring of the waste rock dumps during the first Wet season of the project period, to identify primary erosional and hydrological processes and to assess sampling strategy. Monitoring will involve installation of the following on key sites: erosion pin plots, piezometers and tensiometers wherever possible, tipping bucket raingauges, throughflow pits, gerlach troughs, discharge controls, surveyed cross sections and monumented rocks

   During the Wet season the following will be monitored: sources of sediment and runoff; nature of sediment load in overland flow, rills and gullies; nature of armouring in gullies; gully development processes; throughflow rates and variability; infiltration rates; zones of deposition; and soil water response rates.

   Monitoring of vegetation on the waste rock dump and in natural areas will be undertaken to establish the significance of vegetation on the hydrology and erosion of the soil surface. Specifically, the following will be measured: throughfall energy using splash cups; rainfall distribution beneath the canopies of several key species; and stemflow volumes.

   In addition, rainwater will be collected and an experiment conducted on representative samples of waste rock using rainwater and water from RP1 to assess the impact of the different waters on the breakdown of the rock material. It is planned to use RP1 water in the simulator and it needs to be established that it will not bias the experiment.

4. Conduct simulator experiments on natural and artificial slopes to evaluate erosional and hydrological parameters. Specifically: initial tests on natural slopes to derive baseline information; tests on waste rock dumps, including range of slope angles, slope materials, and slope covers; and measuring parameters of erosional and hydrological models.

   Data will be collected specific to existing models or where monitoring suggests that parameters and processes not incorporated into existing models are important.

5. Testing and construction of hydrological and erosional models based on first years data: calibration of models, assessment of sensitive of parameters, comparison of performance of models, and development of hydrology-erosion modules.

6. Monitoring and simulation experiments in the second year; modifying sampling strategy and experimental design to accord with the results of the first years work and special experiments designed to assess the impact of different landsurface treatments on hydrology and erosion.

7. Final development of erosion model; a fine tuning phase.

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