HYDROLOGIC EFFECTS OF BAUXITE MINING IN THE DARLING RANGE

JOINT STATE GOVERNMENT AND ALCOA RESEARCH PROGRAMME

June 1983

PREFACE

During 1982 the Steering Committee for Research on Land Use and Water Supply was charged with the task of developing a detailed strategy for the establishment of a joint Alcoa and State Government research programme to evaluate the hydrologic effect of bauxite mining in the saline susceptible eastern portion of Alcoa's mineral lease area. Alcoa have funded two positions within Public Works Department to facilitate the development and implementation of this joint programme.

This report sets down the strategy of the proposed programme and identifies the general level of research activity research activity required. While the report necessarily concentrates on priority work programmes jointly involving Public Works and Alcoa personnel, additional collaborative research with other organisations is also required. Areas of possible input from Forests Department, Metropolitan Water Authority, Geological Survey and outside consultant groups have been suggested. Further planning, directly involving these groups will be carried out in the near future to develop a fully comprehensive programme.

CONTENTS

1. BACKGROUND

1.1 Study Region - Resources and Land Use Interactions:

Bauxite mining is a major land use in the Darling Range. The principal mineralised area (PMA) extends from Armadale south to Harvey and from the Darling Scarp east to Boddington (Figure 1). It covers 50-60% of the Northern Jarrah Forest, encompassing most of the developed metropolitan water supply catchments, the irrigation catchments in the Harvey River Basin, and the northernmost portion of the Collie River Basin.

Shallow (2-5m) bauxite deposits 1-100 ha in area cover 10-15% of the PMA. The bauxite is generally best developed on well-drained slopes in the high rainfall zone near the Scarp; but substantial ore reserves are known to exist in lower rainfall areas further east.

Soil salt storage levels increase rapidly with distance inland from about the 1100mm rainfall isohyet. Extensive land clearing for agriculture in these drier areas (mainly below 900mm) has lead to large increases in river salinity. For example the Murray River is already too saline for potable use as a consequence of agricultural development upstream of the PMA.

Rights to extract bauxite from the PMA are held by Alcoa of Australia Limited and Worsley Alumina Pty Ltd. Alcoa currently operates 3 minesites within the high rainfall zone. Some 30-40% of its ore reserves are located in more eastern areas - mainly concentrated in the "transitional" (900-1100mm) rainfall zone separating the areas of low and high soil salt storage. Worsley Alumina's mineral lease lies entirely within lower rainfall areas. Its main bauxite reserves are centred at Mt. Saddleback in the Murray River Basin.

1.2 Alcoa's Environmental Management Commitments:

In May 1978 Alcoa submitted to the State Government an Environmental Review and Management Programme (ERMP) for the Wagerup alumina refinery project. This project involved the commissioning of a fourth minesite. The Environmental Protection Authority recommended that the project be approved subject to the Company's acceptance of a number of environmental management commitments. These commitments were made in a revised ERMP submitted to the State Government in September 1978.

In terms of constraints on access to ore reserves, the most significant commitment was that relating to water resources protection. Its implications with respect to the longevity of Alcoa's operations are substantial:

> "MINING WILL NOT TAKE PLACE IN THE EASTERN, LOWER RAINFALL PORTION OF ALCOA'S LEASE, UNTIL RESEARCH SHOWS THAT MINING OPERATIONS CAN BE CONDUCTED WITHOUT SIGNIFICANTLY INCREASING THE SALINITY OF WATER RESOURCES. This commitment excludes any trial mining and rehabilitation which the State and Alcoa may agree is desirable for the purposes of gathering long-term data on the effects of mining and rehabilitation in the eastern, lower rainfall zone. Alcoa supports the concept of such a trial programme and will fully co-operate with the State in its implementation and monitoring".

1.3 Background to Report:

In June 1979 a working group was appointed by the Hunt Steering Committee to consider bauxite mining research, with particular emphasis on research needs in the transitional rainfall zone. This group submitted a preliminary report in August 1979. However, through lack of availability of appropriate professional staff in the relevant State Government departments there was little further progress on formulating a co-ordinated research programme.

In October 1981 Alcoa agreed to provide the Research Co-Ordinating Committee with funds for recruiting additional staff to facilitate progress on planning and research associated with the proposed trial mining project in the transitional zone. Through this initiative three additional professional staff were appointed in the latter half of 1982, two in the Public Works Department for hydrologic research and one in the Forests Department for rehabilitation research.

To develop the research programme presented in this report Alcoa and Public Works personnel have held many effective and searching working meetings and have gained valuable advice from other research groups. This report concentrates on what research needs to be done and why it needs to be done. Details on how the experiments and monitoring programmes will be conducted are not included here, and in some cases have yet to be determined.

A clearer understanding of forest hydrological processes and the effects of mining on them is an essential pre-requisite for trial mining in the eastern areas of Alcoa's lease. Much of this work can only be done in an active mining area. The report therefore includes proposals for upgrading hydrological processes and small catchment research in current mining areas. The proposed research in the west will also contribute substantially to a more thorough evaluation of the effect of mining in the high rainfall zone on water and sediment yield and catchment flood response.

1.4 Factors Expected to Determine Hydrologic Impact of Mining:

Bauxite mining in the Darling Range poses three main hydrologic questions:

1. The impact of the mining and subsequent rehabilitation on the salinity of current and potential water resources.
2. The impact of bauxite mining on the spread of dieback disease and its subsequent hydrologic effect.
3. The impact of permanent removal of significant areas of deep porous soils and related modification of soil hydrologic properties in so far as they affect the water yield and flooding characteristics of streams in the region.

There are a number of other important factors which may well affect final decisions about the extension of bauxite mining into eastern areas and therefore require attention. They are, however, water resources planning issues which do not directly relate to the hydrologic impact of mining. Consequently they will not be considered further in this report other than to list them below. The factors include:

1. Whether and/or when particular water resources will be developed,
2. how future water resources will be integrated with existing supplies, and
3. economic factors such as the costs of increased salinity in relation to the benefits derived from bauxite mining.

