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A new approach to extending stage- discharge relations

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Abstract
The gradex idea suggests that at large recurrence intervals the rainfall and flood frequency relations for a basin should be parallel. If this idea is correct it can be used to define the high flow part of stage-discharge relations for basins where actual flow measurements have not been obtained. The idea is tested on some Australian basins for which high-flow measurements are available and it gives good results. Examples are given of application of the method to data for other basins where only low-flow discharge measurements have been made, and the stage-discharge relations are defined for these basins up to the largest observed floods.

INTRODUCTION

The standard method of measuring the discharge of rivers is to observe water level (stage) either continuously or at fixed intervals, and to use a calibration curve to obtain discharge from the water level. These calibration curves, called stage-discharge relations or rating curves are defined by making simultaneous measurements of both stage and discharge or by using hydraulic principles. Experience has shown that under most of the circumstances met in natural streams, use of hydraulic principles can only provide very approximate stage-discharge relations. However the alternative of making actual flow measurements using velocity-area methods or dilution methods is very expensive. Considerable effort and commitment is required to obtain measurements of discharge over the whole range of flows experienced at each site.

There are few difficulties in obtaining measurements of low flows since these occur most of the time. High flows, on the other hand, occur rarely and the chance of having personnel at the site at the moment of occurrence of a high flow is extremely small unless a concerted effort is made. For small basins personnel usually need to be at the measurement site before the causative storm begins. This would inevitably mean that many of the visits to the site would produce only a low flow measurement because precipitation forecasting techniques are far from perfect. If the site of interest is remote the effort and expense of each of these (often fruitless) visits is very large. Measurement of high flows can also be a dangerous activity. Therefore it is very common for stage-discharge relations to be well-defined at low flows but to be only approximately defined at high flows. This is particularly the case in arid and semi-arid regions where flows are infrequent and the population density and transport routes are sparse.

Stage-discharge relationship extension (or extrapolation) methods such as log-log and the Chezy equation method, often referred to as the $A\sqrt{D}$ approach, are discussed in most text books (see for example Maidment, 1993, p.8-24) but these involve assumptions which mean that they can only give approximate estimates. Some data collection bodies do not even use these methods, preferring "experience" and the draughtsman's smoothly drawn curves on linear or log-log paper as their chosen approaches to defining the high flow part of the stage-discharge relationship.

All water resources assessment and flood estimation work is dependent on having accurate streamflow data. Since the underlying mechanisms of runoff production are not totally understood most water resources and hydrological analysis is very dependent on the availability of accurate streamflow data. If the streamflow data that are available are of low accuracy or reliability then any water resources project or engineering design (for reservoirs, spillways, bridges, culverts) will also be unreliable, or will need to be "over-designed" to allow for the low reliability of available information. Hence any proposal to obtain greater accuracy in estimation of observed flows has potential to provide large economic benefits.

A technique that has recently been used for water resources assessment in parts of Europe offers a possibility for improving definition of the stage-discharge relation for measurement stations where the stage-discharge relation has been defined only for low flows. This is the so-called gradex approach which will now be discussed briefly.

THE GRADEX CONCEPT

The gradex idea appears to have originated with French hydrologists (Guillot, 1993). In essence the gradex assumption or concept is that for a basin the frequency curves of rainfall and flood peaks will diverge for frequent events, but for large and extreme events the two curves are likely to be parallel, as shown in Figure 1. The divergence at frequent events occurs because the losses from small storms are large and may account for most of the precipitation. However in very large events the losses probably approach some constant value. An alternative explanation is that in a very large event there is a large runoff. If any further precipitation occurs almost all the additional precipitation will run off because the basin is already saturated. Intuitively this concept seems reasonable. However, as yet, there is no proof that it is correct, and indeed before testing the method with real data, as described below, the authors were among the skeptics. As will be shown later, data from basins where a long period of high accuracy flow information is available tends to confirm the reasonableness of the concept, that is that at low frequencies, for high rates of flow, the rainfall and flood frequency curves do become approximately parallel.

If it is accepted that the gradex concept is correct, then it becomes possible to define the high flow part of the stage-discharge relationship for basins with long records (say more than 20 years) where simultaneous stage and discharge measurements have only been obtained for small to medium flows.

