



Identification of Floodplains and Estimation of Floodplain Flow Velocities for Sediment Transport Modelling

NLWRA Sediment Project (CLW12)

Geoff Pickup and Alan Marks

CSIRO Land and Water, Canberra
Technical Report 14/01, July 2001



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1. Introduction

Floodplains may act as sediment sinks during high flow conditions and, as such, may limit downstream transmission of material eroded from hillslopes and upstream gully networks. Floodplain and valley topography will also influence river channel behaviour, by providing limits on lateral migration or channel widening in confined reaches.

Sedimentation on floodplains requires a different approach to that implemented in the hillslope model. On hillslopes and in channels, sediment transport results from overland flow and the transport rate is a function of discharge and energy slope. Uniform flow is assumed, making energy slope the same as terrain slope, and discharge is a function of upslope area. Erosion and deposition are calculated from the difference between upstream and downstream sediment transport capacity. On floodplains, sediment transport is accomplished by overbank flow and the major process is transmission or deposition of sediment. Erosion is limited and is largely accomplished by channel widening or channel lateral migration.

Sediment transport on floodplains involves mainly fine material transported in suspension or as wash load. Only a small proportion of transported bed material reaches the floodplain from the channel during overbank flow and most of that is quickly deposited. Deposition of suspended load occurs in areas of low water velocity, in backwater zones, and in areas of standing water in off-channel storages. Identifying these zones of deposition and estimating their relative intensity requires information on floodplain hydraulics.

Flow on floodplains is often complex and may require hydrodynamic models to deal with complex topography. Use of these techniques is not justified given the limited resolution of information on floodplain elevations over the project area. We have therefore taken a simpler approach in which floodplain flow is assumed to be steady in time, sub-critical or critical in state, and gradually varied in space. This allows us to apply a step-backwater approach to flow profile analysis and floodplain flow calculation that takes into account expansions and contractions in the active flow zone. We also attempt to distinguish between the active flow zone and inundated areas such as backwater zones that do not contribute to downstream flow in the floodplain cross section. Floodplain behaviour is represented by single flow equivalent to the 25 year flood on the annual series.

2. Flow Computations on Floodplains

2.1 Hydraulic Calculations

Flow profile analysis is usually carried out by surveying a series of channel cross sections and carrying out gradually varied flow calculations using a computer package such as HEC-2 (Hydrologic Engineering Center, 1982) or its successor, HEC-RAS. Both of these apply the standard step method (Chow, 1959). Where flow is sub-critical, the calculations are carried out cross-section by cross-section in the upstream direction using

step-backwater analysis.

Step-backwater routines assume flow conditions that are steady with time and gradually varied in space. Flow is described by the one-dimensional energy conservation equation and a uniform flow formula, such as the Manning equation, is used to evaluate the energy slope at each cross-section. The energy conservation equation for a reach (Chow, 1959) (see Figure 1) is given by:

$$Z_1 + Y_1 + \frac{a_1 v_1^2}{2g} = Z_2 + Y_2 + \frac{a_2 v_2^2}{2g} + h_e$$

in which:

Z is channel bed elevation;

Y is flow depth;

g is gravitational acceleration;

v is mean flow velocity;

a is a coefficient accounting for non-uniform velocity distribution in a subdivided channel; and

h_e is the head loss between cross sections.

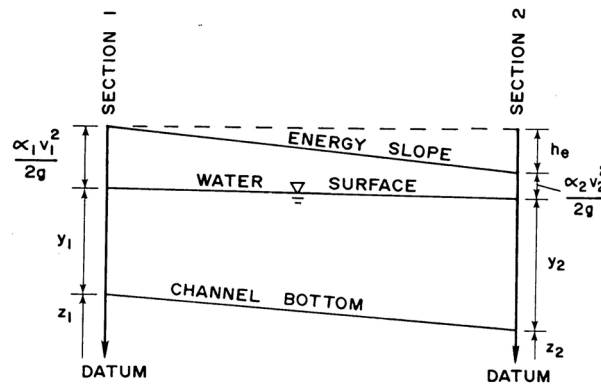


Figure 1: Definition sketch for step backwater calculations

Head loss (h_e) consists of frictional losses created by flow boundary roughness elements, eddy losses associated with turbulence, and flow separation generated by channel constrictions and expansions. Friction losses are estimated by the Manning equation:

$$S_f = \frac{n^2 v^2}{R^{4/3}}$$

in which:

S_f is the local friction slope;

n is the roughness coefficient; and

R is hydraulic radius.

Eddy losses are calculated from the change in velocity head between cross sections:

$$k \left| \frac{a_1 v_1^2}{2g} - \frac{a_2 v_2^2}{2g} \right|$$

Where k is taken as 0.0-0.1 for narrowing reaches and 0.2-0.5 for expanding reaches.

Critical flow conditions are handled in the same way as the procedures in HEC-2 (Hydrologic Engineering Centre, 1982). A check for sub-critical flow condition is carried out at each cross-section using the criterion:

$$a \frac{v^2}{2g} > 0.94 \frac{Area}{2W}$$

where $Area$ is cross sectional area and W is total width. Where this criterion is met, critical flow elevation is calculated. The critical flow elevation is the elevation at which total energy head, defined as $WS + av^2/2g$, is a minimum (where WS is water surface elevation). It is determined using trial and error over a range of test water surface elevations. If flow elevations calculated by the step-backwater procedure are below the critical elevation, critical flow is assumed and the critical water surface elevation is used for that cross section.

If the source data for the hydraulic calculations come from a DEM, flow directions and channel locations must first be identified before extracting channel cross-section data. Cross sections must also be sorted so the calculations proceed in the upstream direction in reaches where flow is sub-critical. Both HEC-2 and HEC-RAS require manual identification and sorting of cross sections, making them unsuitable for use on the scale of the Audit. We have therefore developed an automated procedure for cross section identification and extraction.

2.2 Identification of Drainage Lines and Extraction of Flow Cross Sections

Several terrain analysis packages offer routines for calculation of slope and aspect, identification of flow directions, downstream accumulation of contributing areas and, if necessary, pit removal from DEM data. We use the routines in *ARC/INFO*. These routines produce a pitless DEM and route flow down slopes and across flats using an algorithm which passes the flow from a given grid cell into a single downstream neighbour based on the steepest direction of flow. This gives us a data layer in which contributing drainage area increases progressively downstream and allows sorting of cross sections into downstream or upstream sequences.

The next step is to identify cross-section locations and to extract cross-section profiles. We firstly set a minimum drainage area that is used to define the stream network (usually 50 km²). Grid cells with a drainage area that exceeds this minimum are classed as channel centreline locations and sorted by decreasing drainage area. A second sorting pass orders channel centreline grid cells with a similar drainage area by increasing elevation. The procedures arrange channel centreline grid cells so that gradually varied flow calculations may be carried out in the upstream direction. The calculations begin by

assuming uniform flow in locations where the channel intersects the DEM boundary or where the channel terminates in a lake or swamp. Slopes for uniform flow calculations for terminating drainage lines are assigned an arbitrary starting value of .0015. Channel cross sections are identified by determining the aspect of the centreline pixel and extending orthogonals outwards on each side. The gradually varied flow calculations produce a water depth, a friction slope, and the location of the inundated area. Water depths in grid cells between cross sections are calculated by interpolation.

2.3 Identifying Active Flow Zones and Floodplain Limits

The gradually varied flow algorithm, as described above, does not distinguish between active flow zones and areas of slackwater or backflow. These occur at expansions and contractions of the channel and the flooded area. If the slackwater or backflow areas are included in the flow calculations, they will produce errors in cross-sectional area and mean velocity. We therefore conduct two passes through the calculations. The first pass makes no distinction between the active flow zone and other inundated areas but it does provide estimates of channel width. From this, we identify all constrictions along each channel. Active flow zones are then identified by restricting upstream and downstream flow expansions to a user-specified angle (usually 15 degrees) on each side of the channel (Figure 2). The gradually varied flow calculations are repeated with cross-sectional areas restricted to active flow zones. Inundated areas outside the active flow zone are also identified using a maximum flow expansion angle of 45 degrees but only in the downstream direction.

