Using climate to relate water-discharge and area in modern and ancient catchments

Christian Haug Eide*[1], Reidar Müller[2] and William Helland-Hansen[1]

[1]Department of Earth Science, University of Bergen, Norway

[2]Department of Geosciences, University of Oslo, Norway

*Correspondence: christian.eide@uib.no

Running head: Relating water-discharge and catchment area

Submitted to: *Sedimentology, revision 2, September 22nd, 2017*

Number of figures: 5

Number of tables: 3

Number of references: 52

Number of words: 5721 (4244 excluding references)

Supplementary material: A1, Cross-plots and regression lines used to determine values for *k* and *m* by runoff class; A2, Spreadsheet containing the database used for calculations and plots.

Abstract

Models relating sediment supply to catchment properties are important in order to use the geological record to deduce landscape evolution and interplay between tectonics and climate. Water-discharge (Q_w) is an important factor in the widely used BQART-model, which relates sediment load to a set of measureable catchment parameters. Although many of the factors in this equation may be independently estimated with some degree of certainty in ancient systems, water-discharge (Q_w) certainly cannot. An analysis of a world database of modern catchments with 1255 relevant entries shows that the commonly applied equation relating catchment area (A) to water-discharge ($Q_w=0.075A^{0.8}$), does not predict water-discharge from catchment area well in many cases ($R^2=0.5$ and an error spanning c. 3 orders-of-magnitude). This is because the method does not incorporate the effect of arid and wet climate on river water-discharge. The inclusion of climate-data into such estimations is an opportunity to refine these estimates, because generalized estimates of palaeoclimate can often be deduced on the basis of sedimentological data such as palaeosol types, mineralogy and palaeohydraulics.

This paper investigates how the relationship between catchment area and river discharge vary with four runoff categories (arid, semiarid, humid, and wet) which are recognizable in the geological record,

and modifies the coefficient and exponent of the abovementioned equation according to these classes. Our modified model yields improved results in relating discharge to catchment area (R^2=0.95 and error spanning 1 order-of-magnitude) when core-, outcrop- or regional palaeoclimate reconstruction data are available in non-arid systems. Arid systems have an inherently variable water-discharge, and catchment area is less important as a control due to downstream losses. The model here is sufficient for many geological applications and makes it possible to include variations in catchment humidity in mass-flux estimates in ancient settings.

1. Introduction

The extent and quality of geomorphological and subsurface datasets has increased greatly in recent decades, and has made it possible to attempt to reconstruct ancient sedimentary systems from source-to-sink (e.g. Sømme et al., 2009; Galloway et al., 2011; Allen et al., 2013; Michael et al., 2013; Hampson et al., 2014; Holbrook and Wanas, 2014; Bentley et al., 2015). The goals of such studies are to understand the coupling between sediment producing catchments (or *source* areas*)*, sediment-storing sedimentary basins (or *sinks)*, the sediment routing systems connecting these systems, and how these interact to record earth history (e.g. Hinderer, 2012; Helland-Hansen et al., 2016). Such studies may be undertaken in order to predict or estimate parameters of sedimentary transport-networks which are inaccessible to study due to erosion or burial (Martinsen et al., 2010), understand the propagation and fidelity of environmental signals through time (Paola et al., 1992; Romans et al., 2016), and characterise the evolution of past landscapes (e.g. Sømme et al., 2009; Bhattacharya et al., 2016; Eide et al., *in press*).

The BQART-approach, based on an empirical model relating sediment load in modern rivers to catchment parameters, was developed by Syvitski and Milliman (2007). This method has recently been applied to investigate ancient deposits (Weight et al., 2011, Sømme et al., 2013, Allen et al., 2013). The details are outlined below, but the model is on the form of an equation with the following parameters valid for ancient systems: sediment load, catchment area, catchment relief, catchment lithology, catchment temperature, degree of glacial cover, and water-discharge of the river. Depending on the available dataset and the questions asked, some of these parameters may be measured, estimated or modelled, while some parameters are kept as variables (e.g. Sømme et al., 2013; Allen et al., 2013; Eide et al., *in press*).

In the absence of good palaeohydraulic data, such as dimensions of trunk channels and bedforms within them (e.g. Bhattacharya and Tye 2004; Holbrook and Wanas, 2014), or extremely well-constrained modern analogues with well-chosen regional curves (Davidson and North, 2009), water discharge in ancient rivers is difficult to estimate well. In most studies using the BQART-approach in ancient systems, water-discharge is estimated using a power-law function relating river discharge (Q_w) and catchment area (A), which was proposed by Syvitski and Milliman 2007:

Eq. 1: $Q_w = kA^m$

where Q_w is water-discharge in m^3/s, A is catchment area in km^2, k is an empirical constant set to 0.075, and m is an empirical constant set to 0.8. However, some catchments are much drier than others (e.g. Fig 1; Beck et al., 2015), and this is not taken into account in this model. Therefore, using this model may lead to large, systematic errors in the estimation of water-discharge (up to 2.5 orders of magnitude, excluding outliers, c.f. Figs. 2A, 3).

