EROSION OF UNLINED SPILLWAYS IN ROCK – DOES A 'SCOUR THRESHOLD' EXIST?

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The method of Annandale (1995) is widely used by Australian practitioners for the assessment of erosion in unlined spillways. This method is based on comparison to various case studies, where the geology at each site is characterised using the Kirsten index (a rock mass index previously developed to assess the rippability of rock), and the hydraulic conditions are characterised using the unit stream power dissipation. In this paper, the historical development of this comparative design technique is traced and is critically reviewed against the original geotechnical and hydraulic data, and against a new, independent, dataset gained from unlined spillways in fractured rock in Australia, South Africa and the USA. It is shown that, while erosion can be usefully correlated against rock-mass indices and hydraulic indices, this 'comparative' design technique has been promoted beyond its reach - the data do not support the inference of an erosion 'threshold' as presented by Annandale (1995). It is argued that this type of analysis should be used only as an initial 'first indication of erosion potential', as originally proposed by van Schalkwyk (1994b).

***Keywords: scour; erosion; spillways*.**

INTRODUCTION

Many spillways for large embankment dams are designed and constructed with a concrete ogee crest, or gated structure with a section of lined chute downstream. These discharge into an unlined rock channel or into the river bed either directly, through a flip bucket, or other energy dissipator. Plunging flows from concrete arch or gravity structures may similarly discharge onto a rock channel, plunge pool or concrete-lined section. Generally the unlined channel is sited in rock which is judged to be resistant to erosion at least for high frequency floods. Often it is accepted that under larger low frequency floods there will be some erosion, but this will be limited and will not endanger the dam.

Currently, to assess the risk of erosion, industry relies largely on a 'scour threshold' that is said to exist as a function of the hydraulic stream power dissipation, and a rock-mass index developed for excavability (eg Annandale, 1995). This scour threshold has been determined based on interpreted erosion from various case studies.

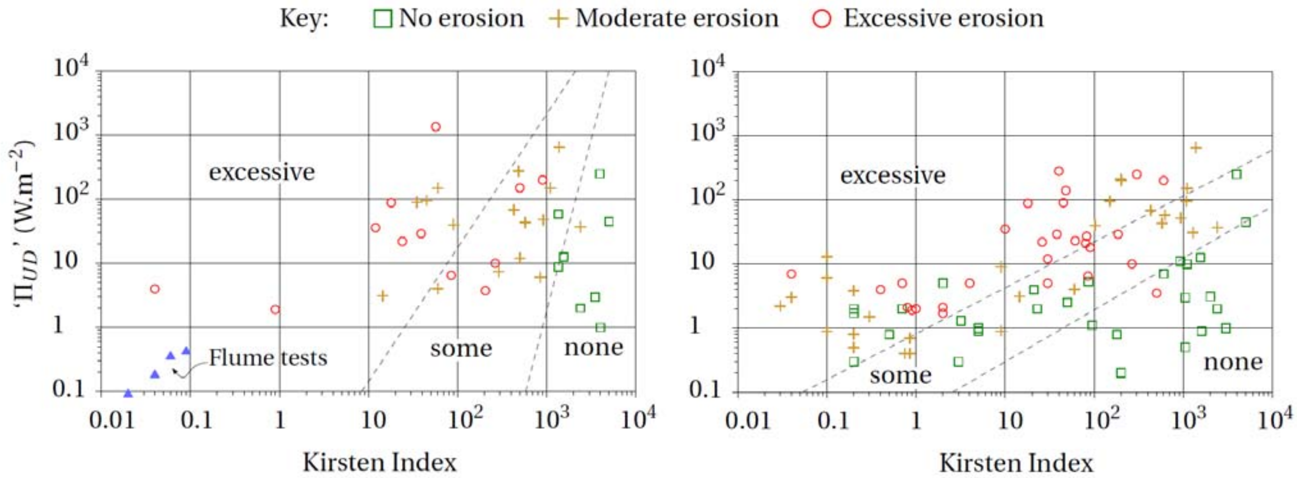
A study project has been undertaken to develop improved methods for assessment of the risk or spillway erosion. As a first phase of investigation, the existing 'scour threshold' proposed by Annandale (1995) was critically reviewed against the original geotechnical and hydraulic data. Detailed geotechnical and hydraulic data from additional dams in Australia, South Africa and the USA, were further used to appraise this type of design methodology and, ultimately, develop an improved design method.