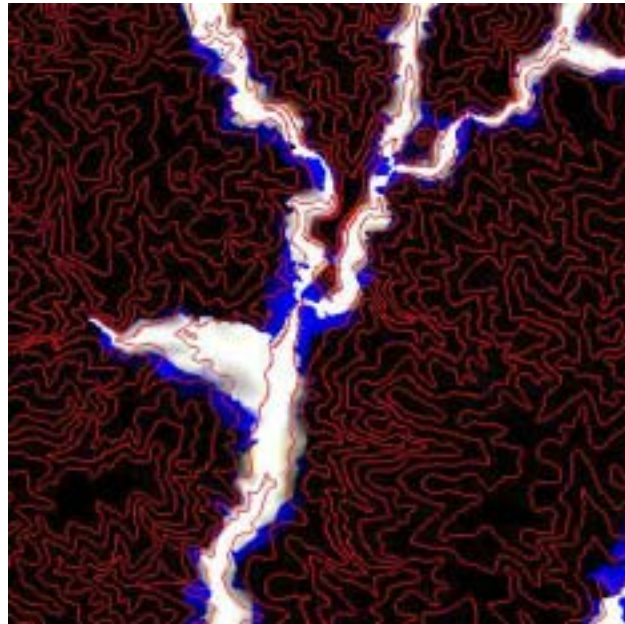


Figure 2: Example of results from step backwater calculations for the 100 year flood on an 8 x 8 km area of upper Jugiong Creek. The image shows the active flow zone (grey) and areas of standing water or backflow (blue). Contour interval is 10 m. Calculations were carried out on streams with a catchment area of $> 10 \text{ km}^2$ so smaller elements of drainage net are not included.

While this approach works reasonably well, there can be problems. No DEM is artefact-free, and in flat areas, small errors in aspect can result in substantial misalignment of cross sections. This is especially true with high-resolution DEMs, and it is sometimes better to re-sample to a lower spatial resolution or to smooth the DEM before calculating channel aspect and setting the orthogonals that define each cross-section. A badly aligned cross-section may point upstream and downstream rather than across a valley. Where this happens, water depths continuously increase in the downstream arm of the cross-section. In some cases, they may even cross a watershed, resulting in ridiculous flow depths and preventing the gradually varied flow calculations from converging on a solution. This problem is largely solved by having maximum flow expansion angles but we also have the option of preventing cross sections from extending beyond grid cells that lie below the channel centreline or thalweg elevation minus a user-specified threshold value.

2.4 Estimation of Discharge (Regional Model)

While steady flow conditions are assumed in the calculations, flow may be spatially variable. We have allowed for downstream increases in discharge by developing a regional relationship in which discharge of a particular frequency is a function of upstream drainage area and a design rainfall intensity for each location. Selection of the discharge frequency was made on the following grounds.

Sediment transport on floodplains is accomplished by a range of flows from bankfull discharge upwards. Virtually nothing is known about the relative importance of individual flows in the sediment transport/deposition regime, making it difficult to select a representative discharge or range of discharges. Also, procedures for calculating transport and deposition on floodplains are largely untested and of unknown reliability. This makes it difficult to justify going beyond the use of a single discharge to represent floodplain behaviour. We have therefore selected the 25 year flood on the annual series to represent floodplain behaviour on the following grounds:

- This flood occupies a large part of the floodplain and so provides reasonable delineation of floodplain areal extent.
- It can be estimated with greater accuracy than more extreme events such as the 100 year flood given available streamflow and rainfall data.
- flood extents modelled using the 9 second DEM tend to be greater than those obtained from high resolution DEMs (see below). In reality, our modelled 25 year flood extent may represent more extreme events.

25 year flood discharges were derived from an empirical regression equation:

$$\log Q_{pred_{25}} = 0.9155 + (0.726 \log Area) + (1.45 \log AdjUSRF_{25,12})$$

in which:

$Q_{pred_{25}}$ is the predicted 25 year flood discharge in ML/day,
 $Area$ is upstream drainage area in km²,

$AdjUSRF_{25,12}$ is the 25 year, 12 hour rainfall intensity in mm/hr averaged over the upstream contributing area of the drainage basin. This value is adjusted for the decline in rainfall intensity with increasing drainage basin area .

25 year flood discharges were obtained from a database of synthetic flows derived by Peel *et al* (2000) for the Land and Water Audit. 25 year 12 hour rainfall intensities were calculated using the *AUSIFD* computer program (Jenkins, 1997) for all rainfall stations in the *AUSIFD* database and interpolated across the project area using the triangulation routine in the *MicroImages TNT MIPs* GIS package (MicroImages, 1999). Correction of rainfall intensity for increasing drainage basin area used the following equation from *Hydrological Recipes* (Grayson et al, 1996):

$$C_1 = 1.0 - (0.1((Area^{0.14}) - 0.879)) - ((0.029(Area^{0.233}))(1.25 - \log D))$$

where

C_1 is the correction factor, and
 $D (= 12)$ is storm duration in hours.

The area adjustment was obtained by multiplying the rainfall by C_1 .

Figs. 3 and 4 show the relative influence of drainage area and the design rainfall intensity on modelled 25 year floods. Fig. 5 shows how well the modelled values are predicted by the regression equation.