Because generalized interpretations of large-scale climate can be made from simple geological observations (e.g. Retallack, 1997; Parrish, 1998; Hay, 2008), it should be possible to improve estimates of water-discharge of ancient catchments if geological data are available. In this paper, a global database of catchment properties of rivers discharging into the ocean (Milliman and Farnsworth, 2011) is used to improve the model for water-discharge from catchments. This model is presented as Eq. 1. It is shown that discharge may be predicted from catchment area (and *vice versa*) at an acceptable level of precision and accuracy by using *the method presented in this paper*: choosing appropriate values for *k* and *m* in *Eq. 1* by classifying studied deposits into four runoff classes (arid, semiarid, humid and wet). These classes can readily be estimated by geological palaeoclimatological indicators (e.g. palaeosol types, presence of climate-sensitive sedimentary environments such as evaporites and aeolian dunes) and published palaeogeographic reconstructions. This yields simple, reliable and well-constrained inputs to source-to-sink models.

Thus, the goals of this paper are threefold: (1) to present an improved model for estimating relationship between river discharge and catchment area for different climate types in modern environments, (2) to outline how these relationships may be employed in deep time stratigraphic successions where proxies for palaeoclimate can be retrieved, and (3) to investigate in which settings this model might be inappropriate.

2. Background

2.1 The BQART-model

In deep-time systems (>> 1 Ma), significant parts of sediment sinks are often preserved in sedimentary basins, but the sediment source areas are commonly eroded or extensively modified (e.g. Blum and Pecha, 2014; Eide et al., 2016; Eide et al., *in press*). Ancient catchment areas may be reconstructed to some degree using different thermochronological methods, such as detrital zircon and fission track data (e.g. Gallagher et al., 1998; Fedo et al., 2003; Lisker et al., 2009). However, these methods require significant skill, time, funds and material. Thus, a popular and well-established method used to investigate source-to-sink relationships in ancient systems is to apply the BQART-method developed by Syvitski and Milliman (2007) (e.g. Weight et al., 2011; Allen et al., 2013; Sømme et al., 2013). It is an empirical model, based on global regression of modern catchment data, and uses the following equation for catchments with average mean temperatures > 2°C:

Eq. 2: $$Q_s = \omega B Q_w^{0.31} A^{0.5} R T$$

where Q_s is sediment load (Mt/yr), ω is a constant of proportionality set to 0.0006, Q_w is long term water-discharge (km^3/yr), A is catchment area (km^2), R is maximum relief in the catchment (km), T is long-term average temperature in the catchment (°C) and B is a factor based on the glacial erosion factor (I), lithology (L), trapping efficiency of lakes and reservoirs (T_e), and human-influenced soil erosion (E_h), given by the following equation:

Eq. 3: $$B = IL(I-T_e)E_h$$

In non-glaciated, pre-human catchments, the factor B simplifies to lithology (L) only. Some inherent limitations to this model should be pointed out: it only includes suspended load (which is commonly taken to be > 90% of total load); and that it is based on time series in the order of 30 years, and thus

underestimates sediment transport related to rare, catastrophic events (Milliman and Farnsworth, 2011). Furthermore, although water-discharge is a weak variable in the Eq. 2 (i.e. it has the lowest exponent), it is also the most *variable* of the variables. For natural systems in the database (Milliman and Farnsworth, 2011), water-discharge varies across six orders-of-magnitude, versus 5 orders-of-magnitude for area, three orders-of-magnitude for relief, two for temperature and one for lithology. Thus, compared to the natural variability of the other factors, it the second-most important variable controlling sediment discharge.

2.2. Catchment relief, lithology and temperature

For ancient catchments, factors such as relief, bedrock type, catchment palaeotemperature and presence and extent of glaciers may often be approximated based on regional geological evidence, and from published global data. Relief (*R*) may be estimated through modern topographic analogues (systems draining uplifted rift shoulders, flat plains or large orogens; c.f. Parrish, 1998), fission track analysis, or preserved palaeosurfaces (e.g. Leturmy et al., 2003; Sømme et al., 2009). Bedrock type (*L*) may be estimated through provenance studies of detrital mineralogy and clast composition, and extrapolation of geological maps into now eroded areas. Catchment temperature (*T*) may be estimated from global palaeo-general circulation models (e.g. Sellwood and Valdes, 2006), isotope-based palaeotemperature-estimates (Sun et al., 2012), reconstructions based on plant communities and palynofloras (e.g. Paterson et al., 2016), and geological evidence such as palaeosol types (e.g. Wright, 1990; Mack and James, 1994; Kraus, 1999; Parrish, 1998; Retallack, 2001; Müller et al., 2004; Nystuen et al., 2014).