BACKGROUND TO THE EXISTING 'SCOUR THRESHOLD'

Research at the University of Pretoria in the late 1980's reviewed case studies of erosion at the spillways of over 30 dams in South Africa (Pitsiou, 1990, and Dooge, 1993, *in Afrikaans*). The findings from 18 selected dams were compiled and presented in detail in van Schalkwyk *et al* (1994a, *in Afrikaans*) and van Schalkwyk *et al* (1994b). At each site, 'erosion points' were identified, and the geological and hydraulic conditions at these points were characterised. Prof. van Schalkwyk (*pers comm.*, 2014) indicated that numerous rock-mass indices were trialled, producing similar results, but a slightly preferable fit was found with the Kirsten Index. The Kirsten Index is a rock-mass index developed by Kirsten (1982) to assess the excavability (`rippability') of rock. The Kirsten Index was selected because its units, he argued, could be expressed as $kN.m^{-2}$, which, when plotted against stream power dissipation ($kW.m^{-2}$) inferred a unit of length vs time (van Schalkwyk 1994a, pg. 89), which he considered to offer a comforting denouement. Various hydraulic indices (ie velocity or average bed shear stress) were also trialled, but the Unit Stream Power Dissipation Π_{UD} was selected as the preferred indicator, based on: goodness of correlation; the work of Rooseboom and Mulke (1982), and; discussions with Kirsten and Moore (discussed below). The observed erosion was qualitatively defined (the ICOLD publication used three categories of "none", "some" and "excessive") and the results were plotted, as reproduced in Figure 1a.

Dr H. Kirsten, the author of the Kirsten Index, described the conceptual similarity between rock rippability and erodibility at a conference in the late 1980's (Moore, 1991; USSD, 2006). This led to collaboration with Dr Moore, who had compiled cases studies of spillway erosion from the U.S Department of Agriculture (USDA), primarily in soils and soft rock. Moore *et al* (1994) presented a line demarcating an erosion 'threshold' for these cases studies, using the Kirsten Index to represent the geology and a truncated form of stream power dissipation ('qH') to represent the hydraulic loading.

Van Schalkwyk (1994) presented updated findings that included the data compiled by Moore (Figure 1b). The perceived line of scour threshold was changed considerably, principally from inclusion of the new data. Original flume testing data (Dooge, 1993) were removed, citing scale effects and limitations in the Kirsten Index.



(a) Original dataset as presented in van Schalkwyk et al. (1994b)

(b) After inclusion of data from Moore et al. (1994) (van Schalkwyk, 1994)

Figure 1 – Observed erosion, unit stream power dissipation versus Kirsten Index, van Schalkwyk et at 1994b (left) and van Schalkwyk 1994 (right)

Annandale (1995) combined the datasets used by Moore (1991) and van Schalkwyk et al (1994a) with data from Bartlett Dam, Arizona, and "published data on incipient motion of non-cohesive earth materials" (Annandale, 2005, pg 221), presenting data on a plot of 'Π_{UD}' versus Kirsten Index, and finding an alternative curve to demarcate between eroding and non-eroding conditions.

Kirsten *et al* (2000), presented a plot of case studies of erosion from the USDA database, and using South African dams presented in Dooge (1993). Again, case data were plotted as Π_{UD} versus Kirsten Index, and a threshold of erosion was interpreted.

The lines demarcating the onset of scour based on 'Π_{UD}' versus Kirsten Index from the above cited authors are summarised in Figure 2. In each case, these plots were used to present a design technique – the risk of erosion at a particular site could be assessed by calculation of the 'Π_{UD}' and Kirsten index, and comparison to these thresholds.

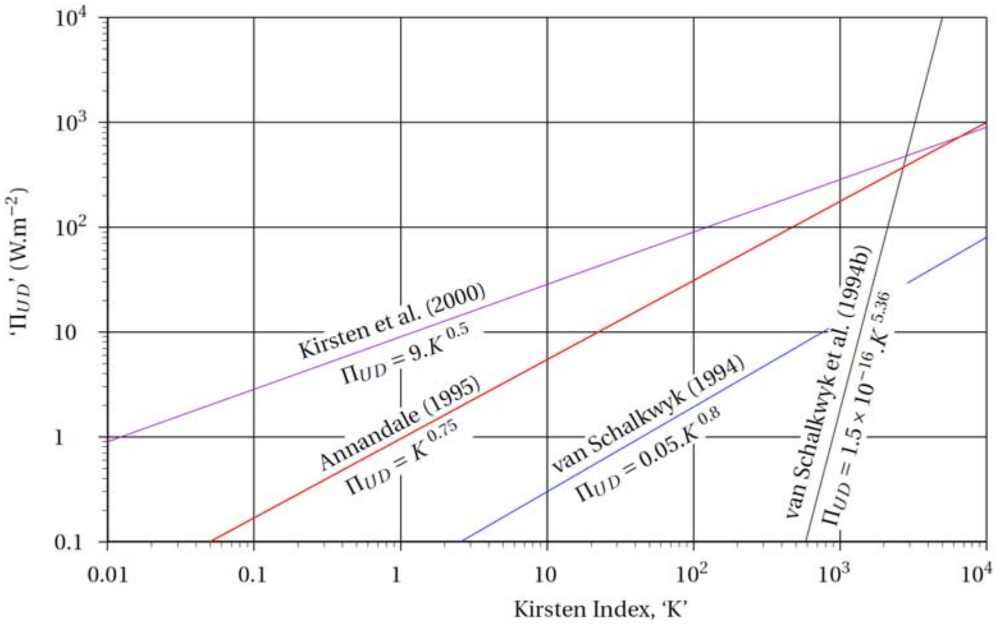


Figure 2 – Scour thresholds, various authors

QUESTIONS ON THE 'SCOUR THRESHOLD'