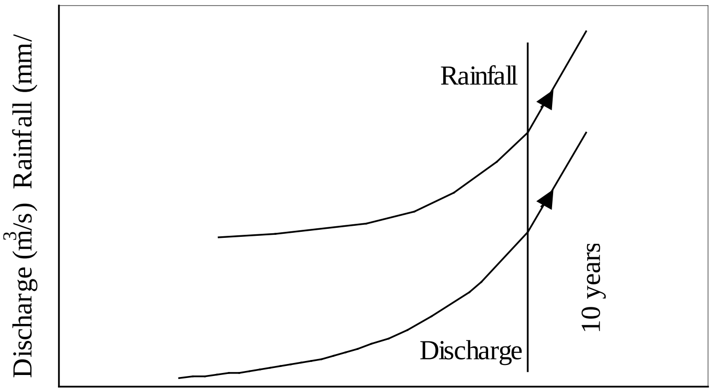

Figure 1. The logic of the gradex model.

DEFINING THE GRADEX CONCEPT WITH HYDROLOGICAL DATA

Data used in this exercise were obtained from two sources. Firstly all streamflow data was supplied by the Department of Land and Water Conservation, the statutory body responsible for surface water resources in the state of New South Wales, Australia. This included continuous observations of water level, actual discharge measurements made at the stream-gauging stations and the adopted stage-discharge relationships. Most of these data were obtained from the CD rom "Pinneena."

Precipitation data was obtained from the Australian Bureau of Meteorology's published intensity-duration-frequency (I-D-F) analysis of all its data, which is given in Australian Rainfall and Runoff (Pilgrim, 1987). These data are provided in the form of a series of maps from which the statistical characteristics of the I-D-F distributions can be extracted. From these characteristics the distribution of the I-D-F relations for any location in Australia can be constructed. Use of these data is probably superior to use of data from a single station in or near the basin of interest for three reasons. Firstly, it is possible to obtain a representative estimate for the basin by selecting values for the location of the basin centroid. Secondly, the analysis included data from all precipitation stations in the region with long records and therefore provides as reliable a set of intensity-frequency data as can possibly be obtained for all locations in Australia. Its only deficiency is that data collected after 1983 were not included in the analysis. However, since over 100 years of data were available for many stations this should not provide a major deficiency. Thirdly, whenever precipitation is used for any form of flood analysis in Australia the I-D-F data given in Australian Rainfall and Runoff (Pilgrim 1987) are used, and so any examination of estimation of floods or accuracy of data should include some reference to, or comparison with this body of data.

For each basin of interest in this study both flood and rainfall frequency curves were derived as shown for the Williams River at Glen Martin (national station number 210010) in Figure 2. For the rainfall frequency curve an arbitrary decision was made to use data for a duration of 12 hours. Each basin will be responsive to different durations of storms but examination of I-D-F curves for any location in Australia shows that the curves for different durations at a single location are approximately parallel and therefore any duration could have been adopted because the key feature of interest for the present study is the slope of the I-D-F curve at low frequencies. The rainfalls are expressed in the same units as the observed flood discharges, incorporating the effects of basin size, in the diagrams shown.