2. GENERAL OBJECTIVES OF RESEARCH PROGRAMME

The objectives of the bauxite hydrology research can be expressed as follows:

1. Develop a quantitative understanding of the effect of a range of bauxite mining, rehabilitation and related forest management practices on the hydrologic and water quality characteristics of different regions of the Northern Jarrah Forest. In particular, evaluate by the year 2000 the effect on stream salinity of mining in the transitional rainfall zone.

2. Identify combinations of bauxite mining, rehabilitation and forest management techniques which improve the value of or minimise the adverse effects on the water resources of the region.

3. Predict the effect of different bauxite mining, rehabilitation and forest management strategies on the quality, quantity and variability of major water resources of the region.

3. REVIEW OF PREVIOUS RESEARCH

A detailed review of previous research on the hydrologic effects of bauxite mining is being prepared for the Steering Committee for Research on Land Use and Water Supply. Appendix A is a brief summary outlining the main conclusions from this review. It includes a short description of the hydrology of the study region.

4. MAIN RESEARCH TASKS

Research aims should remain flexible within the broad framework of the objectives listed in Section 2. We should be prepared to change priorities and planned research work in response to new information and the availability of new techniques. In this respect, regular reviews of current knowledge will be an important aspect of the research programme.

Current perceptions of the main research tasks are outlined below. There is a strong concentration on water balance and hydrological process studies. These need to be conducted over a range of space and time scales in order to meet objectives 2 and 3. In addition to detailed studies at a restricted number of experimental sites, we need to clarify the variability of the controlling processes within and between small catchments over the region of interest. Only in this way will we be able to develop a useful predictive capability at a more regional scale. Clearly a different approach will be necessary at the different space scales.

4.1 Site Water and Salt Balance:

Re-establishment of an appropriate water balance on disturbed areas will be essential for salinity control in eastern areas. Better understanding of the influence of changes in canopy cover on catchment yield and flood response are also needed for forest management and minepit rehabilitation treatments in the west.

A review of present knowledge (summary at Appendix A) points up the need to measure the important components of the water balance independently. At present there is much conjecture about major components of the water balance and certain associated processes, particularly the following.

1. The relative contribution of piston flow and rapid flow through preferred pathways to groundwater recharge, and the conditions under which the latter occurs.

2. The partioning of evaporation among tree and understorey transpiration, and evaporation from the canopy and soil surface.

3. The effect of different tree species characteristics (leaf area, canopy conductance, root distribution) on the annual evaporative water loss and on groundwater recharge.

4. The ability of vegetation on lower slopes to utilise excess moisture resulting from disturbance upslope.

5. The magnitude of deep drainage losses from experimental catchments, either as underflow or as deeper seepage losses through the basement rocks and how these losses vary with geological factors throughout the region.

The influence of alternative vegetation communities and physical soil treatments usable in rehabilitation need to be evaluated. This will require a number of comprehensive site water balance studies, plus the development of suitable simulation models. One and 2-dimensional (longitudinal) models are currently under development at CSIRO (Forest Research) and W.A.I.T. Dept. Physics and Geosciences.

4.1.1 Evaporation

Evaporation is by far the largest component of the water balance in the jarrah forest. Unfortunately it is also the most difficult component to directly measure. Current research is based on use of the Ventilated Chamber method to provide parameter estimates for a one-dimensional simulation model of vegetative water use. The model will have an important role in providing a suitable framework for E_t research. Its practical uses will include the following:

1. Provide estimates of sub-surface drainage across the area of interest, for input into hillslope and catchment response models.

2. Establish water relations criteria for selection of tree species usable in rehabilitation of disturbed areas.

3. Design vegetation communities for such rehabilitation (species composition, stand density and structure).

4. Estimate the increased drainage due to canopy loss resulting from dieback disease or thinning, and establish criteria for revegetation of affected areas.

5. Help evaluate the effects on subsurface drainage of alternative physical treatments of minepit floors.

Proposes sites for more detailed water balance studies are Area C of the Del Park experimental catchment (to be mined in 1986) and at least two hillslopes in the selected eastern trial mining area. Pre-and post-mining studies need to be undertaken in these areas.

Less detailed evaporation studies will be undertaken on a range of sites including the following:

1. Arboreta in west and east forest areas and at existing minesites.

2. Trials of high density replanting options which may be appropriate for rehabilitation in the transitional zone. this work has commenced with a trial at Huntly F4702.

3. Possible revegetation trial in a dieback affected area in the transitional rainfall zone.

Because many of the inaccuracies in 2-dimensional models will be attributable to errors in estimating E_t, it is important that an attempt be made to verify these estimates by direct measurement. Suitable micrometeorological techniques are still undergoing development, but it is hoped they will be available for application during the time frame of this research. Failing that, cross checks using an emperical approach such as that devised by Morton (Jour. of Hydrol., 38, 1-32, 1978) may be necessary.

Verification of the transpiration component of E_t estimates using the subsurface moisture flux method is considered impracticable for general application in the jarrah forest. Usable results may be achieved from one or two intensively studied sites but the main benefit of this would lie in elucidating subsurface processes. However, the technique should be more practicable in mined rehabilitated areas where the laterite layer has been removed. In these circumstances, the approach should prove helpful in evaluating alternative rehabilitation options.

4.1.2 Hillslope Hydrological Processes and Water and Salt Balance:

The primary cause of salinisation in the Darling Range is the movement of excess water into previously unsaturated subsoil horizons, and the subsequent mobilisation of solutes held in the pores of these horizons. Solute transport is thought to be largely a convective process. This needs confirmation by an established research organisation with relevant expertise, such as CSIRO or U.W.A. Dept. Soil Science.

An adequate working knowledge of the principal hydrological processes operating in the native forest, and of the effect of mining and rehabilitation on those processes, is fundamental to the whole research programme. Most of the process studies will be done on a hillslope scale. They will aim to:

1. Identify the pathways of water and salt movement through the undisturbed landscape and estimate the fluxes involved for representative areas in the west and east of the study region (Note: the relative effort involved will depend on the similarity between the main processes in these 2 areas).

2. Clarify the role of macropores or 'preferred pathways' in groundwater recharge and their influence on the distribution of moisture and salt in the soil matrix.