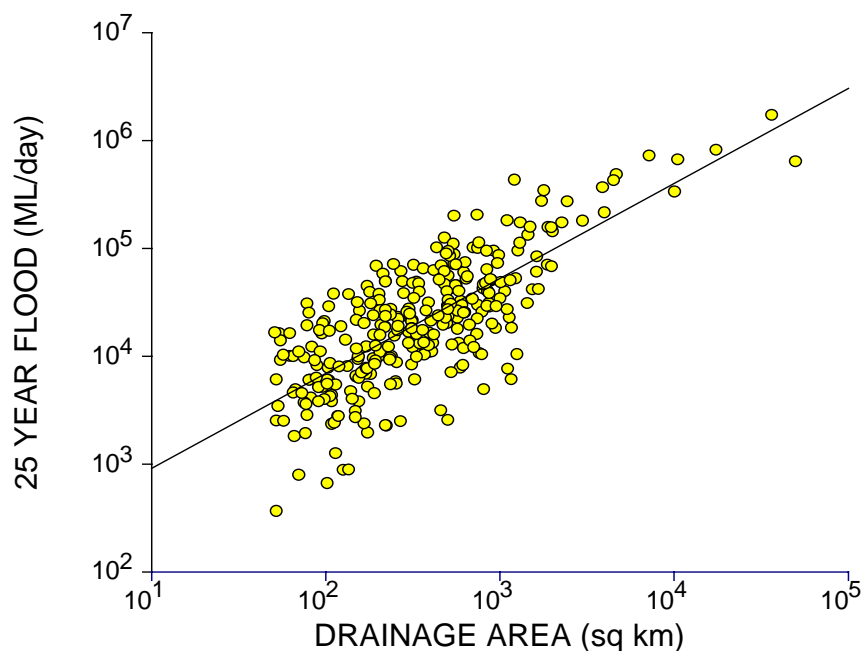


Figure 3: Drainage area v. modelled 25 year flood discharge

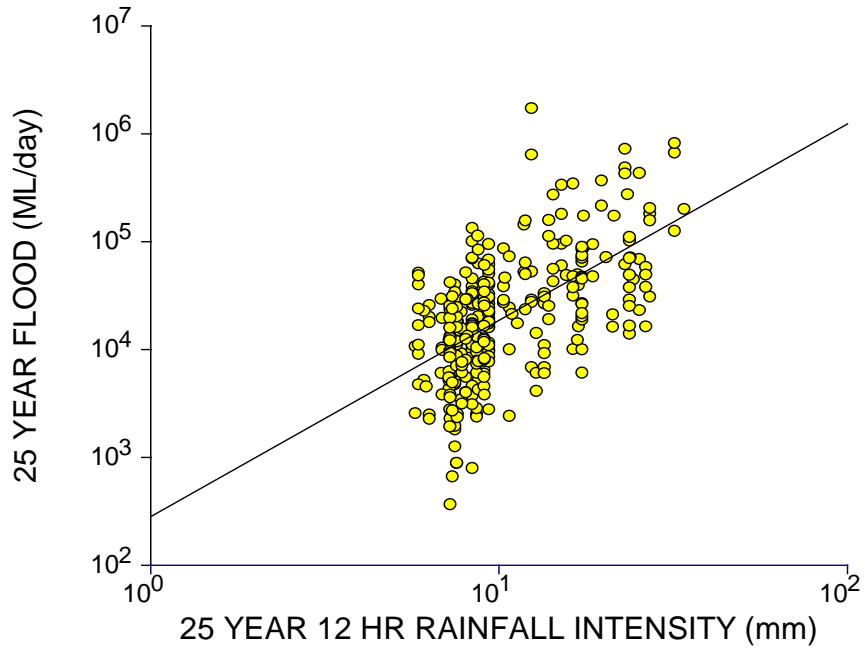


Figure 4: 25 year 12 hour rainfall intensity v. modelled 25 year flood discharge

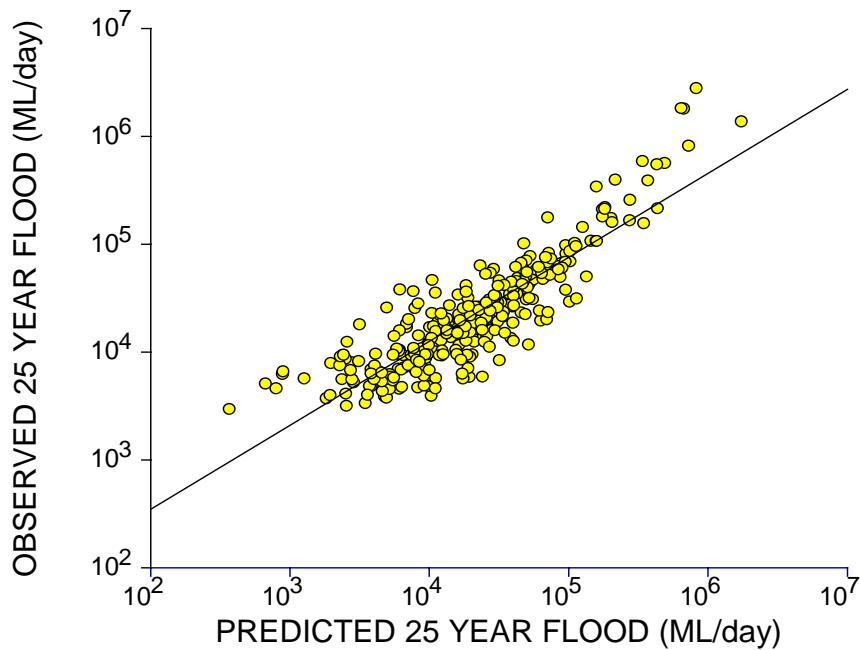


Figure 5: Predicted 25 year flood (from regression equation) v. modelled 25 year flood discharge

2.5 Estimating Flows in Large Murray Darling Basin Rivers

The regional flood frequency model was largely derived from drainage basins with areas of less than 10,000 km². We have tested its suitability for use on large rivers of the Murray Darling Basin by carrying out a flood frequency analysis on observed and a small number of synthetic gauging station flow records supplied by the University of Canberra. 25 year floods were determined after fitting 3 parameter lognormal or log Pearson III probability distributions using the ESFFAN program (Engsoft, 2000)

The regional flood frequency model predicts increasing 25 year flood discharges with drainage area. This only occurs in drainage basins up to a certain size in the Murray Darling Basin. Beyond this point, discharge *decreases* with drainage area (Fig. 6).

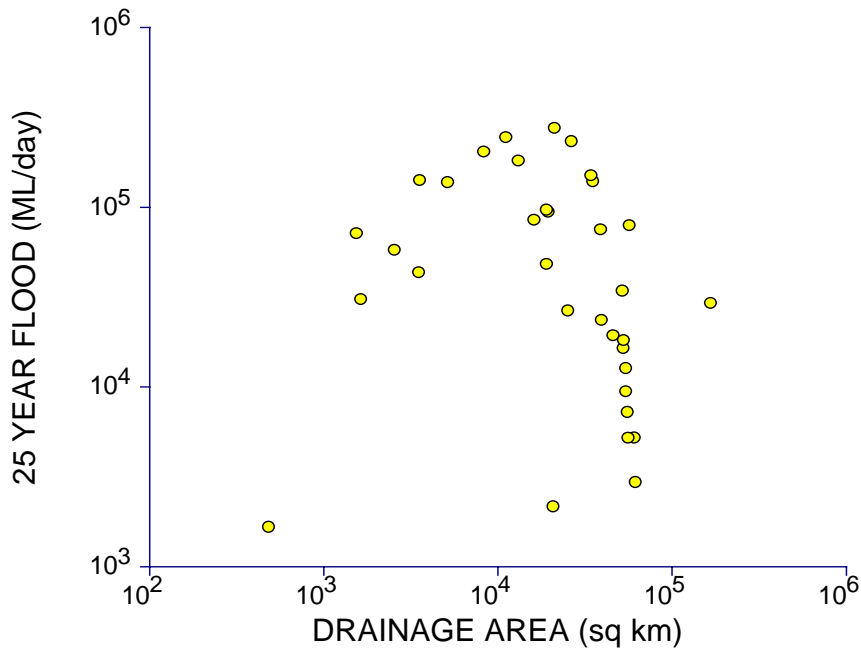


Figure 6: Downstream changes in the 25 year flood with drainage area for Murray Darling Basin rivers.

Figs. 7, 8 and 9 show that this behaviour affects the accuracy of 25 year flood values predicted from the regression equation for various river systems in the basin. If the regression model applied over the full range of discharges, the observed: predicted ratio should be 1.0 (equivalent to 0 on the graphs after log normal transformation). However, there is a progressive increase with drainage area. (Note that some gauging stations on or immediately below large dams are not included in these graphs.)

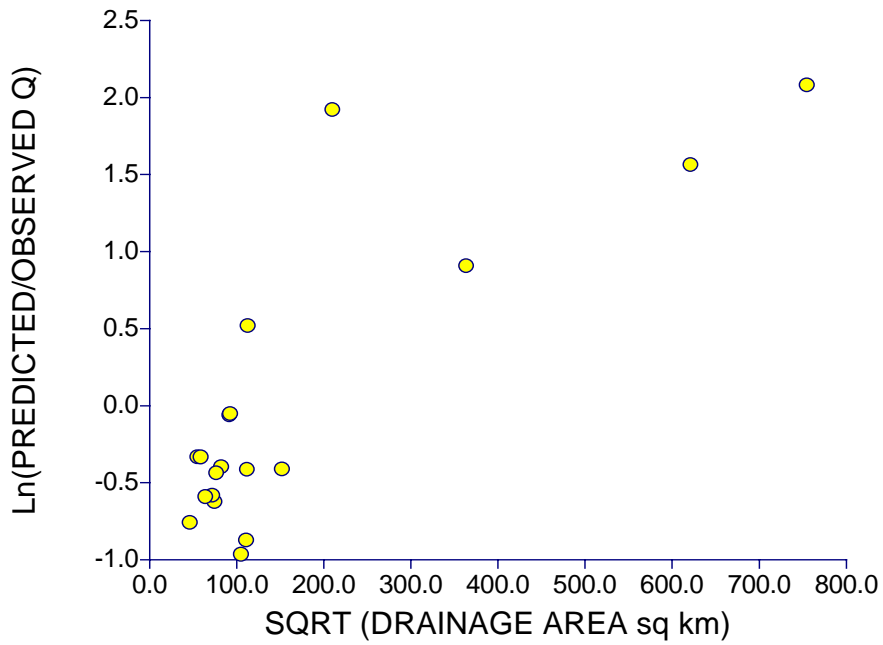


Figure 7: Deviations from predicted 25-year floods in the Border, Barwon and Darling River systems