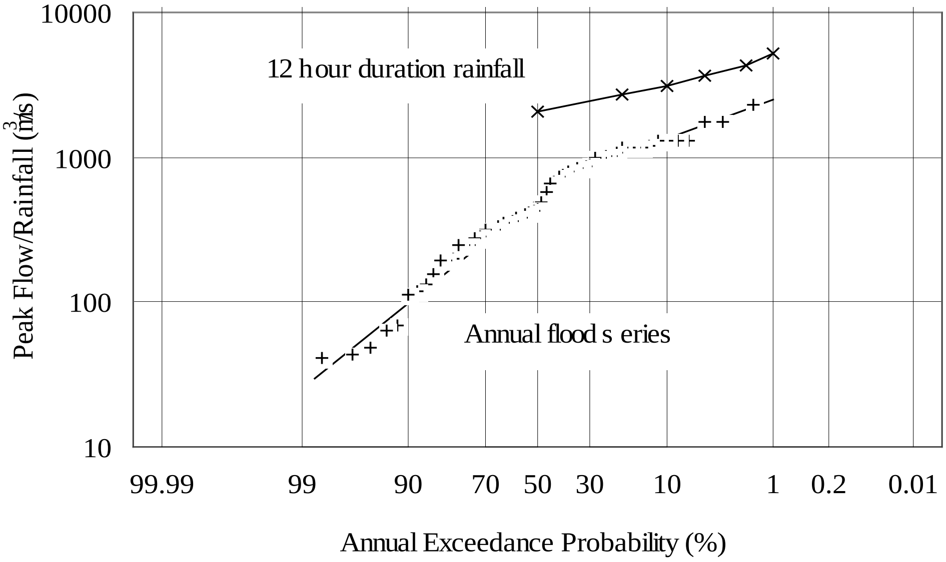

Figure 2. Williams River at Glen Martin (210010) Frequency relationships.

For each basin where good quality high flow measurements had been obtained the flood and rainfall frequency curves were plotted as shown in Figure 2. For the Williams River at Glen Martin shown in Figure 2, where the highest flow measurement of 2200 m^3/s was equal to about the 50 year flood, it can be seen that the rainfall and flood frequency curves are approximately parallel for ARIs greater than about 10 years. For other basins where good quality flow measurements have been obtained at similar very high flows the rainfall and flood frequency curves were parallel for the low frequency end of the plot, similar to that shown in Figure 2.

The study discussed here began as an exercise to refute the gradex idea. As suggested by other authors (Beran 1981, Reed 1994) the gradex idea is interesting and appears to be backed by some logic, but it has not been proved, or supported by an abundance of evidence. However, as discussed above, when data were assembled for a number of basins in New South Wales, Australia the overwhelming impression obtained was that perhaps there was some basis for this concept, though there is no real theoretical basis for it.

Data from a total of 41 basins, which ranged in size from 25km^2 to 42000km^2 were considered in this study. Of those, 20 had actual measurements of discharge at high flows and for them the low frequency end of the flood and rainfall frequency curves were approximately parallel, as shown in the example in Figure 2 and as suggested by gradex. Of the 21 basins which had only low-flow discharge measurements, ie where the maximum measured discharge was less than 30% of the estimated maximum discharge (in some cases less than 5%), the gradex approach suggested the stage-discharge relations of 17 needed adjustment, usually to reduce the discharge of the largest floods, with only four out of the 21 with only low flow measurements appearing not to need adjustment for their flow observations to conform to the gradex idea.

These results suggested, in spite of the authors intention to show that the gradex idea was unrealistic, that the rainfall intensity and flood frequency curves are usually approximately parallel at low frequencies (high ARIs).

EXTENSION OF STAGE-DISCHARGE RELATION USING GRADEX

An example of use of the gradex approach to define the stage-discharge relation is given for the Fish River at Tarana (421035). A plot of the discharge measurements and the adopted (1995) stage-discharge relation is shown in Figure 3. It can be seen that the highest flow measurement was at 172 m^3/s but the largest observed stage was 3.9 m with an estimated discharge of 540 m^3/s. Data collection began in 1954 and so over 40 years of record are available at this site. When the adopted stage-discharge relation was used to estimate the discharges of the annual series of floods (from stage observations) the flood frequency relation shown in Figure 4 resulted.

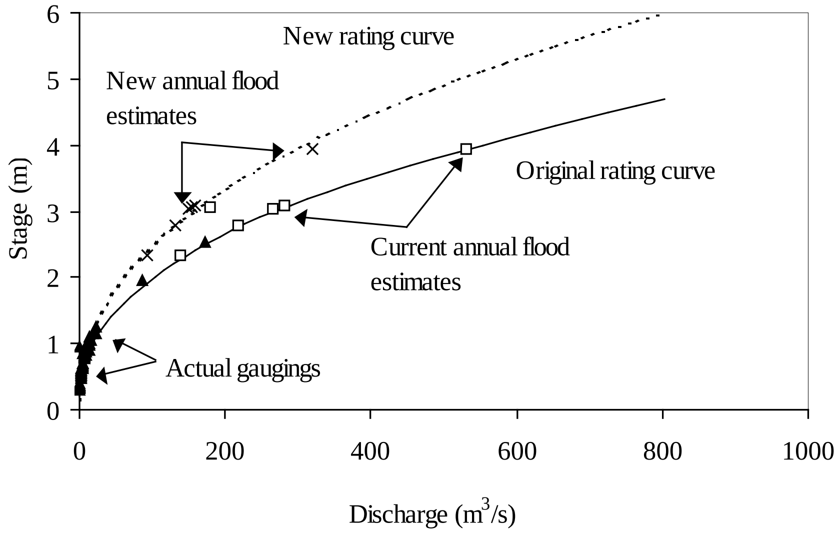

Figure 3. Fish River at Tarana (421035). Original stage-discharge relation and new relation