3. Clarify the interactions between the shallow and deeper subsurface fluxes and the pattern of salt accumulation in different parts of the landscape.

4. Provide the basis for developing and evaluating a two-dimensional (hillslope) physical process model to simulate the effects of alternative mining and rehabilitation procedures on the partitioning of the additional water resulting from the mining operations. Particular attention will be paid to the influences of:

    - disturbance in different parts of the landscape on salt mobilisation and relocation;

    - different pit floor treatments on salt mobilisation and relocation;

    - different pit water management and forest management techniques on the disposition of downslope areas to dieback disease; and

    - different vegetation communities in controlling the amount of subsurface drainage in both the short and longer term.

5. Evaluate field trials of a limited number of alternative mining and rehabilitation procedures prior to trial mining in the transitional rainfall zone.

The modelling exercise mentioned in (4) will require more detailed characterisation of the subsurface system than has previously been attempted in this region. Model formulation is seen to be an important priority for 1983 because of the interaction with experimental design. Alcoa already has a physically based rainfall-runoff model for use in the design minepit rehabilitation earthworks. This will be upgraded and integrated with the proposed hillslope model through 1983.

ALCOA has recently installed a micrometeorological station near Del Park to provide essential input data for this modelling work. The study of interception and transpiration through simulation using this micrometeorological data and through field investigations will be an important task. A micrometeorological station will be required at the trial mining site in about two years time.

To enable valid extrapolation of the hillslope process work to other sites and the integration of these results at the larger scale will require a detailed documentation of the local, physical and geological characteristics of the sites and how these fit into the regional pattern.

As with the E_t studies, the hillslope processes and water balance work will be conducted at 2 levels of detail - intensive studies on a limited number of sites, and a larger number of less intensive studies for evaluation of process variability and of field trials of alternative mining/rehabilitation procedures. The detailed sites will be the same as for the E_t studies (Del Park Area C and at least 2 hillslopes in the trial mining area). Less detailed sites are expected to include the following:

1. Hillslopes on a number of small gauged catchments in the west and east - preferably in at least 2 of the Dandalup catchments and at least 1 of the Yarragil catchments (hydromet station in the latter to be upgraded).

2. A number of hillslopes in current mining areas where alternative pit water management techniques are being

evaluated, commencing with the 1983 trials at Del Park E4815 and D4807.

3. Continued monitoring and evaluation of some existing Hunt Steering Committee and Alcoa groundwater investigation sites.

The importance of balancing the effort between process studies in the east and west has been mentioned previously. The advantage of undertaking such work in the west is the presence of the mining operations and the more rapid response of the hydrologic system to disturbance. An important early task will be to confirm the similarity of the hydrological processes in the two areas. If they are substantially different, emphasis will need to be placed on more detailed evaluation in the east - possibly including partial simulation of mining by clearfelling forest overlying bauxite orebodies in one of the eastern catchments, and/or excavating a number of small trial pits. This work would precede the actual trial mining operation, but should not be seen as a substitute for trial mining at this stage.

4.2 Small Catchment Studies:

There is considerable argument about the value of small experimental catchment studies to answer questions about the hydrologic effects of land use changes. Such studies cannot substitute for an understanding of the hydrological processes involved and the predictive capability which should arise from that knowledge. However, they do have substantial benefits when conducted in conjunction with process studies. These benefits can be summarised as:

1. Integrate smaller-scale process studies over a landscape unit which is more relevant to the management problem i.e. the ultimate interest is in the time distribution

of water and salt discharge from river basins comprising groups of small catchments.

2. Test hypotheses and simulation results derived from smaller-scale process studies.

3. Evaluate effects which are not easily considered at a smaller scale (convergence; lateral heterogeneity in subsurface conditions; interaction between hillslope fluxes and streamflow source area dynamics).

4. Help identify the important components that need to be incorporated in predictive models usable at a water resource scale.

5. Provide additional insight into hydrologic processes and assess their variability from catchment to catchment e.g. from time series analysis of streamflow.

6. Demonstrate the effects of a land use change, albeit at a particular site.

These advantages are such that small catchment studies are considered an essential component of the research effort. Two main study areas are envisaged - one in the west (mainly to assess the effects of mining and associated forest management practices on water yield and stormflow) and one in the east (mainly to assess the effects on stream salinity). These will need to be supported by statistical analysis of streamflows from a range of small catchments in both areas, in order to assess the variability of the runoff generating process and the representativeness of the selected experimental catchments.

4.2.1 Eastern (Trial Mining) Catchments

An evaluation of possible sites in the transitional rainfall zone has been underway since 1979. Progress has been slow due to the importance of operating within the forest quarantine regulations. The last of a number of possible sites under consideration was drilled in the 1982/83 summer and the samples collected are currently being analysed. The sites under consideration are all within the following four general locations:

- Cornwall Forest Block - East of Willowdale
- Balmoral Forest Block - East of Jarrahdale
- Pindalup Forest Block - East of Del Park
- Cameron Forest Block - East of Huntly

A detailed assessment of the various possible sites will be made later this year when all the relevant information becomes available. The catchments finally selected must have soil salt storages that are representative of the more salt susceptible sections of the transitional rainfall zone, have similar geologies and depths to groundwater in their valley sections (eg absence of gross differences in the dolerite dyke formations between the catchments), have sufficient area of minable bauxite and have a general similarity in hydrologic characteristics. Acceptable access to a likely crusher site is also an important consideration.

A range of data on regional terrain attributes including soil salt storage, stream salinity, vegetation, bauxite and landform characteristics are being compiled to aid final selection of the trial mining catchments.

It is possible that trial mining on the scale presently envisaged (approx. 2 million tonnes) will not be necessary. By the proposed commencement date (1989), confidence in our knowledge of hydrological processes and in our modelling capability may be such that a partial simulation of the sort outlined in Section 4.1.2 may be sufficient. However, the project should proceed according to schedule on the assumption that trial mining will be required. The hillslope process and water balance studies are required regardless of whether the area is mined or some other partial simulation is carried out.