The question was asked: why were such diverse scour thresholds interpreted, when each were based on primarily the same data set? Comparison of the data points from van Schalkwyk (1994a) and Annandale (1995) shows that there are no common data points – there has been reinterpretation of Π_{UD}, the Kirsten Index and the degree of erosion. Subject to this re-interpretation, the data presented by Annandale (1995) and Kirsten (2000) cluster faithfully around an interpreted threshold, while the data presented by van Schalkwyk (1994a) show considerable scatter. The basis for re-interpretation of rock mass indices and the amount of erosion is unknown.

It is surmised that independent hydraulic calculations were undertaken by authors. Hydraulic calculations presented in van Schalkwyk et al (1994b) show that, for bed-parallel flows, stream power dissipation estimates were undertaken by assuming uniform flow conditions (i.e. $\Pi_{UD} = \rho\ g\ q\ S_f$ where $S_f = S_o$). For plunging flow conditions, van Schalkwyk et al (1994b) assumed that $S_f = 3$. The basis for this assumption was not given. Hydraulic calculations were not presented in Annandale (1995) but more detailed *methods* for calculation of stream power dissipation were presented, with analytical solutions for: uniform flow; knick-points; hydraulic jumps, and; plunging conditions. These analytical solutions apply to idealised geometries, in practice, are seldom represented in case studies. Additionally, the analytical equations presented in Annandale (1995) had some errors: the *length* over which dissipation occurred was neglected (a length of unity was thus required for dimensional consistency), and an equation for energy loss in a back-roller under a plunging nappe predicted energy loss in excess of the available energy. The equations were rectified in Annandale (2005), but an adoption of a length of unity was defended as providing a conservative estimate. Analysis undertaken in Pells (2015) found this assumption to be unacceptable, with the length of dissipation being typically significantly larger (e.g. for hydraulic jumps, Henderson (1996) recommends a dissipation length of 6 times the downstream flow depth). Inasmuch as these equations were applied, the unit stream power dissipation estimates supporting the erosion threshold of Annandale (1995) were likely to be significantly overestimated.

FIELD TRIP TO SOUTH AFRICA

In light of the above questions, a study program was undertaken in South Africa by the writer to undertake independent field assessments of selected dams in South Africa, the data from which, forms the backbone to the comparative design method presented by van Schalkwyk *et al* (1994a) as well as the data for fractured rock environments, in Annandale (1995). An inspection of South African spillways independently characterised the observed erosion; geology and rock mass indices, and; analysis of historical floods and hydraulic loading at 10 of the spillways reported by van Schalkwyk et al (1994a). In most cases, care was taken to also review the same locations of erosion reported in van Schalkwyk et al (1994a) and provide an independent assessment of erosion, geology and hydraulics at that same location. The resulting data is summarised in Table 1, and shown in Figure 3.

It is evident that significant scatter is observed in the characterisation of the same points on spillways. Further investigation (presented below) found that this does not discredit the work of Pitsiou (1990), Dooge (1993) and van Schalkwyk et al (1994a) but rather highlights the variability that should be expected from analysis of this nature. Estimates made at locations in two Australian spillways included in Figure 3 show a similar degree of discrepancy between independent sources.

SUBJECTIVITY IN THE INTERPRETATION OF ROCK MASS AND HYDRAULIC INDICES

A separate study was undertaken in which a group of 13 independent, experienced engineering geologists where requested to undertake mapping and interpretation on three selected rock exposures (Pells et al 2015). The participants were required to independently, and anonymously, undertake observations, and whatever mapping considered appropriate in order to classify each of the exposures according to the Q-system (Barton et al 1974), a widely used rock-mass index that the Kirsten Index is closely based upon (other rock-mass indices were also interpreted, but these are not discussed in this paper). The results relevant to the Q-system are presented in Figure 4.

As seen in Figure 4 there is significant variability in the sub-indices to the Q-system (which are common to the Kirsten index), which culminate in a wide range of assessed final values.