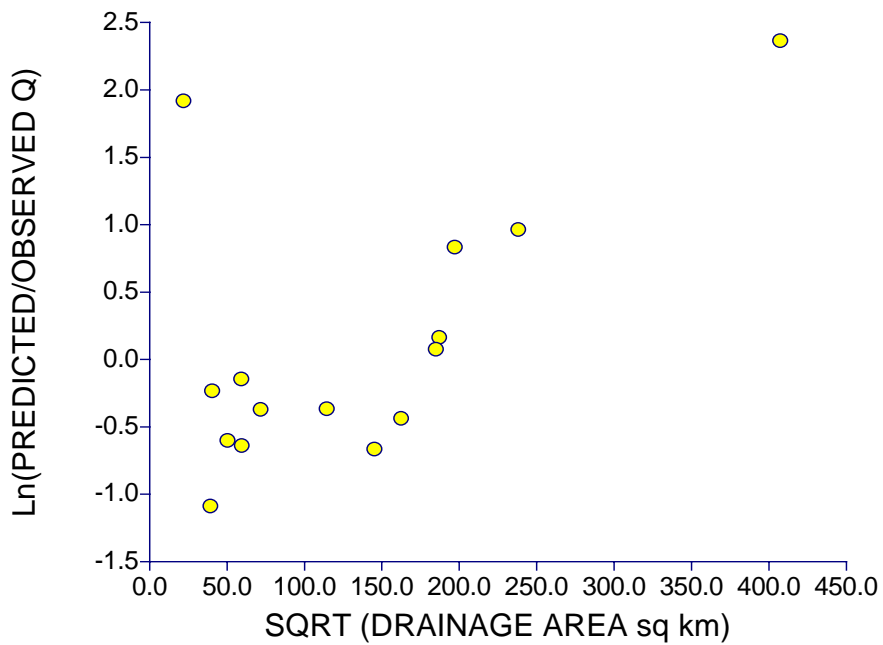


Figure 8: Deviations from predicted 25-Year floods in the Murrumbidgee River system

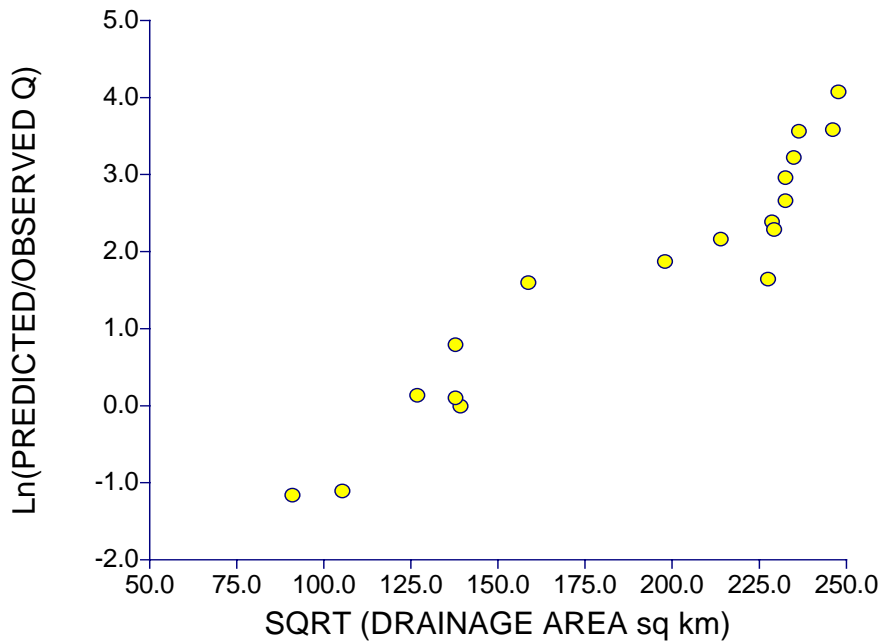


Figure 9: Deviations from predicted 25-year floods in the Lachlan River system

Correction factors based on gauging station records have been calculated to allow for downstream decreases in discharge with increasing drainage area. These are:

High rate of downstream decrease (based on the Lachlan):

$$C_2 = 1.0 / (\exp(0.029(\sqrt{Area})) - 3.899) \text{ for } \sqrt{Area} > 134$$

Moderate rate of downstream decrease (based on the Murrumbidgee):

$$C_2 = 1.0 / (\exp(0.00815(\sqrt{Area})) - 1.1) \text{ for } \sqrt{Area} > 135$$

Low rate of downstream decrease (based on the Darling, Barwon and Border Rivers):

$$C_2 = 1.0 / (\exp(0.00374(\sqrt{Area})) - 0.711) \text{ for } \sqrt{Area} > 190$$

The correction is applied by multiplying $Q_{pred_{25}}$ by C_2 .

3. Verification and Calibration

3.1 Comparison with HEC-2

HEC-2 and HEC-RAS are amongst the most widely used computer packages for flow profile analysis on channels and floodplains and are widely regarded as standard procedures. While not suitable for use on the scale required in the Audit, they can be run

on selected reaches for comparison with our floodplain modelling results. This provides a check on our implementation the step-backwater procedure.

Figs 10 and 11 show test results from a 20 km test reach. The computed water surface elevations are almost identical to those derived from HEC-2. The HEC-2 velocities are slightly lower because the calculations did not divide the cross section into an active flow zone and a slackwater/backwater zone. The cross sectional area occupied by moving water was therefore greater, resulting in lower velocities. This also means that HEC-2 water surface elevations should be slightly lower which is the case. The differences in both water surface elevation and velocity near distance zero reflect different assumptions in defining computation starting values. Overall, the comparison shows that our modelling results are consistent with those from HEC-2

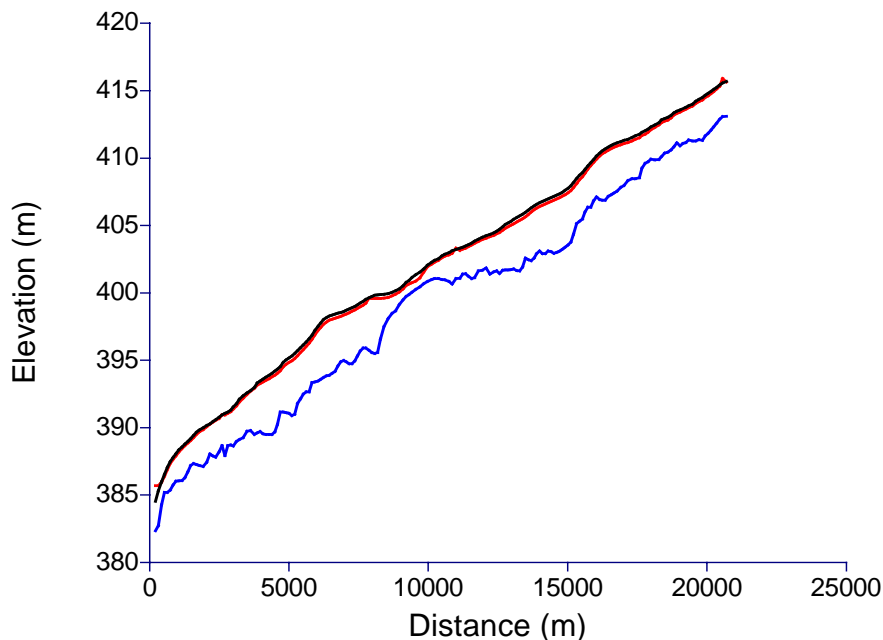


Figure 10: Floodplain long profile (blue) and water surface elevations derived from HEC-2 (red) and our implementation of the step-backwater method (black) for a 20 km test reach.