4.2.2 Western Catchments

The highest intensity of mining within the PMA will be in the high rainfall zone near the Scarp and at Mt Saddleback. Streams draining the high rainfall zone have a much higher yield than those further east. The potential exists to increase water yields by appropriate manipulation of the forest canopy cover and adopting minepit rehabilitation procedures which favour water yield. Possible disadvantages of this approach are adverse changes in flood response, turbidity and sediment yield.

A western catchments study is required to help evaluate the effects on streamflow and sediment yield of mining/rehabilitation and associated forest management activities such as FIRS.

Assessment of sediment yield on an individual minepit/haul road basis is an ongoing activity carried out in conjunction with the evaluation of existing design criteria for minepit rehabilitation earthworks and haul road drainage control works. However, a more thorough assessment could be incorporated in the proposed western catchment study.

It is proposed that the study be undertaken on one of the existing Dandalup catchments. Because of the particular interest in peak flows, a longer calibration period than has been customary to date is desirable. With the current 25 year Huntly mine plan proposal, the first of the Dandalup catchments to be mined would be Higgins about 1991-93.

5. SIMULATION AND PREDICTION AT CATCHMENT SCALE

Catchment scale modelling will play an important role throughout the research programme for the following purposes:

1. Assess existing streamflow data and make inferences concerning the processes influencing the responses of particular catchments.

2. Evaluate the variability in the hydrologic responses of catchments in the study region, and conversely, establish similarity criteria for experimental catchments.

3. To assist in the direction and priority of field research.

4. Simulate the effects of changes in forest canopy cover and alternative mining and rehabilitation treatments on water yield and quality from individual small catchments. Make predictions for evaluation on experimental catchments.

5. Predict the effects of changes in forest canopy cover and alternative mining procedures on the water yield and quality from river basins.

Both statistical and physical process models will be required at the small catchment scale. A physical process scale model is specifically required for points (3) and (4).

Although the small catchment model in point (4) need not be used for simulation purposes for at least 12-18 months, careful attention needs to be given to its formulation now to ensure compatability with the 2-dimensional hillslope model mentioned previously. It would be premature to forecast the structure of the model at this stage. However, the SHE model outlined in the attached paper gives a guide to the general type of model capability required.

Models will require simplification for application at the river basin scale. However, the task of developing an appropriate basin scale prediction capability based on the knowledge gained from the process and small catchment responses is substantial. While not specifically detailed in this report, it is recognised that significant attention to this area will be required. This is seen primarily as the responsibility of the water authorities.

The development of a reliable predictive capability at a river basin scale is partly dependent upon the successful development and evaluation of the more detailed small catchment model. This 'from the bottom-up' approach is desirable to establish confidence in the conceptual understanding and quantification of the important processes operating at each level.

The resource-scale models will require the compilation of a substantial inventory on:

- landform characteristics
- salt storage
- profile variability
- meteorological characteristics
- runoff characteristics
- vegetation characteristics
- mining development alternatives.

6. RESEARCH SCHEDULE

6.1 Hillslope Monitoring & Modelling (including Site Water Balance)

STUDY	LOCATION	START OF MONITORING	TIME OF TREATMENT
Detailed:			
Mine & Rehabilitate in eastern style (including FIRS)	Del Park Area C 1983-84	1983	1986
Trial mining area (minimum 2 hillslope)	To be decided 1983 (Cameron, Pindalup or Yarragil)	1984-85	1989(?)
Less Detailed:			
One hillslope in each of two of the Dandalup catchment controls.	To be decided early 1984	1984	-
Dandalup catchment to be mined in typical western style.	Higgins	1987(?)	1991-3(?)
Minepit water management trials & parameter estimation	Del Park E4815 & D4807 (followed by others from 1984)	1983	1983+
Eastern-style vegetation	Huntly F4702 (followed by others from 1984)	1982	1982+
Minesite arboretum	Del Park E255 (possibly followed by others)		
Forest arboreta	Marrinup and George Blocks		
Possible eastern-style dieback vegetation	Transitional rainfall zone (to be decided)	1984	1984
Groundwater response to mining & rehab.	Some existing Hunt Steering Committee sites (to be selected 1983 - some upgrade may be necessary).	From 1974	From 1973

6.2 Small Catchment Monitoring

TREATMENT	CATCHMENT	START OF MONITORING	TIME OF TREATMENT
Mine & Rehabilitate in eastern style	Del Park	1975	1986
Possible clear felling of orebody areas	Eastern Yarragil or one of trial mining catchments	1983 (upgrade)	1986
Trial mining (if considered necessary at time)	Cameron, Pindalup or Yarragil (to be selected 1983)	1983 (temp) 1984	1989
Mine & rehabilitate in normal western style	Higgins	Existing	1991-3
Control	Lewis	Existing	-
Mine & rehabilitate in eastern style	Mt Saddleback	"	1986

7. RESOURCES REQUIRED

In addition to the core group of research staff located within Alcoa and the Public Works Department, essential assistance will be provided by personnel from other interested departments, and outside consultants and tertiary education institutions. The people resources required will vary through the life of this long term research programme and it is not possible at this early stage to be precise about personnel requirements.

The following list is indicative of the personnel who are likely to be required in the early years of the programme.

ORGANISATION	LEVEL	AVAILABILITY	FUNCTION
Public Works	SP	0.5	Co-ordination, planning*
	P	2	Process and water balance studies, modelling.
	T	2-4	Technical support.
Alcoa	SP	0.5	Co-ordination, planning*
	P	2	Process and water balance studies, modelling, rehab. design.
	P	1	evaporation and plant water relations (rehab. areas), rehab design.
	T	3-4	Technical support
Forests Dept	SP	0.5	Co-ordination, evaporation & plant water relations (forest/arboreta), rehab. design.
	P	0.5	Field process studies (small catchments).
	T	1-2	Technical support.
Metropolitan Water Authority	P	0.5	Regional attribute modelling and inventory, basin and small catchment scale modelling.
Mines Dept	P	0.5-1	Hydrogeology and geophysics.
Consultants			Experimental design, modelling, other functions as required.
Tertiary Institutions			Input to modelling, liaison on process studies.