2.3. Catchment area

Catchment area (*A*) is in most cases hard to constrain accurately in ancient systems, due to erosional and tectonic modification. In systems with a marked topographic axis, such as in convergent and transpressive regimes, catchment area may be estimated using distance to the topographic axis and Hack's Law (Hack, 1957; Rigon et al., 1996). However, these are also the most short lived and unstable source-to-sink systems, and sediment transport networks are prone to change through time (Woodcock, 2004).

2.4. Water-discharge, climate and runoff

In uplifted, dissected and well-exposed systems, water-discharge (Q_w) may be estimated using palaeohydraulic methods based on exposed trunk river channel dimensions (Bhattacharya and Tye, 2004; Holbrook and Wanas, 2014). These methods may also be applied to subsurface datasets: attribute maps derived from 3D-seismic data may give full plan view control of parts of deposits of fluvial systems, and thickness of channels and bedforms can be measured in core. However, such comprehensive datasets are commonly not available. In cases where very well-constrained modern analogues have been determined, regional hydraulic geometry curves from comparable modern systems could be applied to derive catchment area and water-discharge (Davidson and North, 2009). However, there is generally significant uncertainty in defining suitable analogues for regional hydraulic geometry curves, especially in ancient times with varying global climates and equator-pole temperature gradients (c.f. Hay, 1998).

Syvitski and Milliman (2007) presented Eq. 1 as a simple method to estimate water-discharge from catchment area. However, this method is clearly inadequate to relate discharge and catchment area, because two equally large catchments in different climates will have very different water-discharge

(Fig. 1), owing to varying amounts of rainfall and evapotranspiration (e.g. Mu et al., 2007; Beck et al., 2015).

The *runoff* (ratio of annual river discharge to catchment area) of rivers varies with climate (Fig. 1). Runoff of rivers is commonly given in mm km^{-1} yr^{-1}, and is therefore easily compared with catchment-averaged rainfall. The *runoff efficiency* of a catchment is the ratio of runoff to catchment-averaged rainfall, and is commonly lower in drier catchments due to higher evapotranspiration and infiltration losses, and high in wetter catchments due to moister soil (e.g. McCabe and Wolock, 2016). Thus, runoff of rivers is strongly dependent upon climate, as more precipitation will lead to higher runoff due to increase in both the availability of water, and increase in runoff efficiency.

3. Dataset and methods

This study is based on analysis of the global database of catchment properties presented by Milliman and Farnsworth (2011), which collates a wealth of information from modern catchments debouching into the ocean, such as sediment supply, relief, climate, location, and most importantly for this study: catchment area and water-discharge. These systems are investigated using cross plots and power law regression (Figs. 2-4), and are further investigated using published data and publically available satellite imagery. The database (Milliman and Farnsworth, 2011) contains 1531 entries, and 1255 of these have information about catchment area and river discharge. Furthermore, 72 of these systems have information about pre-dam discharge. For these systems, the pre-dam discharge is used to provide values for runoff and discharge. It is worth noting that many of the rivers with pre-dam discharge-values are well-known rivers with extensive water management systems (e.g. Murray-Darling, Nile, Colorado), indicating that these are the catchments which have been changed most by human intervention. Although most other catchments will likely have some amount of damming or watercourse interventions, this cannot be accounted for using the utilized database.

The boundaries for runoff categories employed by Milliman and Farnsworth (2011) in their compilation, (arid 0-100; semiarid 100-250; humid 250-750; and wet >750 mm km^{-1} yr^{-1}) gave good results and are adopted in this study.

4. Results

4.1. Analysis of accuracy using fixed constants in Eq. 1

Figure 2A presents the actual catchment area for all catchments in the database, versus predicted catchment area using Eq. 1 and the fixed constants from Syvitski and Milliman (2007). This plot shows that using this method, catchment area is underestimated for arid systems, and overestimated for wet systems. Furthermore, this method leads to large variation in error (c. 2.5 orders of magnitude when outliers are excluded) of estimation of catchment areas for arid systems (Fig. 2A). Semiarid, humid and wet systems generally show little variation in error and generally constrain the input with some accuracy (within 30x).

Figure 3 presents the runoff of all systems in the database (Milliman and Farnsworh, 2011), plotted against the error of the catchment area estimation. Using fixed values for *k* and *m* in Eq. 1, error in the catchment area estimation is dependent on runoff alone. Using this method, catchment area is systematically and strongly underestimated in arid systems (median error: 0.06x), systematically

underestimated in semiarid systems (median error: 0.4x), correctly estimated for humid systems, and systematically overestimated for wet systems (median error: 4x).

4.2. Determination of coefficients in Eq. 1 for each runoff class

In order to obtain new constants for each of the four runoff classes, power-law regression was performed on cross plots of catchment area versus runoff for each of the four runoff classes (Appendix A1). Determined best-fit exponents and correlation coefficients (R^2) are presented in Table 1. Plots of actual versus estimated catchment area using the proposed model are presented in Fig. 4. These show a significant improvement compared to using fixed constants (c.f. Fig. 2A), but also large variations in arid systems. The previous and the proposed model are compared in Figures 2B and 2C, including and excluding arid systems, respectively. This shows that estimates of catchment area are significantly improved using the proposed method. However, catchment area estimation appears to be too variable to be useful in arid catchments.