The methodology used during the present study at dam sites applied a combination of analytical hand calculations and 1-D numerical modelling (HEC-RAS, USACE, 2010). The numerical modelling provided a more detailed analysis of the slope of the total energy line S_f in the context of changing channel width, slope and roughness. In most cases, the numerical model was considered to provide a more accurate estimate than simply assuming $S_f = S_o$ (ie uniform flow). The numerical model also reported the total energy upstream and downstream of prominent features such as drops and hydraulic jumps, from which a more confident assessment of energy slope over the feature could be made. Numerical model sensitivity testing showed that, where reasonably accurate ground survey data was available, the numerical modelling techniques provided estimates of unit stream power dissipation remained within the range of +/-30%. In the few cases where the eroded spillway geometry was constant for a sufficient length, analytical solutions (by assuming an energy slope and flow width) produced similar estimates to the numerical model. However, for more complex channel geometries, the flow width may be difficult to assess analytically, and the energy slope is subject to tailwater conditions, requiring a more detailed backwater analysis. Hence, analytical estimates of unit stream power dissipation at the erosion locations ranged by up to +/- 300%.

The results of this study highlight the variability that must be anticipated for data of this nature.

Identical techniques were applied to the erosion, geology and hydraulics at over 18 dams in Australia and 2 in the USA, gaining over 100 data points of erosion in fractured rock environments.

The error bars that are appropriate to such a data set, where erosion is plotted as a function of the unit stream power dissipation and Kirsten index, are visualised in Figure 5.

Table 1 – Comparison of erosion, rock mass index and hydraulic index, van Schalkwyk et al (1994a) and Pells (2015)

Dam	Erosion Point	Van Schalkwyk et al (1994a)				Pells (2015)			
		Erosion	Peak Q (c.1992) $m^3.s^{-1}$	Peak Π_{UD} $kW.m^2$	K	Erosion	Peak Q (c.1992) $m^3.s^{-1}$	Peak Π_{UD} $kW.m^2$	K
Applethwaite	1-E1	Moderate	889	54	647	Minor	250	15	206
Floriskraal	5-E1	Moderate	907	36	2289	Minor	720	12	-
Floriskraal	5-E2	Large	1913	263	322	Moderate	2200	120	100
Goedertrou	7-E1	Minor	590	11	285	Minor	750	90	2934
Goedertrou	7-E2	Large	590	21	28	Moderate	750	90	26
Goedertrou	7-E4	Large	590	26	60	Moderate	750	22	26
Mokolo	8-E1	Negligible	82.3	1	2713	Negligible	63	1.0	5385
Mokolo	8-E2	Large	82.3	34	183	Moderate	63	23	29
Mokolo	8-E3	Large	82.3	17	57	Moderate	63	7	29
Mokolo	8-E4	Negligible	82.3	6	564	Negligible	63	1.3	5385
Mokolo	8-E5	Large	82.3	14	0.1	Moderate	63	4	0.7
Hartbeespoort	9-E1	Moderate	1048	67	394	Moderate	1000	50	36
Kammanassie	10-E1	Minor	2471	82	142	Minor	1310	5	369
Kammanassie	10-E2	Negligible	2471	13	1538	Negligible	1310	27	6024
Kammanassie	10-E3	Large	2471	82	19	Large	1310	49	61
Klipfontein	12-E1	Negligible	735	3	2052	Negligible	756	1.2	11002
Klipfontein	12-E2	Moderate	735	41	103	Minor	756	6	6
Klipfontein	12-E3	Large	735	33	10	Moderate	756	11	6
Klipfontein	12-E4	Negligible	735	2	2195	Minor	756	7	11002
Garden Route	17-E1	Moderate	54.2	21	76	Moderate	44	15	3