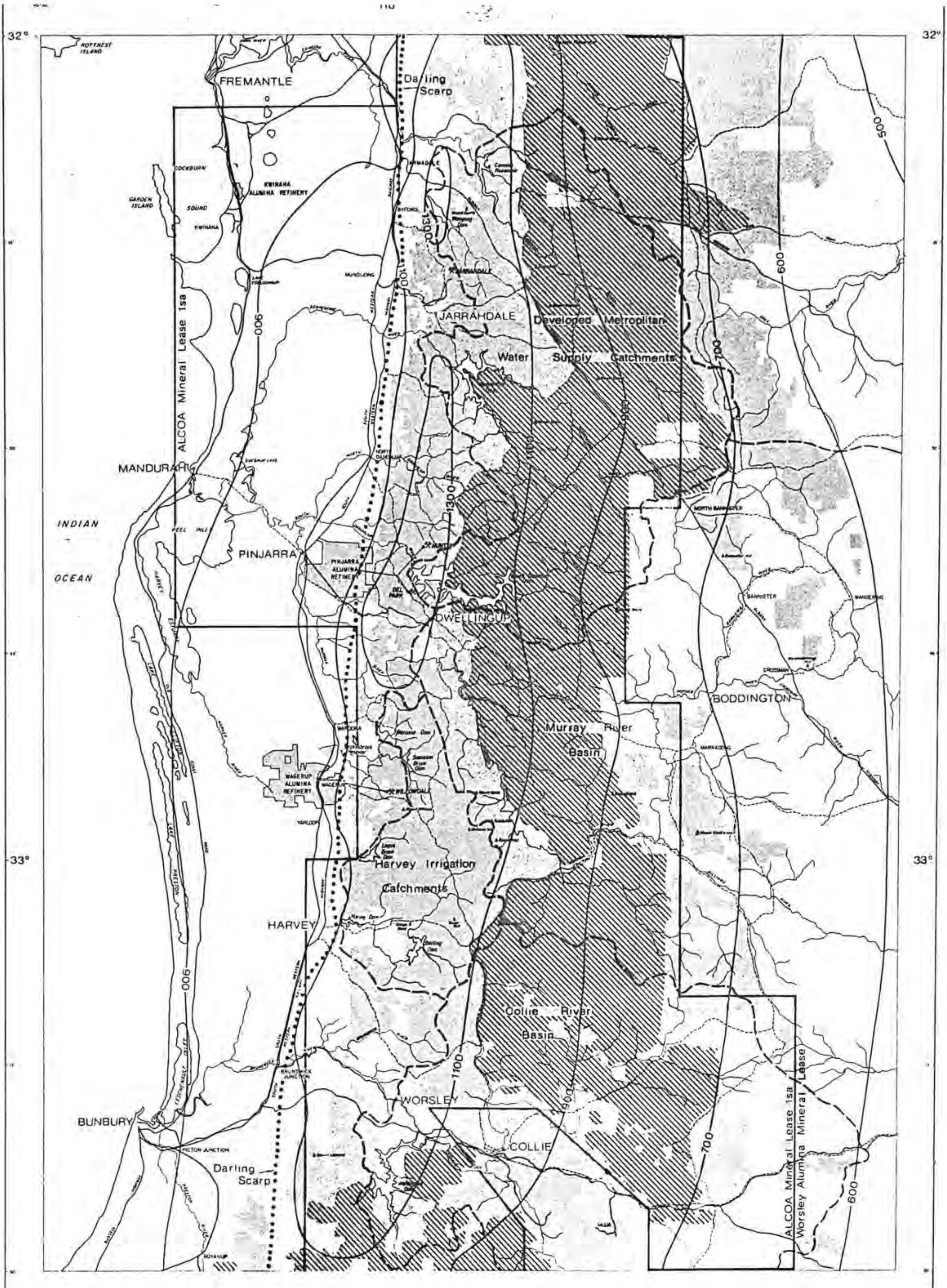
*Note: In consultation with the Metropolitan Water Authority and other interested organisations.

SP = senior professional
P = professional
T = technical/hydrographer

The manpower resources listed above are considered adequate to meet the needs of the hydrological processes and modelling components of the research programme. It has been recognised that further technical support will be essential for the field research component and a submission has been made through the Research Co-ordinating Committee for two hydrographers (Level 3 and Level 2) within the Public Works Department. Obtaining the necessary hydrographic personnel through the Public Service Board is a high priority.

There appears to be a major deficiency in the water balance segment of the programme, particularly in the assessment of forest evaporation and the soil moisture regime. The latter has proved to be a very difficult task in Darling Range conditions and one of the professional officers and at least one technician will need to be assigned to soil moisture studies. Independent assessment of above-ground components of the forest water balance is also a major undertaking. Although some of this work may be suitably handled as post graduate student research projects at Tertiary Institutions, the major components of the programme require a continued commitment at existing levels for at least another 12-18 months.

Alcoa is prepared to meet the costs of instrumentation and data processing associated with field experiments which are directly relevant to the trial mining project. The costs of services such as surveying, drilling and geophysics will be shared by Alcoa and the departments who have resources available to contribute to these activities. Alcoa will meet the cost of consultants employed by it in relation to the trial mining project. An additional consideration requiring early attention is the compatibility of field data acquisition and data transfer systems. Both Alcoa and Public Works Department are expected to contribute instrumentation to this work. Ready interchange of equipment is desirable and rapid, accurate transfer of data is essential.



▨ STATE FOREST

▨ QUARANTINE AREA

FIGURE 1
REGIONAL MAP
SOUTH WEST OF W.A.

APPENDIX A

REVIEW OF PREVIOUS RESEARCH

The hydrologic characteristics of the region are strongly interrelated to the gradation of rainfall, vegetation, soils and landforms from west to east across the bauxite lease areas. Annual rainfalls range from over 1300 mm in the west where current mining operations are taking place to about 700mm where mining is planned to commence at Mt. Saddleback in mid 1983. Climate is Mediterranean with mild wet winters and warm to hot dry summers. Over 80% of the annual rainfall occurs in the six months from May to October while about 75% of pan evaporation occurs during the six months November to April. Average monthly rainfalls are usually only in excess of average monthly pan evaporations for the 5 months from May to September. This excess approximates 45% of the annual rainfall in the western regions (or 550 to 600mm) but only about 35% (or 250mm) in the eastern regions of the bauxite lease. In the eastern regions monthly rainfall usually only exceeds pan evaporation in the four months May to August.