5. Discussion

5.1. Recognition of runoff classes in ancient deposits

Defining the runoff class of ancient deposits makes estimations of river discharge and catchment area more accurate (Fig. 2B, Table 1). The key assumption in this work is that the runoff classes defined in this study would correspond to geologically observable factors. As the study of ancient climates is a science in itself, only a superficial overview can be presented here. For a comprehensive view, see important works by e.g. Hay (1998; 2008), Hay and Floegel (2012); Parrish (1998) and Driese et al. (2005).

There are several depositional features which are preserved in sedimentary systems (c.f. Fig. 5) and observable in the geological record (Table 2) that makes it possible to interpret whether deposition occurred under arid, semiarid, humid or wet conditions. These include particular palaeosol types (calcretes, oxisols, coals) and features (e.g. Mack and James, 1994; Bestland, 1997), aeolian dunes, plant communities (e.g. Paterson et al., 2016), soil color, mineralogy, fluvial architectures (Retallack, 2001; Nystuen et al., 2014), and isotopes (Cerling, 1984). However, care must be taken as climate in the basin can be different from that in the catchment area (Fig. 1; c.f. Nystuen et al., 2014). Furthermore, it must be pointed out that several of the features mentioned here are not controlled by runoff alone, but are also partly a function of temperature and evaporation. Models for estimating runoff in cold and polar systems are not well-developed, and the method presented here would likely not work well in such systems.

5.2. Comparison to method using fixed constants

Comparison between the method presented here (varying constants by climate class) versus the method using fixed constants in Eq. 1 is presented in Fig. 3. This figure shows that the method using fixed constants performed well for systems with runoff within the ranges 200-800 mm km^{-1} yr^{-1} (Fig. 3), a range which contains 43% of the catchments in the database. For the wet category, which contains 30% of the data, the proposed method is significantly better than using fixed constants (Fig. 3). Furthermore, this study shows that it is difficult to estimate runoff for arid systems, as annual discharge is not primarily controlled by catchment size in such systems. Still, the proposed method decreases the error of arid systems by two orders of magnitude. Finally, this study shows that water-discharge and

234 catchment area can be related with a high degree of confidence if the runoff class of the system can
235 be determined, with the exception of arid systems.

236 The results of sediment mass-flux calculations from ancient catchments, made using the BQART-
237 approach (Syvitski and Milliman, 2007), change significantly when runoff class of the studied system is
238 taken into accountThe difference for sediment load (Q_S in Eq. 2) calculated using water-discharge from
239 the two methods presented herein (fixed constants versus variable constants for each class) is greatest
240 for small, dry catchments and for large, wet catchments (Table 3).. For small (100 km^2) arid and
241 semiarid catchments, using varying constants in Eq. 1 yields a 69% and 40% decrease in sediment load,
242 respectively, compared to results using fixed constants. For large (10^6 km^2, 'continental' scale
243 catchments) humid and wet catchments, using variable constants for each climate class gives a 36%
244 and 73% increase in sediment load, respectively. Thus, this study shows that it is important for studies
245 using the BQART-approach in ancient systems to take runoff into account, not only catchment
246 temperatures.

247 5.3. Human influence and validity of methods

248 The majority of world catchments have some degree of human influence. In the database (Milliman
249 and Farnsworth, 2011), 72 of the 1255 catchments also have data about pre-dam discharge. 29% of
250 these are classified as arid based on runoff, 29% are semiarid, 31% are humid and 11% are wet. Post-
251 dam discharge decrease in 71 of the 72 catchments, and the reduction ranges from 11% (Tapti, India)
252 to 99% (Colorado, USA), and no correlation between the amount of decrease and runoff or catchment
253 area exists. This indicates that post-dam discharge reduction is mainly determined by water
254 management strategies and water demand, not natural properties inherent to catchments, making
255 this difficult to correct for in a global dataset.

256 It is worth noting that the catchments with pre-dam discharge-data in the database often represent
257 highly populated catchments with well-known and large water management projects, such as the Nile
258 (NE Africa), Orange (S Africa), Los Angeles (USA), Colorado (USA) and Huanghe (China) (c.f. Fig. 1). It
259 may therefore be speculated that discharge from catchments without pre-dam discharge data is
260 generally less affected by human intervention than catchments with pre-discharge data. Thus, it is
261 estimated that the coefficients presented here, which are conditioned to post-dam catchment
262 discharge, might underestimate final discharge to some degree. However, further research would be
263 needed to constrain this amount.