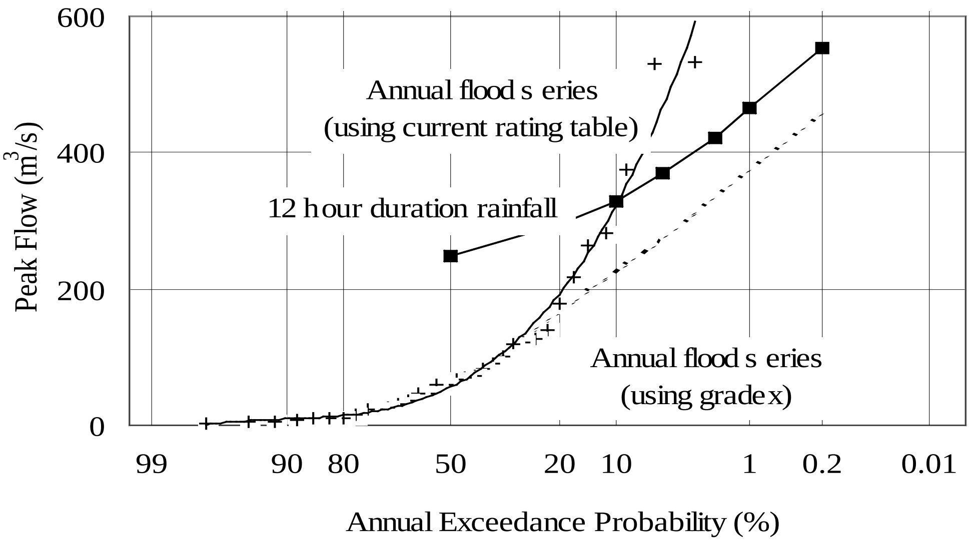

Figure 4. Fish River at Tarana (421035). Frequency relationships.

Also shown on Figure 4 is the 12 hour duration rainfall intensity-frequency relation for the basin. It appears from Figure 4 that the discharges above about 120 m^3/s are overestimated since in this region the flood frequency curve has a larger gradient than the rainfall frequency curve and the highest discharges exceed the rate of rainfall on the basin. However if the gradex idea is correct the two curves should be approximately parallel. If the flood frequency relation was modified to be parallel to the rainfall frequency curve at ARIs greater than 10 years, the broken line on Figure 4 would become the revised flood frequency curve.

The discharges of the 7 largest floods would then be reduced so that they would plot about this revised flood frequency curve. When these revised discharges were transferred back to the stage-discharge curve for the site, shown in Figure 3, they plotted as the crosses above and to the left of the current (1995) stage-discharge relation. The stage discharge relation was then revised to be the line of best fit through the observed flow measurements and these 7 revised flood estimates, and this revised relation is shown by the broken line on Figure 3.

It can be seen that at the upper end of the stage-discharge curve the estimated discharges are reduced by about 50% - a significant change in terms of both flood peak discharge and also in terms of volumes of flood flow. A change such as this, though only affecting flows in 6 or 7 events in 40 years is likely to reduce the estimated mean annual flow volume by several percent.

Another example is shown for the Duckmaloi River at Duckmaloi (421036). Figure 5 gives the stage-discharge relationship and Figure 6 shows the rainfall and flood frequency curves. When the flood frequency relation is modified for discharges above about 30 m^3/s to conform to the discharge measurements and the gradex concept it appears as the broken line on Figure 6. This change would only have a significant effect on the estimated discharges of the largest four floods. Transfer of this modified relation to Figure 5 reduces the higher discharges of the stage-discharge relation quite significantly. However, in general it suggests that the current rating table is probably reliable for all stages up to 1.5m, which is estimated to have an ARI of 5 years.