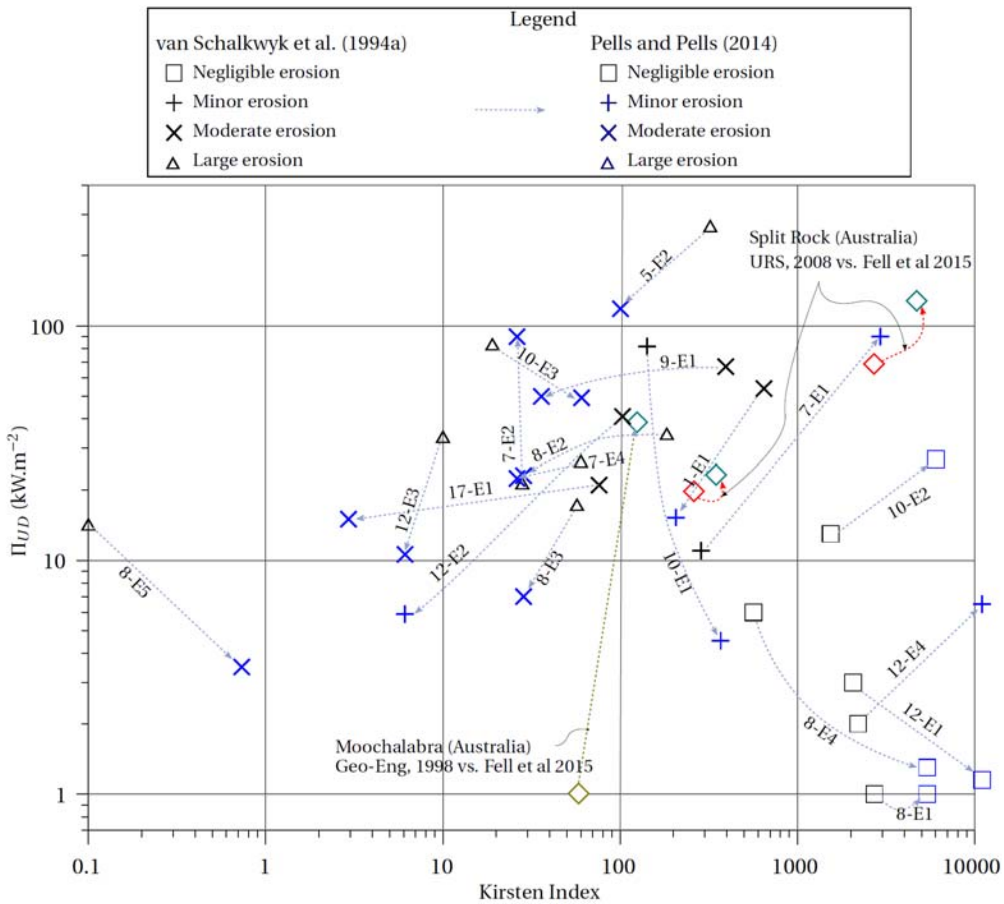


Figure 3 – Comparison of interpreted indices, van Schalkwyk et al (1994a) and Pells (2015) at erosion points of South African dams. Indices for two Australian dams by independent investigators are also shown

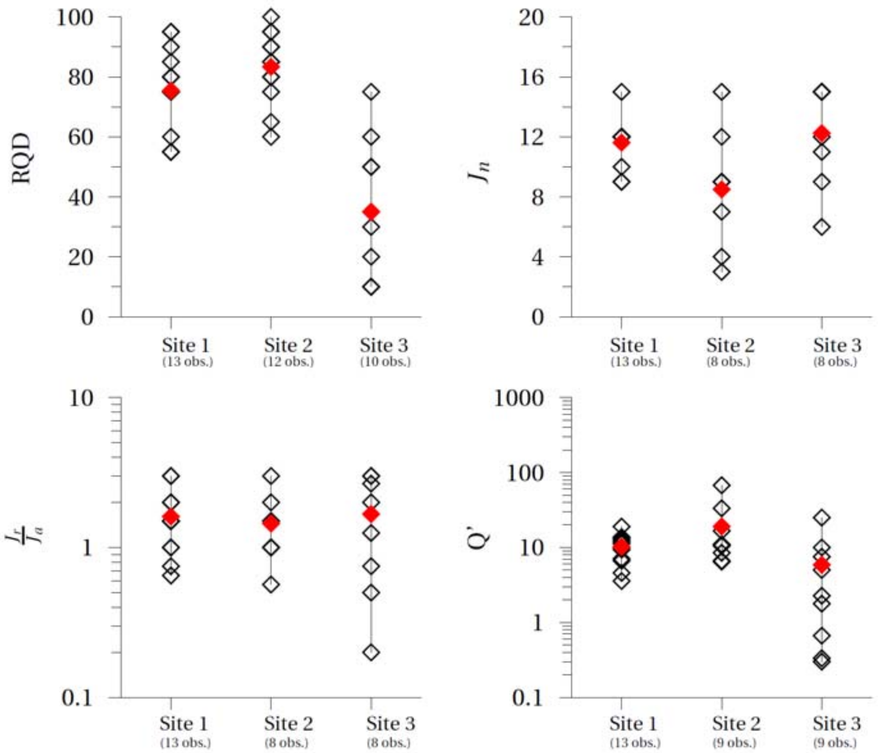


Figure 4 – Comparison of interpreted components of the Q-system by independent experienced engineering geologists at test sites, as presented in Pells et al (2015). (Average valued are highlighted in red)