264 5.4. Large discharge variations in arid systems

265 This study illustrates that discharge from arid catchments is not controlled to a great degree by
266 catchment area. This is not surprising, as rivers in arid catchments show flashy discharge and have
267 significant downstream discharge losses. Because of this, discharge during one flood event may be
268 greater than the discharge of several years combined (e.g. Tooth, 2000; Milliman and Farnsworth,
269 2011). Thus, discharge of rivers in arid catchments is more dependent upon the amount and location
270 of rainfall during one single flood, and the degree and extent of wetting prior to the flood, than the
271 size of the catchment itself. Large arid catchments have the potential to loose significant amounts of
272 water through infiltration and evaporation, and this is particularly likely for parts of the catchment
273 located far from the river mouth. This leads to low predictability of discharge in arid systems for a
274 method which uses catchment area as input.

6. Conclusions

When reconstructing ancient source-to-sink systems, estimates of water-discharge (Q_w) and catchment area (A) are crucial in order to apply mass-balance models. Here, it is demonstrated that the previous method ($Q_w=0.075A^{0.8}$) works reasonably well in semiarid and humid settings, but that it yields a significant overestimation of catchment area in wet systems, and a significant underestimation of catchment area in arid systems. Because catchment climate can be readily defined from geological evidence, a new method with different exponent and coefficient for each runoff class is presented. This study shows that it is possible to achieve improved correspondence between measured and predicted values (R^2-values of 0.95) in non-arid modern systems. However, arid systems show too high variability to be reliably predicted in this way, because of the large temporal variation in rainfall and high downstream losses discharge for arid systems. This has important implications for studies which employ the BQART-method in ancient systems, because climatic changes may strongly influence sediment flux from catchments.

7. Acknowledgements

We acknowledge reviewers John Holbrook and Vernon Manville for useful comments and suggestions which greatly improved this manuscript. This work has been funded by the Trias North project under grant 234152 from the Research Council of Norway and with financial support from Tullow Oil Norge, Lundin Norway, Statoil Petroleum, Edison Norge and Dea Norge. The authors would also like to thank all scientists in general, and J.P.M. Milliman and K.L. Farnsworth in particular, who make full datasets available to the public for the advancement of science.

8. Captions

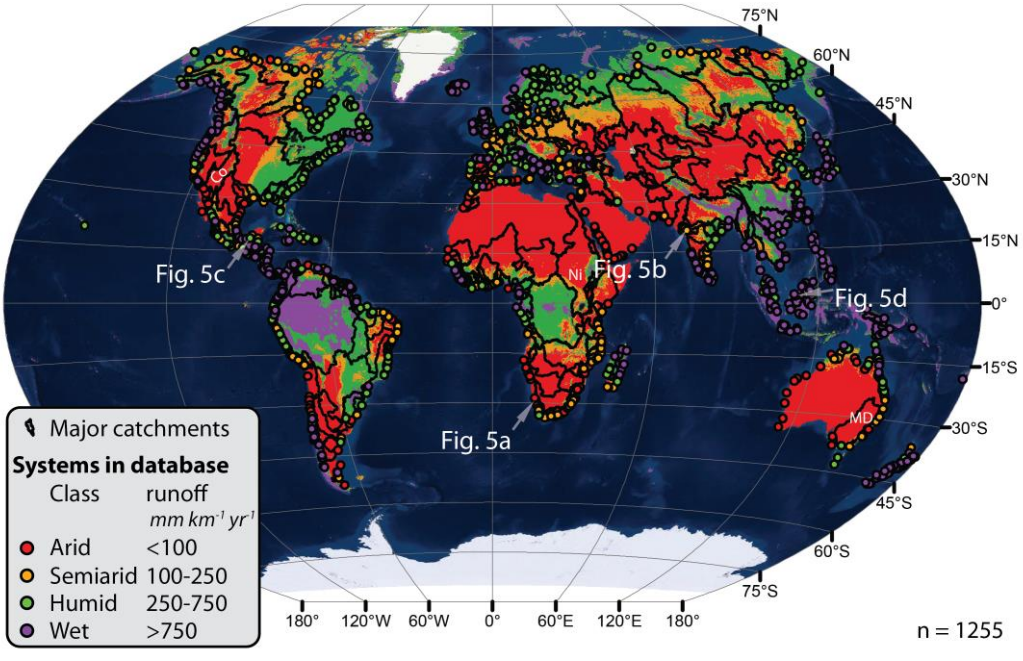


Fig. 1: World map showing present-day global runoff (Beck et al., 2013; 2015), locations of river outlets from catchments in the database of modern systems (Milliman and Farnsworth, 2011), and major world catchments.