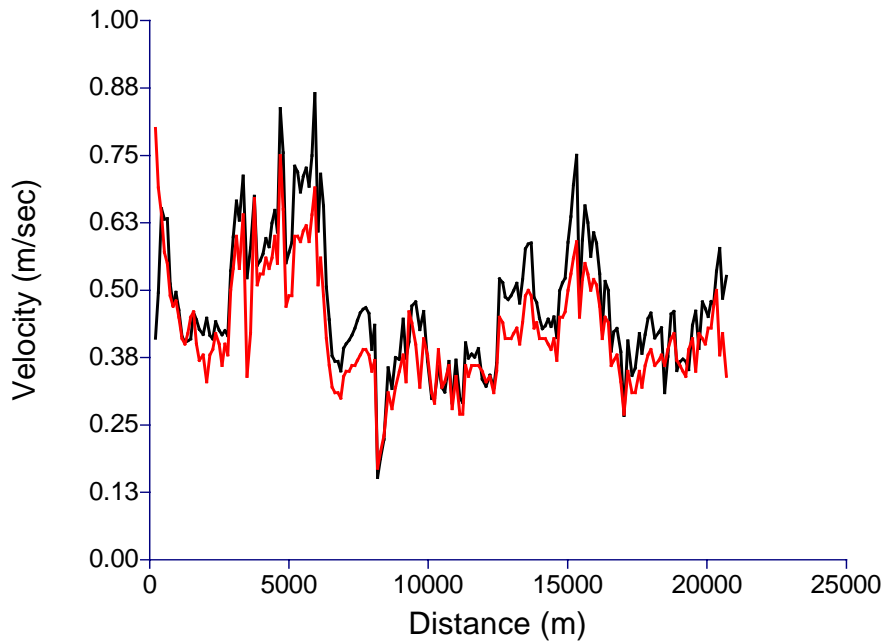


Figure 11: Floodplain flow velocities derived from HEC-2 (red) and our modelling procedures (black) for a 20 km test reach.

3.2 Data Resolution and Scaling

While the nine second DEM captures the basic configuration of many floodplains, it lacks detail and many smaller topographic features will be missing. Given the broad scale of floodplain flows, we do not expect this loss of detail to be as critical as it might be in the hillslope sedimentation model. However, we still need to verify that the nine second DEM has sufficient resolution to allow delineation of floodplains with reasonable accuracy. We also need to verify that downstream patterns in modelled floodplain flow velocities are not distorted by the coarse spatial resolution imposed by the DEM since this would affect the location of sediment sinks and zones of sediment throughput.

We have investigated the effect of DEM resolution on floodplain extents by modelling the 25 year flood on the Logan River drainage basin in Queensland using both the 9 second DEM and a 25m grid cell DEM. This represents a tenfold change in spatial resolution and covers a range of topography from lowland floodplain to narrow confined mountain streams. Figure 12 illustrates the result with the 25 year flood from the 9 second DEM mapped to the nearest grid cell and the result from the 25m DEM shown as a boundary line.

Overall, the results are surprisingly good given the difference in DEM resolution. Modelling with the 9 second DEM overestimates floodplain widths slightly in steep confined headwater reaches compared with the 25m DEM. It also gives wider slackwater zones on largely unconfined floodplains although active flow zones are of similar extent. The greatest differences occur where flow accumulations carried out on the 9 second

DEM fail to identify river courses accurately and on flat coastal plains where small differences in relief only captured by the 25m DEM may be sufficient to confine the flow. The 9 second DEM does not contain these finer elements of relief and allows the model to spread floodwater over a wider area.

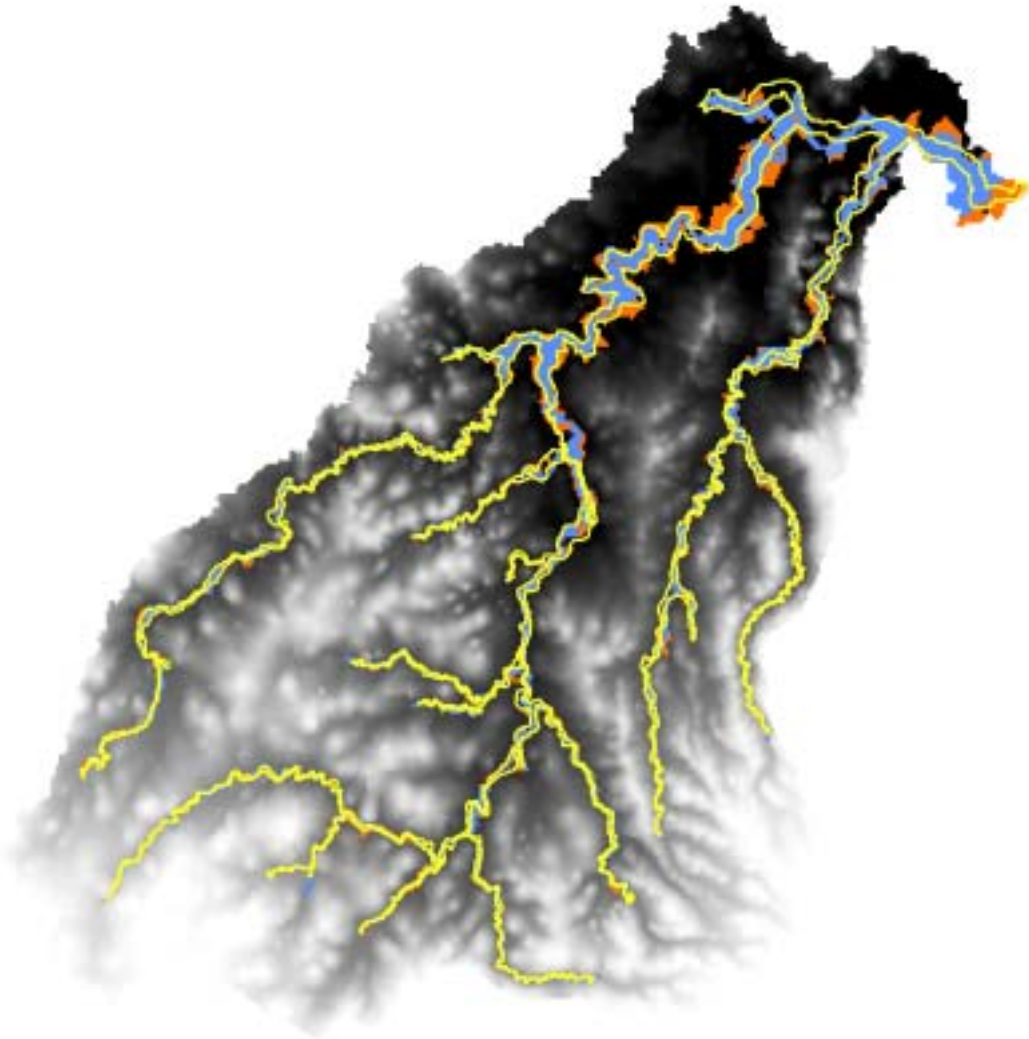


Figure 12: 25 year flood extents overlaid on the 9 second DEM (grey scale) in the Logan River catchment. Blue and orange indicate the active flow zone and slackwater areas respectively obtained by modelling using the 9 second DEM. The yellow lines show the boundaries of the inundated zone obtained by modelling using a 25m grid cell DEM.

Changes in modelled floodplain width with DEM resolution has implications for flow velocity. In the Logan River catchment, the mean flow velocity for the 25 year flood over the whole floodplain system is 0.46 m/sec for the 25 m DEM and 0.71 m/sec for the

9 second DEM. The difference occurs because flow distances are shorter on the 9 second DEM due to directional smoothing which makes hydraulic gradients steeper than on the 25 m DEM. Indeed, the difference in spatial resolution may be enough to change flow distances by 20%. This is more than sufficient to overcome the effect of increased floodplain width on the 9 second DEM which might be expected to reduce flow velocity.

While absolute values of flow velocity are important in sediment transport calculations, it is relative changes in velocity down the drainage system that determine the location and influence of the major sinks on sediment flow through the system. We have therefore standardised flow velocities for each drainage system link by the subtracting the mean velocity for all locations and dividing by the standard deviation. These values are shown in Fig. 13.