Streamflow, generated in response to this relatively small quantity and short period of rainfall excess, usually commences in June but may not commence until mid July in the eastern low rainfall regions. Much of the early rainfall excess, particularly during May, is either intercepted in forest vegetation or stored in the soil profile, thereby reducing the soil moisture deficit developed during the previous dry summer months. Consequently, over 85% of the annual streamflow volume is usually generated between June and October. The average volumes are low, rarely being over 25% of rainfall (325mm) except from distrubed forest in the western region and often being less than 5% of rainfall (35mm) in the low rainfall eastern region. Differences in water yield between specific western and eastern catchments frequently exceed a factor of 10. Large variations in streamflow volumes occur from year to year in response to variations in the volumes and pattern of rainfall. In years of below average rainfall in the eastern region it is common to obtain no streamflow for the entire year.

The dominant source of streamflow is subsurface seepage or drainage of shallow, highly porous surface soils which overlie deep highly weathered profiles of clays and sandy clays of low permeability. Because of the high infiltration characteristics of the surface soils classic Hortonian overland flow rarely occurs except on very shallow soils or rock outcrops. Most of the quick hydrograph response to rainfall is generated by direct rainfall on saturated areas close to stream lines. While overland flow and direct rainfall on saturated areas are important in producing flow peaks, much of the hydrograph recession following rainfall is shallow subsurface seepage. Consequently, surface runoff only contributes about 2% of annual streamflow volumes and would rarely represent more than 5% even in wet years.

In the areas of current bauxite mining, groundwaters which drain the subsoils and weathering profile near bedrock usually discharge to the stream. Groundwater contributions to streamflow (i.e. drainage from the deeper subsoils) have been estimated to be about 10% of the total streamflow but can be as high as 30% in cases where base flows persist through the dry summer period. Therefore, subsurface seepage supplies over 70% and usually about 90% of the annual streamflow volume.

In lower rainfall areas (below 900mm per annum) groundwaters rarely discharge to the surface and virtually all of the small quantities of streamflow is derived from the shallow subsurface seepage and direct runoff from saturated areas.

Stream salinities are governed by the proportions of shallow subsurface flow relative to groundwater flow and the salinities of these two sources. In the region of current bauxite mining the difference between the salinity of groundwater and shallow subsurface seepage has been small (usually less than a factor 2). Stream salinities consequently do not vary greatly with flow rate, season or time of year. Typical stream salinities in the western Darling Range vary between 120 and 250 mg/L TSS.

In the eastern zone where groundwaters do not contribute to streamflow, salinities of order 100 to 150 mg/L are common.

In the transitional zone where moderate groundwater salinities exist and contribute to streamflow, salinities can vary from 100 mg/L to over 1,000 mg/L TSS, and tend to vary dramatically with flow rate and time of year.

Surface water responses to bauxite mining to date have been based primarily on observations of two small catchments which have been extensively mined over the last 13 to 15 years and one nearby catchment which has been subject to normal forest operations over the same period (More Seldom Seen, Seldon Seen and Waterfall Gully Creeks). Simple double mass curve analysis would suggest an increase in the annual streamflow of about 60mm over the last 7 or 8 years. Statistical comparison between the annual flow volume sequences has been hampered by substantial differences between the groundwater flow components of the catchments. Estimates of the increase in water yield of the two mined catchments relative to the forested catchment range from no significant increase to increases of about 150mm over the fifteen years of record, depending on the statistical assumptions made.

Non-linear monthly rainfall-runoff modelling of the two bauxite mined catchments alone, calibrated in the early years when mining was either negligible or small, indicated increases in water yield in the early years of mining but suggested stabilising of water yield in later years when rehabilitation had progressed. These results, however appear sensitive to data input and are based on a short calibration period of three years.

In summary, it appears that bauxite mining has increased the water yield. However, because of differences between the treated and untreated catchments and because of the limited period of record before treatment, the magnitude of the yield increase is uncertain.

Analysis of the components of streamflow suggest that disturbance has occurred in all three components of streamflow, but again, quantification is uncertain. The proportion of summer flows on the treated catchments appear not to have changed relative to the total flow. The implication is therefore that increases have occurred in both shallow subsurface seepage and groundwater discharge in roughly the same proportion.

Statistical comparison of paired samples of annual peak flow rates indicate a time trend of an increasing ratio of peak flows on the two bauxite mined catchments relative to the forested catchment. Over the period of record the ratios of peak flows have increased by about a factor or two to three. These are small increases relative to the variations in flood peaks from year to year and the increase may be partly due to the relatively low flow peaks in the more recent years of record. However, surface runoff mechanisms appear to have been altered by the mining and associated roading activity.

No increases of stream salinity have been identified on the bauxite mined catchments. All catchments are discharging more chloride than coming in through rainfall. Increases in chloride output relative to the forested catchment have occurred on the two bauxite mined catchment over the 15 years of data. This trend is a consequence of the increased water yield and its significance suffers the same statistical uncertainties as the changes in water yield.

Considerable monitoring of groundwater systems has been carried out beneath native forest and to a lesser extent under bauxite mined and rehabilitated areas. Seasonally, groundwaters respond to a winter input of excess rainfall and usually reach a peak between October and November and recede over the summer period reaching minimum levels in May-June the following year. Within this regional pattern large variations between individual bores occur. Some bores in dry years and with large depth to water show little or no seasonal increase. Other bores show a very rapid and large response, often within a week and occasionally within days of rainfall. The presence of preferred pathways such as old root channels and mineral irregularities through the slowly permeable subsoil matrices have been clearly identified and are thought to be important to the distribution of moisture through the profile and groundwater recharge in the forested state. The rapid reponse to rainfall in bores can be explained by this mechanism but could also be caused by faulty bore construction causing leakage from the shallow perched water tables.