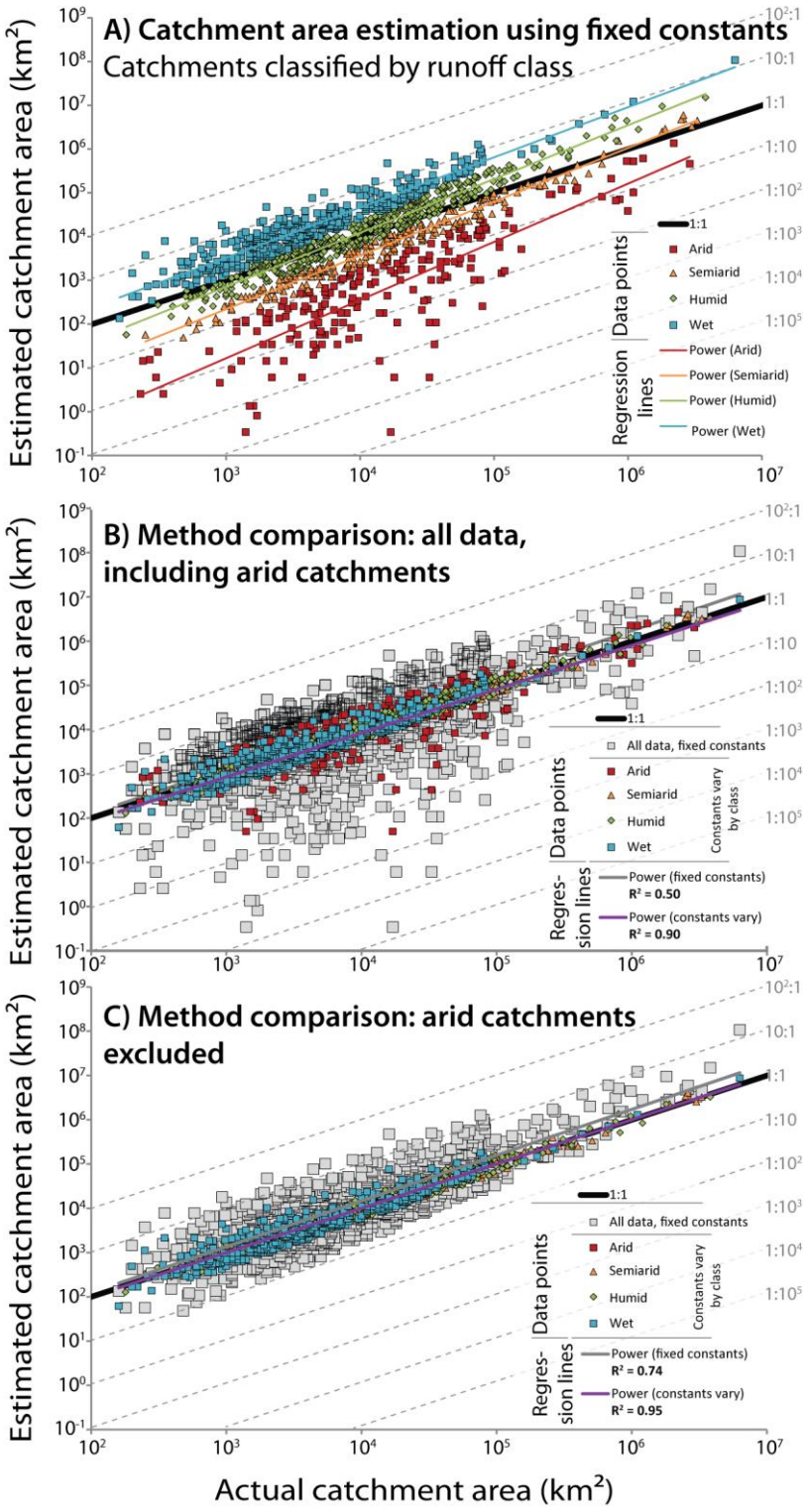
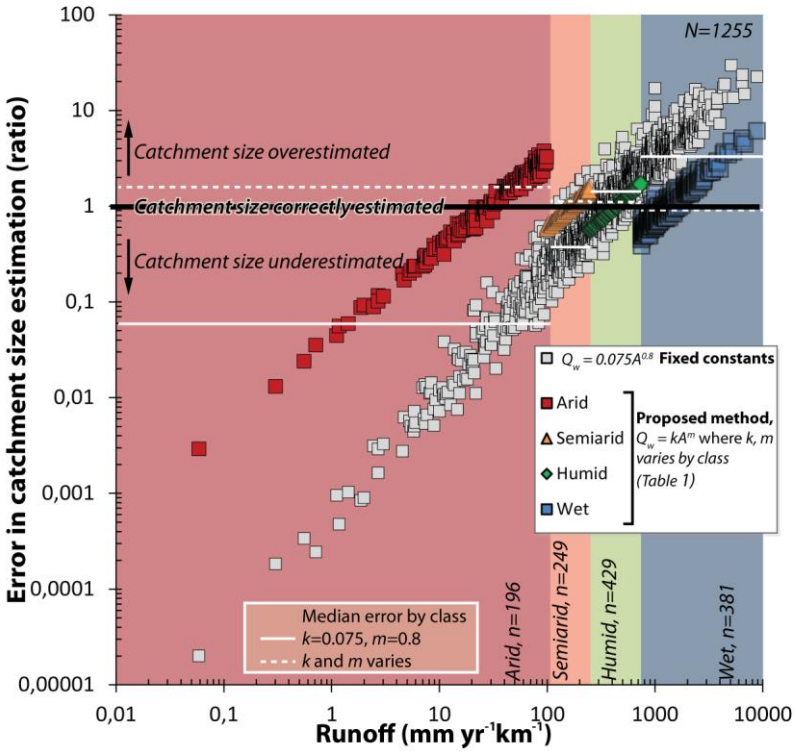