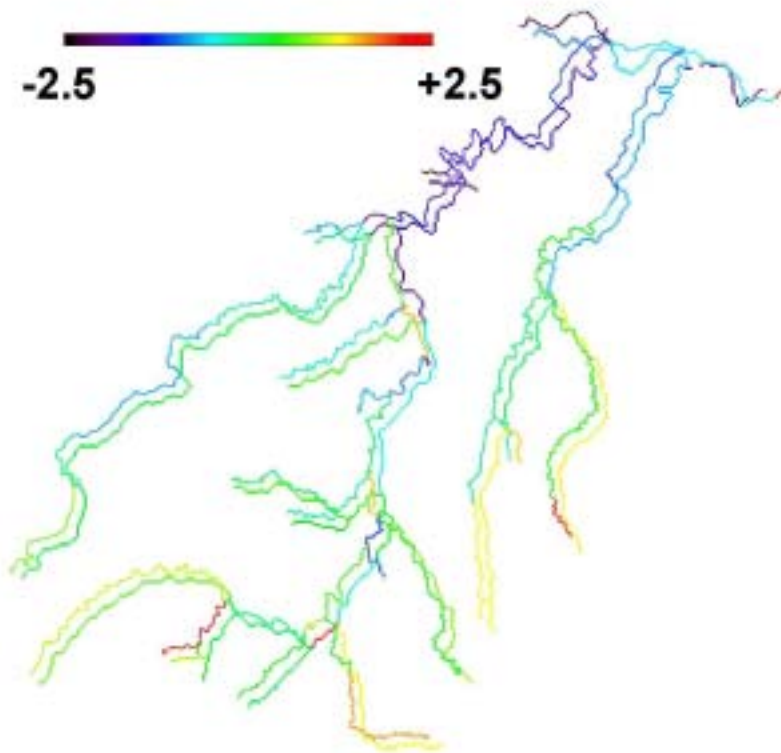


Figure 13: Standardised floodplain flow velocities for the Logan River catchment expressed as standard deviations about a zero mean for the 25 m and 9 second DEMs. 25m DEM values have been relocated 2 km west and 1 km north to allow visual comparison.

The velocity distribution patterns in Fig. 13 are similar in both DEMs and would identify similar zones of sediment throughput and sinks. The results from the 25 m DEM show a wider range of values than those from the 9 second DEM, even after standardisation, and this reflects the effects of smoothing. The effect of having higher velocities in the 9 second DEM would be to move sediment further down the system, to reduce the amount of deposition overall and to increase modelled sediment output to estuaries compared

with the 25 m DEM. It may be useful to compensate for this effect in the floodplain sediment model.

3.3 Floodplain Boundaries and Extent of Flooding.

While we would expect to get better floodplain delineation from higher spatial resolution DEMs, comparison with results from the 9 second DEM does not provide a definitive test of modelling accuracy. A better test is to compare the results with real floods and real floodplains captured by remote sensing.

Previous work with the hydraulic modelling techniques has shown that they give good reproduction of floodplain extents as delineated by Landsat TM data and airborne gamma ray imagery (Pickup and Marks, 2001; in press). However, these studies used 100m grid cell DEMs supplemented by radar altimetry providing additional spot heights at internals of about 70m along flight lines 400m apart. We therefore require comparisons based on hydraulic modelling with 9 second DEM given the differences in floodplain extent that result from differences in DEM resolution.

An extensive search of the Australian Center for Remote Sensing database was carried out to find suitable imagery with limited success except in more arid areas. Satellite passes either did not coincide with floods or the ground was obscured by cloud cover. We have therefore made comparisons where floodplains can be delimited on imagery by a mix of soil differences, variations in vegetation cover and the presence of standing water or wetted soil. These comparisons were made in the Burdekin basin (Suttor River catchment) of Queensland, the Murchison basin in WA, and the Culgoa River on the NSW/Queensland border.

Some results from comparisons with Landsat TM are presented in the Figures below. These examples have been selected to model performance in flatter parts of the landscape since this is where most floodplains occur. Also, where floodplains exist in steeper regions, they are confined by valley sides and are usually reproduced quite well by hydraulic modelling even at the resolution of the 9 second DEM. In these situations, the principal inaccuracy occurs on small basins where floodplain width may be less than grid cell size. Here, final mapping of floodplain extents is to the nearest grid cell even though the hydraulic calculations are done at sub-grid cell level using interpolation between individual points on the DEM.

Figure 14 shows modelling results from the 9 second DEM overlaid on a Landsat TM image of part of the Suttor catchment. We had only partial success in selecting image processing techniques and transforms that distinguish floodplains from surrounding agricultural land use patterns. However, the overlaid floodplain boundaries (black on the image) show that the main floodplains have been correctly identified with only a few errors and exceptions. These occur where drainage basins are below the 50 km² cutoff and where stream channels derived by flow accumulation do not correspond with observed stream channel locations. This may be a function of the simplification in drainage directions introduced by having a low resolution DEM. It may also result from imprecision or inaccuracy in the mapped stream channel locations that were initially used

to force downstream flow when the DEM was initially created. In both cases, these errors arise from problems with the DEM rather than the hydraulic modelling techniques.



Figure 14: A Landsat TM image of part of the Sutor River catchment, Queensland. The black lines delineate modelled 25-year flood extents. The image has been transformed using the LS-FIT algorithm in the ENVI image processing package to find pixels containing features characteristic of clay minerals (Research Systems, 2000). The red band shows the LS-FIT clay residual value (with brighter values suggesting higher clay content), green shows TM band 2, and blue shows TM band 1.

Floodplains are considerably easier to delineate on satellite imagery in arid and semi arid areas than in agricultural areas because their distinctive sediments are not obscured by vegetation. They also have plant communities that differ from those of surrounding non-floodplain areas. At the same time, many arid/semi arid areas pose major challenges to hydraulic modelling because they are often very flat, floodplains are largely unconfined by topography, drainage may be distributary, and mapped drainage lines contain many errors.

The hydraulic modelling techniques were originally developed for arid zone floodplains and cope with flat topography reasonably well *where flow accumulations accurately delineate channel location*. Where this is not the case, substantial inaccuracy may occur. These issues are illustrated in Figures 15 and 16.

Figure 15 shows modelled floodplain extents superimposed on a Landsat TM image of part of the Murchison basin in WA. A very high level of accuracy is achieved, both in stream location on the original 9 second DEM and in floodplain extent.

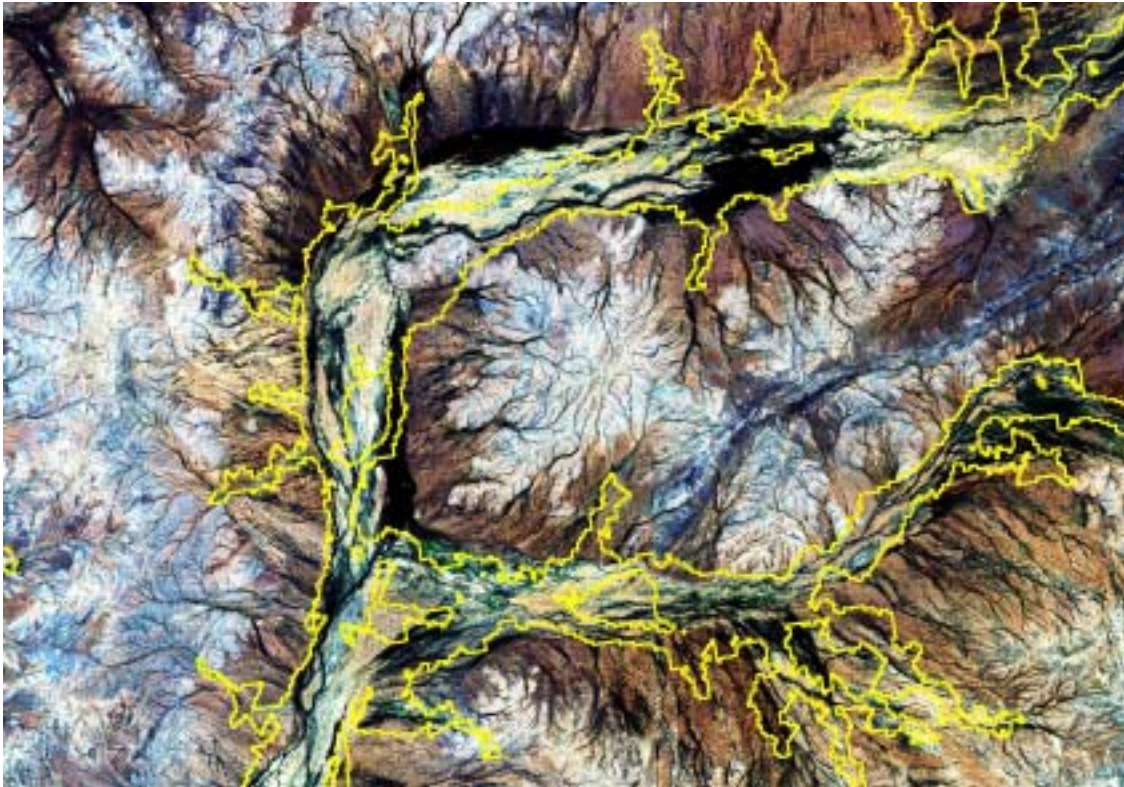


Figure 15: A Landsat TM image of part of the Murchison River drainage basin, WA. Image is true colour with red, green and blue showing TM bands 3, 2 and 1 respectively. Yellow indicates modelled 25 year flood boundaries.