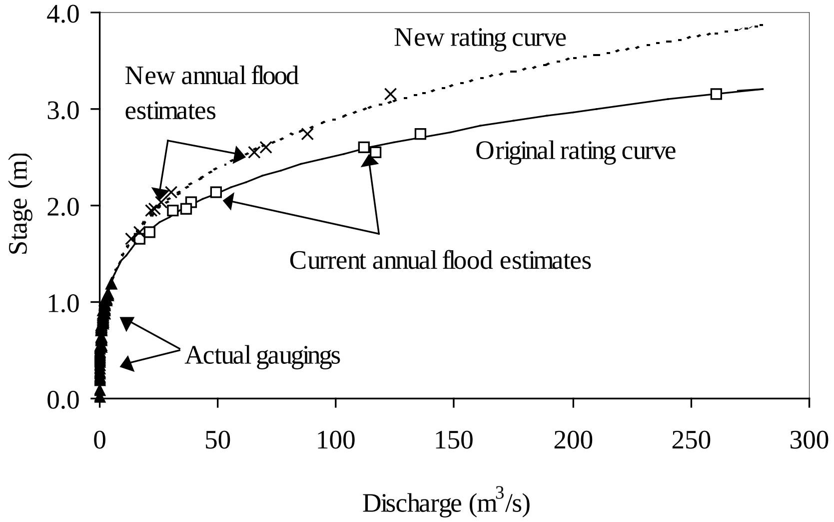

Figure 5. Duckmaloi River at Duckmaloi (421036) Original stage-discharge relation and new relation developed using gradex.

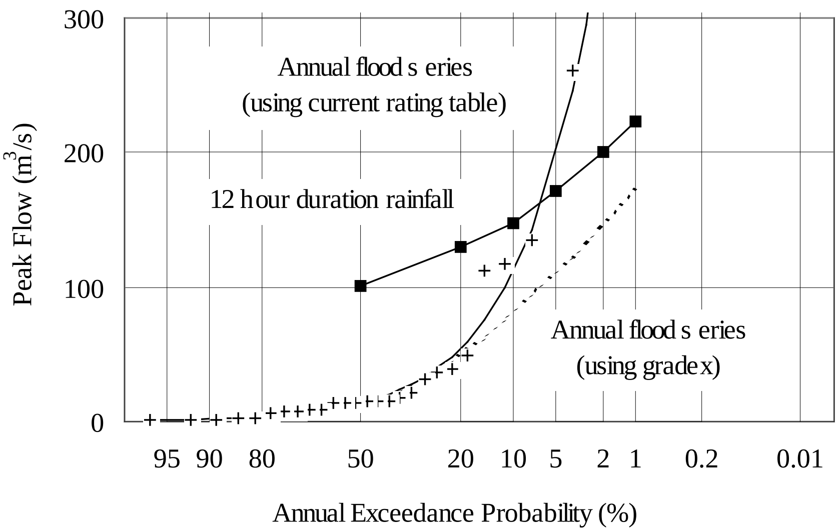

Figure 6. Duckmaloi River at Duckmaloi (421036) Frequency relationships.

FORM OF PLOT OF FREQUENCY RELATIONS

Guillot (1993) and others have suggested the rainfall and flood frequency relations approximate the general extreme value distribution. This is a distribution that is commonly used in Europe, but in other locations other frequency distributions are preferred. In seeking to improve an extrapolated stage-discharge relation it probably matters very little which distribution is fitted to the frequency data, provided the chosen distribution matches the observed data. Occasionally non-linear plots on distorted-scale axes (e.g. log-normal probability) may be most appropriate. The key issue is to show that where high flow measurements have been obtained the rainfall and flood frequency curves are approximately parallel at low frequencies and therefore for the other basins in the same region similarly parallel rainfall and flood frequency curves should be expected. If parallel frequency curves are not obtained, the adopted stage-discharge relation for the basin may need to be changed.

CONCLUSION

At stream-gauging stations where actual measurements of flow have only been obtained for small discharges it may be possible to extend the low-flow stage-discharge relationship to high flows using the “gradex” idea. It has been shown that flood and rainfall frequency relations tend to be parallel at low frequencies. This property can be utilised to allow credible extension of the low-flow part of the stage-discharge curve, which is defined by actual flow measurements, to high flows.

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