Groundwaters in the forested state tend to show a more damped response to rainfall the greater the depth of unsaturated soil. This is not always the case, particularly where bores are located close to where groundwaters discharge to the soil surface. In such cases the bore hydrograph is restricted by the soil surface boundary condition and mid slope bores respond more rapidly than either upslope or lower slope bores.

Following mining, groundwater responses beneath mined pits have shown a somewhat confused picture. In some pits groundwater responses have slightly increased following mining. In others, responses have been very small and possibly decreased, although increases in groundwater responses downslope appear to have frequently occurred. The quantification of water movement through and down slope of bauxite pits is still uncertain but rapid redistribution of moisture through the porous gravel soils and subsequent recharge to the groundwater system downslope is suggested.

In one case development of a dense understorey in the lower sections of a mine pit appears to have reduced groundwater recharge.

In summary, responses of both surface and groundwater hydrology to bauxite mining and rehabilitation have been much less marked than changes induced through agricultural development of forested land.

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SHE: towards a methodology for physically-based distributed forecasting in hydrology

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Abstract. The Système Hydrologique Européen (SHE) is a physically-based distributed modelling system developed by the Danish Hydraulic Institute, SOGREAH (France) and the Institute of Hydrology (UK). This paper discusses the nature of physically-based models and the areas in which they can fulfil a need for hydrological forecasts. A brief description of the SHE model is given and its structure is discussed in relation to the needs of a general methodology for physically-based modelling.

Pour une méthodologie de prévision hydrologique basée sur le comportement physique du bassin

Résumé. Le système hydrologique européen (SHE) est un système de modèle – basé sur le comportement physique du bassin et du réseau hydrographique, mis au point par l'Institut Hydraulique Danois, SOGREAH (France) et l'Institut d'Hydrologie (RU). Cette communication traite de la nature des modèles basés sur les données physiques et des domaines dans lesquels ils peuvent répondre aux besoins de la prévision hydrologique. Une brève description du modèle SHE est donnée et sa structure est discutée en fonction des besoins d'une méthodologie générale pour la mise au point de modèles à base physique.

INTRODUCTION

The Système Hydrologique Européen – European Hydrological System (SHE) has been developed as a general physically-based modelling system in a joint project involving the Danish Hydraulic Institute, SOGREAH (France) and the Institute of Hydrology (UK). SHE aims to provide facilities for simulating one or more hydrological processes in a deterministic distributed modelling framework at scales from small experimental plots to complete basins. At the time of writing the project has reached the stage of testing the first version of the complete model at the basin scale, the individual process components having been developed and tested by the three participating institutions. This paper discusses some of the background to the development of SHE.

THE NATURE OF PHYSICALLY-BASED MODELS

A model is physically-based in the sense used herein if it is derived from equations of mass and energy conservation for the hydrological processes it aims to represent. For most processes these are nonlinear partial differential equations that cannot be solved analytically in other than special cases of restricted interest. Solutions must then be found using approximate numerical methods, such as finite element or finite difference methods. Such physically-based models provide predictions at points that are distributed in at least one dimension. For some processes, such as interception, the equations of flow through the system are not well defined and resort must then be made to empirical generalizations (e.g. Rutter *et al.*, 1971/1972) that may not be explicitly distributed. Indeed, the complexities of the system are such that all the model components ultimately rely on empirical generalizations, such as Darcy's law for subsurface flow or Manning's law for surface flow. However, it is important to recognize that the 'laws' on which physically-based models are based may be validated by experiment, independently of the model itself. This implies that the parameters of those 'laws' (and therefore of the model) are by definition measurable; that the predictions of the model should be capable of validation by measurements of individual processes.

Approaches to physically-based modelling have been notably fragmented in the past. There have been numerous papers on the theoretical aspects of modelling various hydrological processes individually. There is a much smaller literature on models involving more than one process and on the application of such models to real world problems. The concept of a general physically-based distributed modelling system that SHE aims to provide is made viable now that models of individual processes have been shown to be successful. At present data limitations restrict the application of physically-based models to a far greater extent than theoretical considerations.

THE NEED FOR PHYSICALLY-BASED MODELS IN HYDROLOGY

Physically-based distributed models are expensive in terms of both computing and data requirements. They will generally be much more expensive than the simpler lumped models (unless a particular problem requires re-formulation of a lumped model). However, for projects involving considerable capital expenditure, the relative cost of applying a model such as SHE will remain small. It then remains to be shown that physically-based models can be cost effective in terms of the benefits accrued from the additional expense.

Given the wide range of hydrological models available, the choice of a model for a particular problem is never a simple one, and will inevitably be based on economic constraints, data availability and personal preferences as well as purely hydrological considerations. However, any general criteria for model choice should be based on matching the requirements of a management problem with the complexity of the model used. Modelling hydrological systems is an activity that is, in many applications, governed by a law of diminishing returns. Very simple models can often provide a useful, if not necessarily adequate, representation of the system and the benefits that derive from additional complexity may not warrant the corresponding increase in cost. Thus if a problem requires a model to extend basin discharge records from a longer rainfall record it may be sufficient to use a lumped model and probably would not make sense to use a complex distributed model demanding far greater resources.

However, there are some problems for which distributed physically-based models can be used to make forecasts when simpler models may be adequate. Two important areas in which the availability of a proven physically-based distributed model would be particularly useful are forecasting the effect of basin changes and forecasting the response of ungauged basins. A fuller discussion of other uses is given in Beven and O'Connell (1979).

Problems of basin change include land use changes due to forest management, urbanization, deforestation, and the effects of groundwater management. Such changes are almost invariably localized such that basin change is a distributed problem. The parameters of a physically-based distributed model have a direct physical interpretation and their range can be established reasonably well from field and laboratory investigation. It follows that knowledge of parameter values can be directly related to basin characteristics such as soil type and land use and that such knowledge should be transferable, within reason, from area to area. Thus it should be possible to predict the effects of basin changes prior to data becoming available. In addition the localized nature of such changes can be easily incorporated into the spatially distributed model structure The capability of lumped models to predict the effects of basin change has been exaggerated (Beven and O'Connell, 1979).