Figure 16 is a Landsat TM image of part of the Culgoa River and shows the problems that occur if the drainage lines are not accurately located by flow accumulation operations on the 9 second DEM. This image was acquired on the 10th May, 1990 and shows what was close to a 50 year flood that passed the St George Gauging Station about 100 km upstream 17 days earlier. Floodwater in the smaller drainage basins would probably have receded by the time the image was acquired but the floodwater was still moving down the main channels and the inundated area can be clearly seen in blue. The area is virtually flat and most topographic variation is well within the limits of measurement error for the DEM. Stream channel centreline locations therefore rely almost entirely on the mapped drainage lines used to force topographic lows during DEM construction.

While there is some correspondence between modelled floodplains and the observed flood, there are many errors. Indeed, DEM transects across the larger floodplains show thalweg elevations that are not coincident with stream locations on the TM imagery. However, variations in elevation along these transects are very small. For example a 30 km wide cross section of the Culgoa floodplain shows only a 4 m range in elevation so it

is not surprising that errors in channel and subsequently, inundated area locations, occur.

Another source of error lies in the drainage areas used to calculate the 25 year flood using the discharge equations listed above. The ARC/INFO flow accumulation routines route drainage down the path of steepest descent into the single lowest grid cell. No allowance is made for downstream drainage dispersion into more than one cell so flow accumulations in distributary drainage systems will not be correct. What actually occurs in a distributary system is that all flow is routed into a single channel with other distributaries treated as new drainage basins. Discharges in the main channel will be overestimated while those in other distributaries will be underestimated.

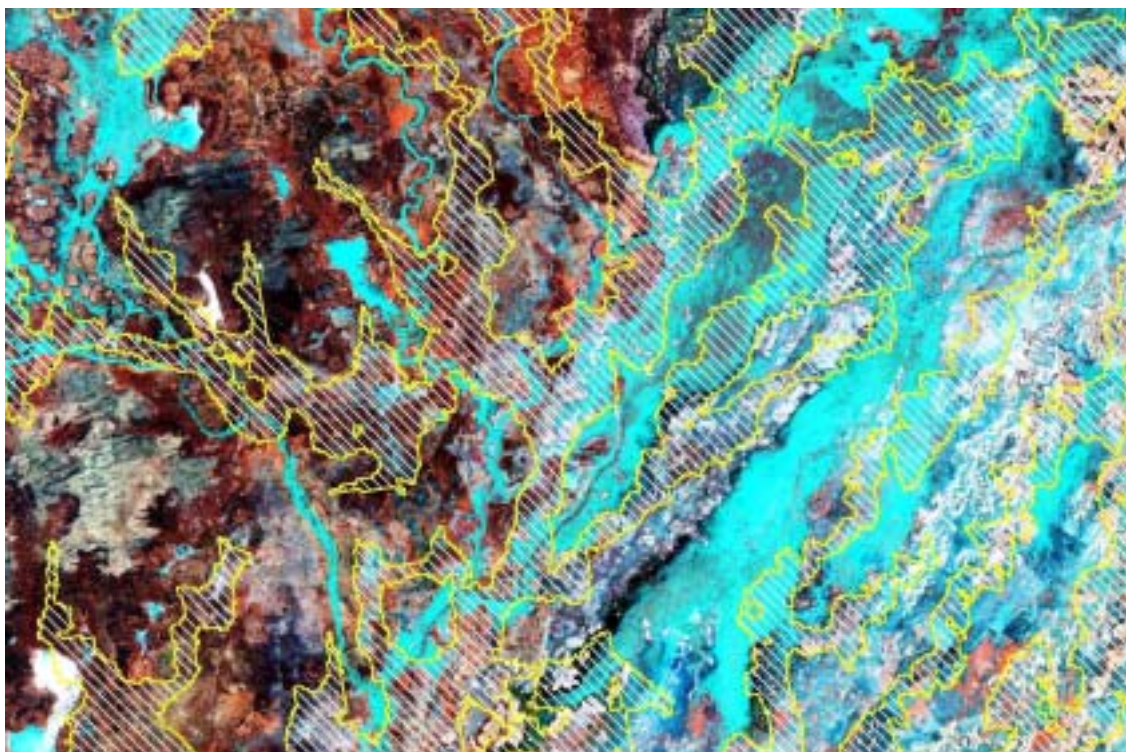


Figure 16: A Landsat TM image of part of the Culgoa River showing the extent of the April/May, 1990 flood. Image is true colour with red, green and blue showing TM bands 3, 2 and 1 respectively. The yellow boundary lines and white cross-hatching show modelled 25 year flood extents.

4. Conclusions

Floodplain extents in many areas can be modelled with reasonable accuracy assuming steady flow at a discharge equivalent to the annual series 25 year flood using the step backwater approach to gradually varied flow profile analysis. Results obtained using the 9 second DEM and empirically derived regional flood frequency relationships show good correspondence with floodplains visible on Landsat TM images, even in relatively flat areas. Principal sources of inaccuracy are:

- incorrectly located drainage lines in the map coverages used to force topographic lows when creating the DEM;
- inability of the 9 second DEM to capture small variations in topography in flat areas; and
- incorrect drainage areas in distributary river systems.

Flow velocities in the 9 second DEM are, on average, higher than in higher spatial resolution data due to directional smoothing.

No overall assessment of accuracy is possible without detailed knowledge of DEM inaccuracy but, in general, the floodplain extents are surprisingly good.

5. Caveats on Data Usage

Data on floodplain extents are indicative only and were derived to allow calculations of sediment storage. They are not suitable for any purpose that requires accurate delineation of flood extent or assessment of flood risk. Levels of accuracy are severely constrained by the spatial resolution and accuracy of the 9 second DEM. Errors may be particularly severe where the drainage line data used to force topographic lows in the 9 second DEM are not accurate. Substantial errors may also occur in distributary drainage systems in flat areas.

Flow velocity files are intermediate inputs to the sediment transport model. They are not for release, distribution or publication. They may contain anomalies or errors, particularly where variations in valley shape or terrain slope violate the assumption of gradually varied flow. The values in these files require extensive smoothing or preferably link by link averaging before use

6. References.

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Appendix 1: Program Files and Usage

A1.1 Description

The gradually varied flow analysis and subsequent extraction of data products involves four FORTRAN 90 programs. These are: GRADQ1.FOR, GRADSETUP11.FOR, GRADRUN11.FOR, and GRADVELOC.FOR. These programs undertake the following tasks and produce intermediate files that are used as input to subsequent programs:

GRADQ1.FOR reads DEM, pitless DEM, flow accumulation and 25 year 12 hour rainfall intensity data. It produces a grid of the average upstream 25 year 12 hour rainfall intensity for each cell in the DEM.

GRADSETUP11.FOR identifies all stream channel grid cells (with an upstream area greater than a user specified cutoff value). These are sorted into downstream order for subsequent flow calculations. 25 year flood values are calculated for each stream grid cell. Floodplain cross sections are identified and orientations calculated. Stream links are also identified. The intermediate file grid cell "link.sub" (4 byte signed integer, flat binary, byte order LSB) containing drainage net link numbers is produced.