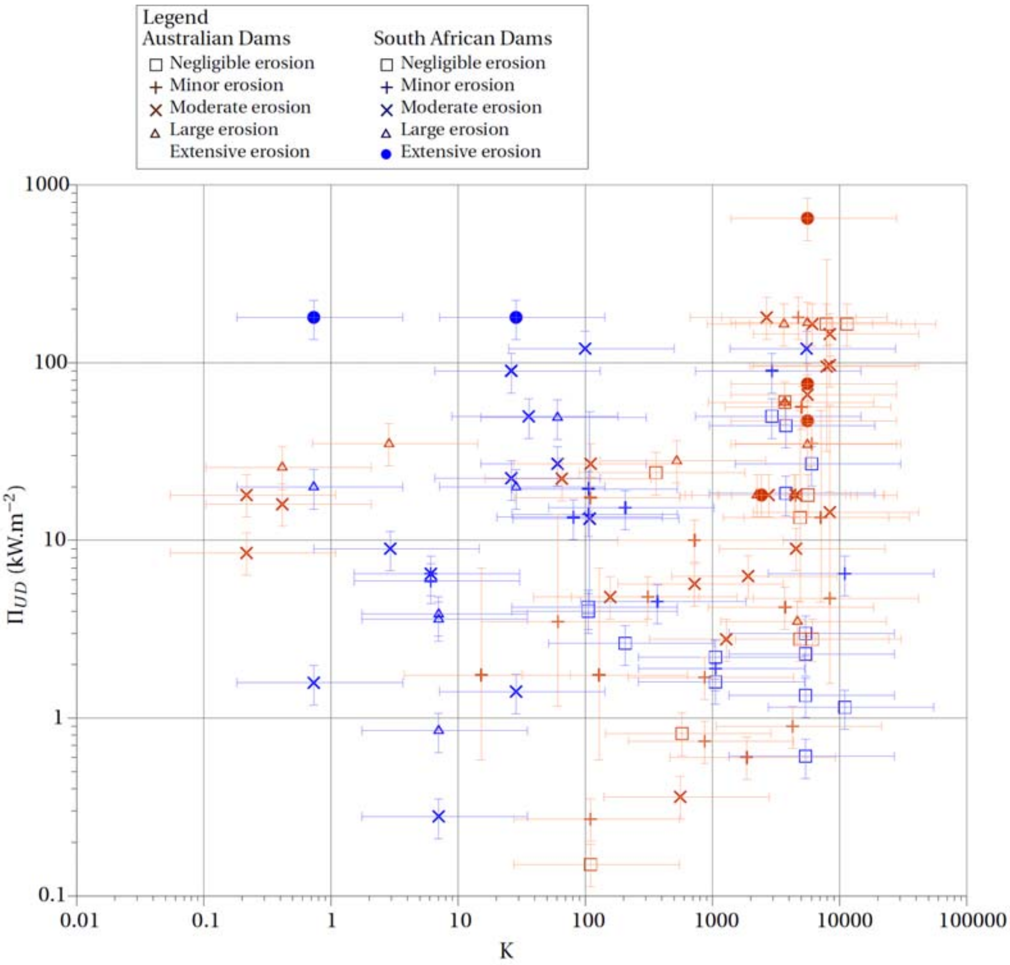


Figure 5 – Postulated error bars

EROSION, POWER DISSIPATION AND KIRSTEN INDEX – AN INDEPENDENT ANALYSIS

Using this entire data set, and with erosion at each site interpreted according to Table 2, the interpreted unit stream power dissipation, Kirsten index and erosion extent are plotted in Figure 6 and have been contoured (as erosion classes) using a digital contouring algorithm, (hence disallowing subjective interpretation of an erosion threshold). Also superimposed on Figure 6 are the erosion thresholds from various authors.

Table 2

Max. erosion depth *m*	General erosion extent *m^3 per100m^2*	Erosion 'class'	Erosion descriptor
<0.3	<10	I	Negligible
0.3 to 1	10 to 30	II	Minor
1 to 2	30 to 100	III	Moderate
2 to 7	100 to 350	IV	Large
>7	>350	V	Extensive