The physical significance of the parameter values for this type of model also allows applications in ungauged basins since it is possible to use intensive short term field measurements to establish realistic ranges of parameter values. These values can then be used to generate at least approximate hydrological forecasts without the benefit of concurrent streamflow and precipitation data for calibration. In fact, any information on the characteristics and hydrology of a basin together with relevant information from elsewhere can usually be incorporated directly into the modelling process. Most alternative methods for making predictions on ungauged basins rely on the use of statistical regionalization of model parameters (James, 1972; Jarboe and Haan, 1974) which of necessity must crudely approximate the causes of variability between basins by the use of surrogate variables in the regression equations.

The use of physically-based models focuses attention on the inadequacy of the hydrological data upon which many water resources management decisions are made. By considering the uncertainties in the parametric data explicitly, estimates of the resultant uncertainty in hydrological forecasting can be made. At present this last stage is at a relatively crude level in applications of complex basin models, generally involving a sensitivity analysis within an expected range of estimated parameter values. However, present studies involving one or two processes (Sagar, 1978; Bresler *et al.*, 1979) show that available techniques may be expected to become considerably more sophisticated. This type of sensitivity analysis should aid the management process in both providing estimates of the uncertainty in hydrological forecasts and suggesting how additional expenditure in field measurements might most beneficially be used.

A BRIEF INTRODUCTION TO THE *SHE* MODEL

The SHE model that is the basis of the Système Hydrologique Européen incorporates components for the processes of overland and channel flow, unsaturated and saturated subsurface flow, developed from the nonlinear partial differential equations of flow

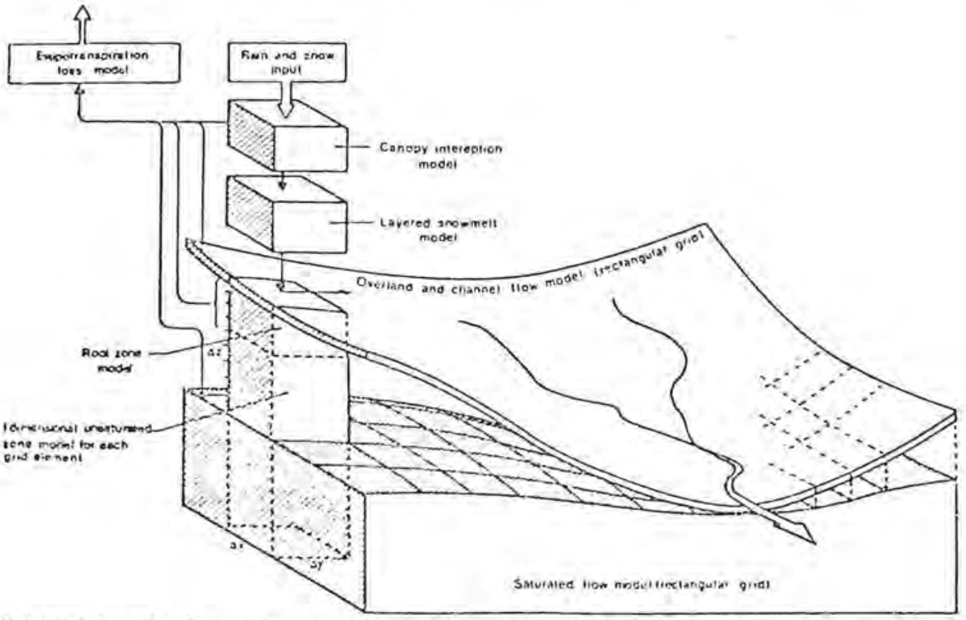

FIGURE 1. A schematic representation of the structure of the SHE model.

and solved by finite difference methods. The model is completed by point snowmelt, interception and evapotranspiration components. While considerable effort has been made to ensure that the solutions for each component are accurate and efficient, the structure of the model represents a compromise between restrictions imposed by the computing and data requirements of the model and the need to represent the complexity of real basins.

It is not yet economically viable to produce an operational model that is fully three-dimensional in space and will also allow the required accuracy of discretization in both horizontal and vertical planes. On the assumption that in the unsaturated zone vertical flow is, on most slopes, far more important than lateral flow the model has been rationally simplified so that one-dimensional flow components of variable depth are used to link two-dimensional saturated subsurface and surface flow components (Fig. 1). It is planned to use up to 2000 grid points in the horizontal and 30 in the vertical to allow adequate definition of a basin areal unit. The programming of the model has been aimed at flexibility allowing different modes of operation demanding different levels of data availability. A fuller description of the model is given in Jønch-Clausen (1979) and some points of technical detail are discussed in Preissmann and Zaoui (1979), and Abbott *et al.* (1979).

TOWARDS A GENERAL METHODOLOGY FOR PHYSICALLY-BASED DISTRIBUTED MODELLING

Formulation of a general methodology will be a continuing process with improving knowledge but must involve considerations of model definition, parameter definition, model calibration/validation, and sensitivity analysis. This section considers only the first, and the way in which the aim of generality is reflected in the structure of SHE. To fulfil this aim the model must:

(1) be physically relevant to the system it represents;

(2) incorporate as much readily available hydrological and other basin data as possible;

(3) simulate a wide range of problems for single processes and combinations of processes;

(4) cope adequately with the difference in response times of different processes and with the time variant rates of change due to different meteorological conditions;

(5) cope adequately with non-stationarity in the model parameters, for example due to seasonal effects on vegetation;

(6) cope with dynamic changes in the component structure of the model such as when the unsaturated zone disappears in variable saturated source areas.

A considerable part of the effort expended in the development of SHE has been concerned with satisfying these criteria in the specification of a flexible model frame structure. The model frame is used to control the input of the basin specification, the nature of the solution that is required, reconciling the dynamic time stop requirements of the individual components and ordering the component solutions with the correct transfer of valid internal boundary data between components. The detailed specification of the frame necessitates the achievement of a satisfactory compromise to maintain stability and accuracy while retaining numerical efficiency. The first version of the frame is already operational with some restrictions on the types of solution that can be handled, but is expected to be revised and extended over time as experience in different applications is incorporated. In this way it is hoped that SHE represents a first step towards a general methodology for physically-based distributed modelling to be used in the context of complex water resources management problems at a variety of scales.

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