Fig. 2: Cross plots showing relationship between actual and estimated catchment area using different constants *k* and *m* (Table 1). Data points are from the catchment database of Milliman and Farnsworth (2011), N=1255. A) Cross plot showing estimates of catchment area of modern catchments using fixed values for *k* and *m* (*k*=0.075 and *m*=0.8) across different runoff classes. Note the systematic underestimation and large spread of errors in estimation of arid catchment area, and the systematic overestimation of wet catchment area. B) Comparison of results using fixed *k* and *m*, versus varying *k* and *m* based on runoff class, as proposed herein. C) Comparison of results using fixed *k* and *m*, versus varying *k* and *m* based on runoff, for all data excluding arid systems (i.e. plot is as (A) without arid systems).



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311 Fig. 3: Runoff and error in catchment area estimation using fixed versus variable constants in Eq. 1 for 1255
312 modern catchments (from Milliman and Farnsworth, 2011). An error value of 1 indicates no error in the
313 catchment estimation, and error values of 0.1 and 10 indicate ten times under- and overestimation of catchment
314 area, respectively. Note the large errors associated with wet and arid systems using fixed constants (grey
315 squares), and how this improves significantly using the method proposed in this contribution (coloured symbols
316 for each class).

317

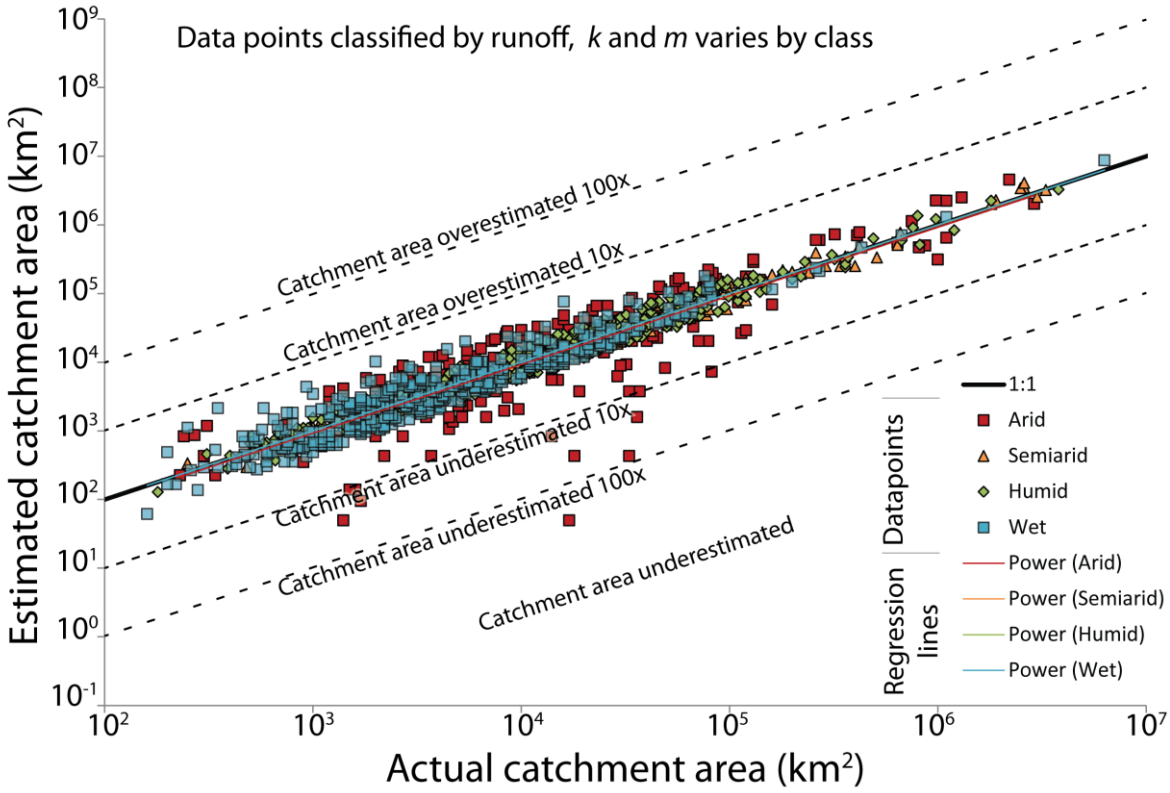

Fig. 4: Cross plots showing actual catchment area versus catchment area estimated from water-discharge in modern catchments, using Eq. 1 and different values of constants *k* and *m* for each runoff class (Table 1). Note the improved fit between actual and estimated area compared to Fig. 2A, and note that errors are still large for arid systems. See Table 1 for correlation coefficients. Data points are from the catchment database of Milliman and Farnsworth (2011), N=1255.