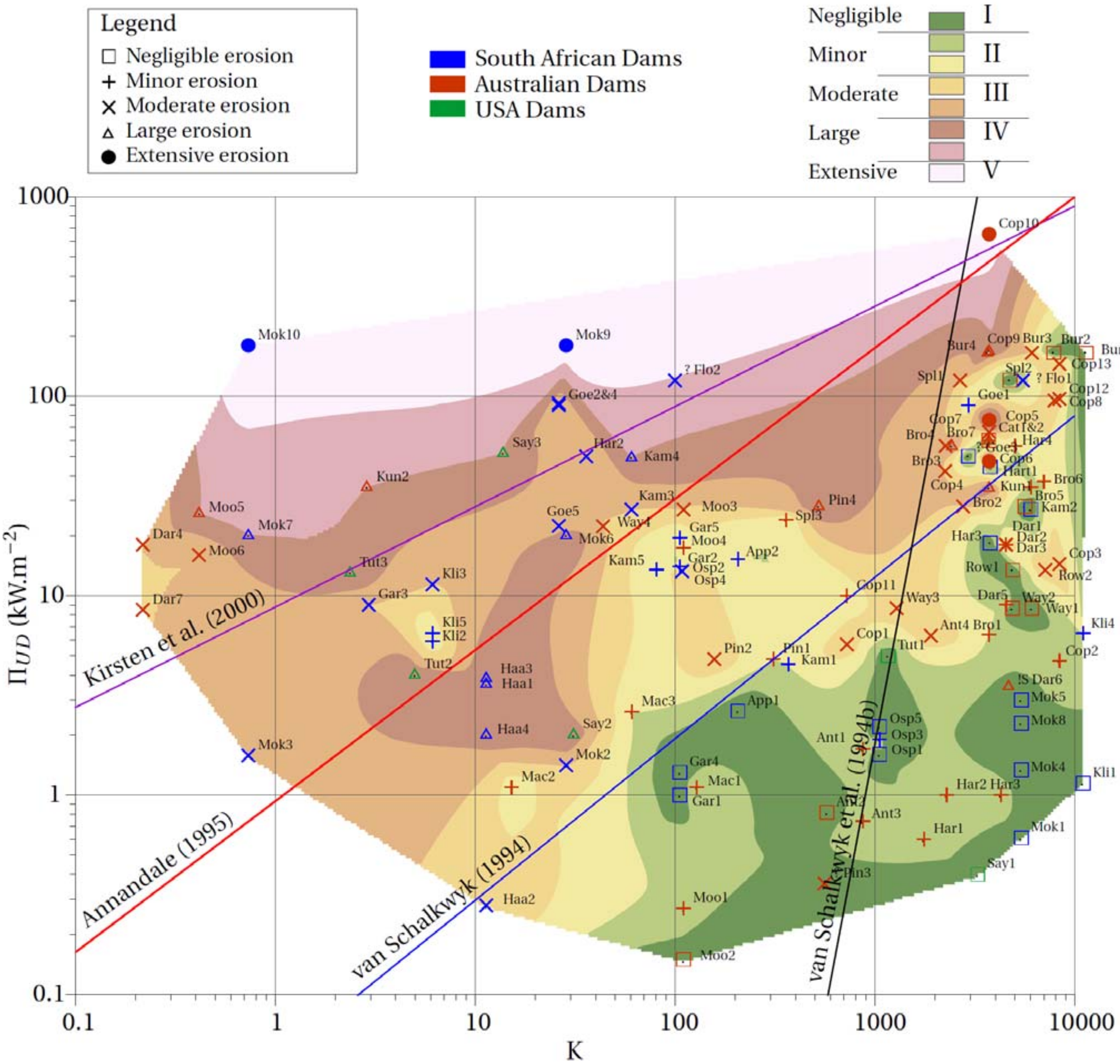


Figure 6 - Contours of erosion class - unit stream power dissipation vs Kirsten index, showing existing scour threshold interpretations

SUMMARY OF FINDINGS

The field data presented in Figure 6 supports the notion that erosion can be correlated with hydraulic loading (as represented by the unit stream power dissipation) and ground quality (as represented by the Kirsten index).

The observed erosion case study data overlay within the range of `erosion thresholds' presented by Annandale (1995) and Kirsten et al (2000). However, the data does not favour either of these thresholds, but rather shows a gradation.

Such a binary `threshold' was also not physically observed at any of the study sites.

The evidence presented above suggests that a high degree of scatter will occur when employing these indices, even where the interpretations are made by experienced and qualified practitioners. Scattered data is also expected to arise from the highly heterogeneous environment that is being characterised. There was a wide range of rock shape geometries and erosion mechanisms observed. It is postulated that the Kirsten index does not represent all of the complexities of the ground conditions. It is similarly postulated that the unit stream power dissipation does not reflect all of the complexities of hydraulic loading.

In view of this uncertainty, it is both physically and statistically unlikely that a binary scour threshold will arise from the data. The integrity of the data presented in Annandale (1995) in which cases of `scour' and `no scour' are clearly divided around a threshold is therefore questioned. Despite the uncertainty, Annandale (1995) expresses confidence that the relationship of stream power dissipation versus Kirsten index "demonstrates a correlation from which a critical threshold to initiate erosion of a material can be predicted for any given set of hydraulic conditions" (pg 471), and in Annandale *et al* (2000) recommends that the threshold line can be used to progressively model erosion depth –a technique which is understood to be commonly practiced within the dam safety community.

With respect to the uncertainty in the data, and in the known limitations of rock-mass indices in representing geology, the author disagrees with the interpretation and recommendations of Annandale (1995) and (2000).

The interpretation given by van Schalkwyk et al (1994a) allowed for `regions' of erosion extent, rather than a threshold. In Figure 7, the interpretation of van Schalkwyk et al (1994a) is presented, overlaying the data obtained from this dissertation. The regions presented by van Schalkwyk et al (1994a) are compatible with the (completely independent) dataset developed by the writer, although even these regions do not fully communicate the range of observations.

The writer concurs with the following qualifications provided by van Schalkwyk *et al*:

> "it must be pointed out that the evaluation chart was based on the observed behaviour of soil and rock formations at a number of dams in the USA and South Africa and it should be realised that the chart may not in all cases be able to accurately predict the behaviour of different material types under various flow conditions." (van Schalkwyk, 1994, pg699)
>
> "this method ... may not be representative of all geometrical, geomechanical and hydraulic situations ... it may be used as a first indication of erosion potential for rock in unlined spillways." (van Schalkwyk 1994b, pg 566)

Such design methods do not model the process of erosion. Rather, they offer the designer with a quick method to assess risk of erosion by comparison to documented case studies, where the comparison of geology is made using a rock-mass index, and hydraulics using a single hydraulic index. Neither of these indices provide a complete description of the problem, but are comparative tools only.