GRADRUN11.FOR carries out the gradually varied flow calculations and produces files describing water depths on floodplains and flow hydraulics. These files are "wdepth2.act" containing water depths in the active flow zone and "slack.sub" containing water depths in slackwater areas. These files are subsequently converted to a file "floodplain.flt" (4 byte floating point, flat binary, byte order LSB) using the *ENVI* image processing package. This file contains values of 0.0 for non floodplain areas, 1.0 for slackwater zones and 2.0 for active flow zones

GRADVELOC.FOR extracts floodplain flow velocities and produces grid files containing flow velocities smoothed using a 3 point moving average scheme and flow velocities averaged by stream link.

A1.2 Usage

Programs should be run in the following order as each generates input files for the next:

1. GRADQ1.EXE
2. GRADSETUP11.EXE
3. GRADRUN11.EXE
4. GRADVELOC.EXE

GRADQ1 uses an input text file: “gradqin” which is described below. All other programs use a single consolidated set of parameter inputs that should be set up as a text file “gradin” before running the first program. Usage is then GRADSETUP11<gradin, GRADRUN11<gradin, and GRADVELOC<gradin. A typical “gradin” file is listed below with explanations of parameter values in the file.

Contents of file gradqin:

1	Use a mask 1=yes 0=no ¹
782 798	No of pixels, no of lines ²
MORTaustdem	DEM file (4 byte floating point) ³
dem.siz	Drainage area file(sq m) 4 byte floating point ⁴
MORTmask	Mask file (byte) <u>optional</u> 1=include 0=exclude ⁵
MORTaustdem	Pitless DEM file (4 byte floating point) ²³

Contents of file gradin:

1	Use a mask 1=yes 0=no ¹
782 798	No of pixels, no of lines ²
MORTaustdem	DEM file (4 byte floating point) ³
dem.siz	Drainage area file(sq m) 4 byte floating point ⁴
MORTmask	Mask file (byte) <u>optional</u> 1=include 0=exclude ⁵
262.2	Average pixel width (m) ⁶
50000000.	Stream cutoff area (sq m) ⁷
10.	Strickler roughness coefficient ⁸
20	Max. floodplain width in grid cells (each side) ⁹
0.	Water surface elevation reduction rate(m) ¹⁰
1	Limit downhill facing cross sections 1=y 0=n ¹¹
2.	Downhill cross section fall tolerance before cutoff ¹²
1	cross section alignment 0=45 degree, 1=corridor ¹³
3	Discharge equation (use 3, 4, 5 or 6 for NLWRA) ¹⁴
15.	Active floodplain expansion angle ¹⁵
1	use total floodplain expansion angle(leave as 1) ¹⁶
45.	Whole floodplain expansion angle ¹⁷
0.	Permissible rise for split flow ¹⁸
1	Output hydraulics text file 1=y 0=n ¹⁹
.0015	Energy slope at outlet & pits ²⁰
5.0	Side slope angle for channel at outlet & in pits ²¹
0	Link no for HEC2 output (leave as 0) ²²
MORTaustdem	Pitless DEM file (4 byte floating point) ²³

Notes:

- ¹ DEMs may be masked or normal rectangular grids. If DEMs are masked, a mask file (see note 4) is required. Masked values in the DEM may be null pixels.
- ² DEM size parameters.
- ³ Name of file containing DEM data. File should be a rectangular grid, flat binary, contain floating point elevation values >0.0 and in LSB byte order. Pixels with a value of 0.0 are treated as null values and handled as sinks if within the body of the DEM.
- ⁴ Name of file containing flow accumulation values in m². File should be a rectangular grid, flat binary, contain floating point elevation values >0.0 and in LSB byte order.
- ⁵ Name of file containing catchment mask. File should be a rectangular grid, flat binary, contain byte values of 0 or 1. Cells with a value of 0 will be excluded from analysis and treated as being outside the catchment. **This line is optional and should only be included if the mask usage flag on line 1 has a value of 1.**
- ⁶ Average grid cell width in m
- ⁷ Minimum upstream drainage area in m² for stream channels to exist. Cells with a drainage area less than this cutoff point are not treated as channel centreline locations.
- ⁸ The roughness coefficient in the Strickler equation (inverse of Manning's n).
- ⁹ Maximum number of grid cells floodplain can extend each side of channel centreline. Provides a limit on floodplain expansion.
- ¹⁰ Decrease in surface water elevation in m with each step outwards from the floodplain centreline. Allows water surface elevations to decline as flooded area extends laterally towards floodplain edges.
- ¹¹ Downhill facing cross sections flag. Set to 1 to prevent floodplain bed elevations decreasing more than a specified value. This is used to stop floodplains extending too far when cross sections are misaligned (for example pointing downstream).
- ¹² Maximum allowable decrease in floodplain bed elevation in m in a cross section as cross section extends laterally. This is used to stop floodplains extending too far when cross sections are misaligned (for example pointing downstream).
- ¹³ Method for calculating cross section alignment. Set to 0 to specify cross section alignments orthogonal to flow direction to next downstream grid cell. These will produce alignment angles to nearest 45 degrees. Set to 1 to calculate a more precise angle.
- ¹⁴ Select method for calculating discharge from drainage area. 3 uses the method described in section 2.4. 4, 5 and 6 use the methods described in section 2.5 with

downstream rates of decrease based on the Darling, Murrumbidgee and Lachlan Rivers respectively.

- ¹⁵ Maximum rate of increase of flow width on each side of channel in degrees in active flow zone in both upstream and downstream directions.
- ¹⁶ Floodplain expansion angle flag. If set to 1, the whole floodplain (as opposed to the active flow zone) increase in width greater than a user specified rate.
- ¹⁷ Maximum rate of expansion of floodplain width on each side of channel in degrees.
- ¹⁸ Maximum height that islands may extend above water surface elevation within a cross section. Use with caution.
- ¹⁹ Output hydraulics data flag. If set 0, no hydraulics data will be written to file. If set to 1, a file "hydraulics.txt" will be written containing data listed below.
- ²⁰ Assumed energy slope to start gradually varied flow calculations from pits or DEM edges.
- ²¹ Assumed bank angle in degrees for cross sections in pits or at DEM edges.
- ²² Diagnostic output flag. Outputs a file suitable for editing to provide input to the HEC-2 program for a specified link in the drainage network with numbers calculated in GRADSETUP11.FOR. Leave as 0. The HEC-2 file requires editing before use. See HEC-2 Reference Manual for details.
- ²³ Name of file containing pitless DEM data generated when calculated flow directions or flow accumulations prior to running this series of programs. File should be a rectangular grid, flat binary, contain floating point elevation values >0.0 and in LSB byte order. Pixels with a value of 0.0 are treated as null values and handled as sinks if within the body of the DEM. May be the same as the DEM file in record 1 **but must be pitless.**

A1.3 Input files not specified in gradqin and gradin

GRADQ1.FOR requires a file containing 25 year 12 hour rainfalls for the DEM area. This file must be named "25yr12hr.sub" and contain 25 year 12 hour rainfall intensities to the nearest whole number. File is byte and flat binary .

A1.4 Flow Hydraulics Data

GRADRUN11.FOR optionally produces a space-delineated text file "hydraulics.txt" containing information on flow hydraulics, system geometry, drainage net link numbers and the order in which calculations are carried out. The number of records is equal to the number of cross sections and the individual column variables contain the following data:

- 1 Cross section number with data ordered by increasing elevation and drainage area
- 2 Cross section x coordinate location in DEM
- 3 Cross section y coordinate location in DEM
- 4 Cross section location in DEM expressed as a vector of length no. of columns times no. of rows.
- 5 Location of cross section immediately downstream in array listed in column variable 1
- 6 Location of cross section immediately downstream in array listed in column variable 4
- 7 Flow velocity in m/sec
- 8 Energy slope
- 9 Distance between cross sections in m
- 10 Floodplain width in m
- 11 Width of active flow zone in m
- 12 x coordinate of left hand edge of floodplain
- 13 y coordinate of left hand edge of floodplain
- 14 x coordinate of right hand edge of floodplain
- 15 y coordinate of right hand edge of floodplain
- 16 discharge in m³/sec
- 17 water surface elevation in m
- 18 elevation of channel grid cell in m
- 19 link number