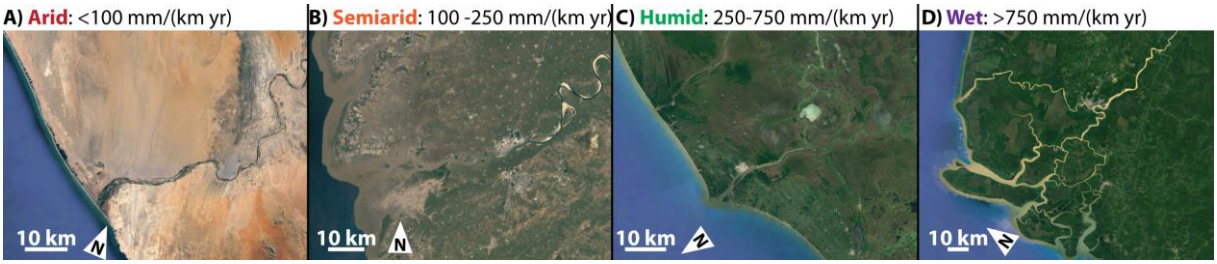

Fig 5: Satellite images of sedimentary systems in the four runoff categories, showing the clearly different landscapes that would be expressed as detectable geological indicators. For locations, see Fig. 1. A) Orange River, Namibia. Runoff = 4.5 mm km^{-1} yr^{-1}. B) Narmada River, India. Runoff = 230 mm km^{-1} yr^{-1}. C) Grijalva River, Mexico. Runoff = 460 mm km^{-1} yr^{-1}. D) Rajang, Indonesia. Runoff = 2 150 mm km^{-1} yr^{-1}. Image data are © Google 2016.

Table 1: Runoff category limits, constants *k* and *m,* and correlation coefficients (R^2) for each of the populations plotted in Figures 2 and 4.

Table 1: Runoff category limits, constants *k* and *m,* and correlation coefficients (R^2) for each of the populations plotted in Figure 2.

Model	Class	Runoff (mm yr^{-1} km^{-1})	*k*	*m*	R^2
Eq. 1, fixed constants	**All data**	**>0**	**0.075**	**0.8**	**0.50**
	All data, arid excluded	>100	0.075	0.8	0.74
Proposed method: Eq. 1, constants vary by class	Arid	0-100	0.0005	1.0633	0.72
	Semiarid	100-250	0.0063	0.9824	0.98
	Humid	250-750	0.0161	0.9839	0.96
	Wet	>750	0.0873	0.9164	0.99
	All data	>0	varies	varies	0.90
	All data, arid excluded	**>100**	**varies**	**varies**	**0.95**

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337 **Table 2**: Generalized criteria for determining palaeoclimate from geological indicators.

	Arid	Subarid	Humid	Wet	Notes	References
Runoff (*mm km^{-1} yr^{-1}*)	*<100*	100-250	250-750	>750	-	-
Palaeosol types	Calcisols, gypsisols, entisols, inceptisols	Calcisols, vertisols	Argillisols, spodsols, gleysols, histosols	Histosols, gleysols, Oxisols, agrillisiols	Extensive well-drained soils not expected in sedimentary basins in wet and humid systems	Mack and James, 1994
Root types	Deep tap-roots	Deep tap-roots	-	Tabular mat		Retallack, 1997; 2001;
Mineralogy	Presence of gypsum, carbonate.	Presence of carbonate	-	High proportion of quartz versus feldspar,	Quartz/feldspar ratio and ratios of smectite and kaolinite to immature clay minerals (illite and chlorite) increase due to increased chemical weathering under higher temperature and humidity.	Robert and Kennet, 1994; Retallack, 1997; Nystuen et al., 2014;
River architectures	Strongly ephemeral/flashy	Ephemeral/flashy	Perennial	Perennial	-	Tooth, 2000; Nystuen et al., 2014
Other:	Nearby aeolian or evaporite deposits	-	-	-	-	-

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340 **Table 3:** Change in calculated sediment load using the proposed method to calculate water discharge
341 as input to the BQART-approach (Eq. 2; Syvitski & Milliman, 2007), compared to using fixed
342 constants, keeping all other variables equal.

343

	Modern river at this	Change in calculated sediment load			
Area, km^2	scale	Arid	Semiarid	Humid	Wet
6300000	Amazon	-24 %	12 %	52 %	84 %
1000000	Ganges	-35 %	1 %	36 %	73 %
100000	Colorado	-46 %	-11 %	20 %	59 %
10000	Severn	-55 %	-22 %	5 %	46 %
1000	Dee	-63 %	-31 %	-8 %	34 %
100	-	-69 %	-40 %	-19 %	24 %

9. References

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