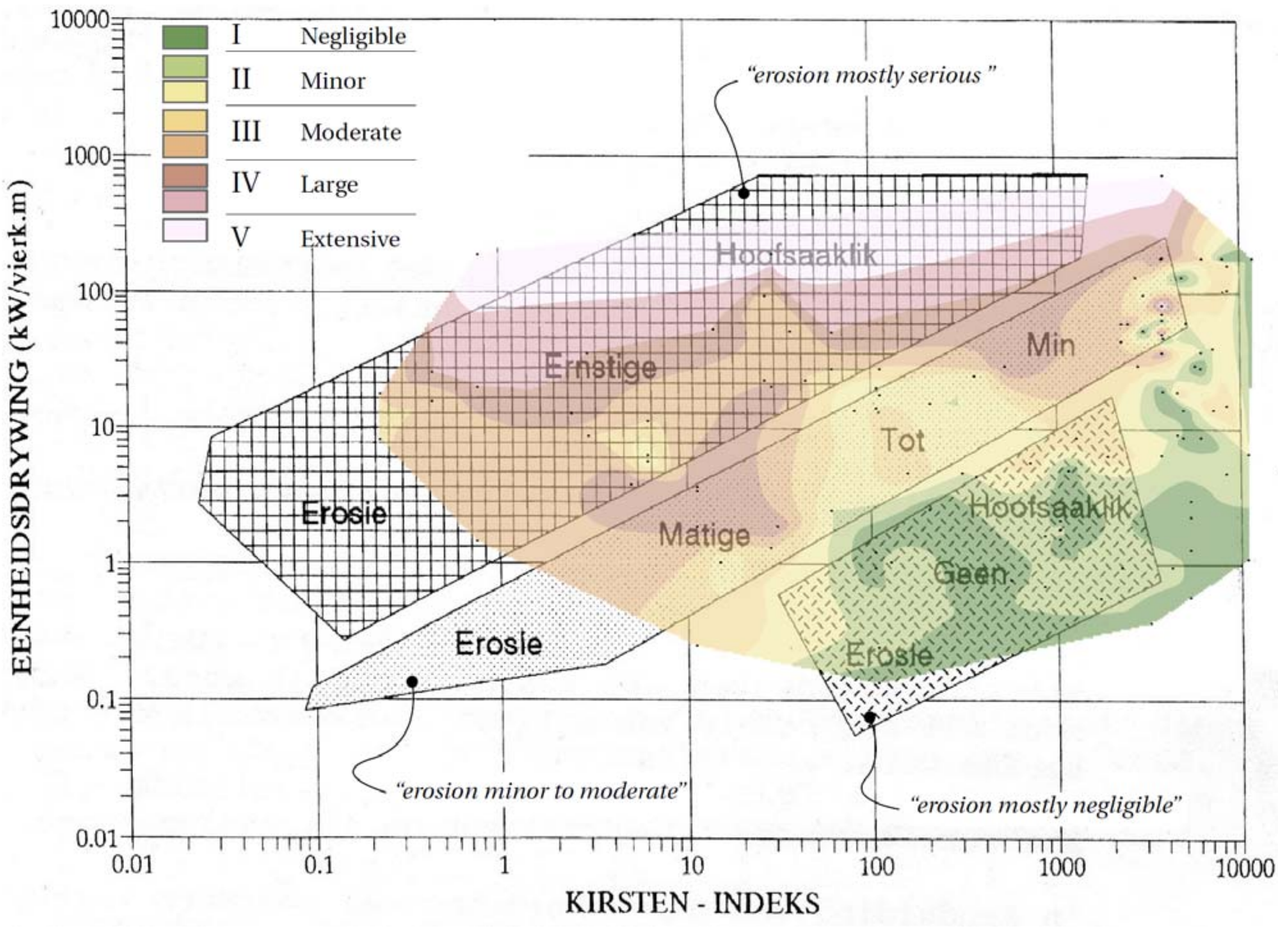


Figure 7 - Contours of erosion class - unit stream power dissipation vs Kirsten index, showing original interpretation by van Schalkwyk et al (1994a)

FURTHER WORK

The investigations presented above demonstrate the efficacy and limitations in the usage of the Kirsten index and unit stream power dissipation to characterise erosion. Further questions are warranted. For example, to what extent is the

Kirsten index representative of erodibility, given that it was not developed for that purpose. Furthermore, do any of the more commonly adopted rock-mass indices (such as the Q-system, RMR or GSI) provide a better or at-least equal representation of erodibility? Can a rock-mass index, developed specifically for representation of erodibility offer a better correlation? Are there preferable indices for representation of hydraulic loading? Given the limitations of a 'comparative design technique', are there more detailed analytical or kinematic models of erosion of fractured rock available?

These questions have been addressed in (Pells 2015), presently being disseminated in various journals.

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