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

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Running head: Relating water-discharge and catchment area

Supplementary material: A1, Spreadsheets used for calculations and plots. A2, Cross-plots and regression lines to determine values for *k* and *m* by runoff class; Find the data here: https://onlinelibrary.wiley.com/doi/abs/10.1111/sed.12426

Abstract

Models relating sediment-supply to catchment-properties are important in order to use the geological record to deduce landscape evolution and the interplay between tectonics and climate. Water-discharge (Q_w) is an important factor in the widely used BQ_wART-model of Syvitski and Milliman (2007), 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 (Milliman and Farnsworth, 2011) 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 4 orders-of-magnitude). Neither does the equation incorporate the effect of arid and wet climate on this relationship. 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 size and river discharge vary with four runoff categories (arid, subarid, humid, and wet) which are recognizable in the geological record, and modify the coefficient and exponent of the abovementioned equation according to these classes. It follows from this analysis that water-discharge from arid catchments is so variable, that water-discharge cannot be predicted from catchment area. Our modified model yields improved results in relating discharge to catchment size ($R^2=0.95$ and error spanning 1 order-of-magnitude) when core-, outcrop- or regional palaeoclimate reconstruction data are available in non-arid systems. In conclusion, this model, in contrast to the previous, is sufficient for many geological applications and will lead to a higher degree of confidence in the application of mass-balance models in ancient systems.

1. Introduction

The extent and quality of geomorphological and subsurface datasets in the geosciences 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; Allen et al., 2013; Michael et al., 2013; Hampson et al., 2014; Holbrook and Wanas, 2014, Helland-Hansen et al., 2016). The goal of such studies is 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. Such studies may be undertaken to predict or estimate parameters of sedimentary transport networks which are inaccessible to study due to erosion or burial (Martinsen et al, 2010), understanding propagation and fidelity of environmental signals through time (Paola et al., 1992; Romans et al., 2016), and the evolution of past landscapes (e.g. Sømme et al., 2009; Bhattacharya et al., 2015).

In deep-time systems (>> 10^6 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). 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, one of the most popular and well-established methods used to investigate source-to-sink relationships in ancient systems, is to use the BQ_wART-method developed through analysis of modern systems by Syvitski and Milliman (2007) (e.g. Weight et al., 2011; 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:

$$\textbf{\textit{Eq. 1: }} Q_s = \omega B Q_w^{0.31} A^{0.5} R T$$

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 proportion of catchment covered by glaciers (A_g), lithology (L), trapping efficiency of lakes and reservoirs (T_e), and human-influenced soil erosion (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).

For ancient catchments, factors such as relief, bedrock type, catchment palaeotemperature and extent and presence of glaciers may often be approximated based on regional geological evidence, and from published global data. Relief (R) may be estimated through modern topographic analogs (systems draining uplifted rift shoulders, flat plains or, large orogens), fission track analysis and 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., 2015), and geological evidence such as palaeosol types (e.g.

Wright, 1990, Mack and James, 1994; Kraus, 1999, Retallack, 2001; Müller et al., 2004; Nystuen et al., 2014).

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). Although attribute maps derived from 3D-seismic data may give full plan view control of parts of fluvial systems in the subsurface, wells and 3D-seismic data are commonly too sparse and to poorly resolved to assess true width and thickness of channels and barforms. Estimation of water-discharge in the subsurface is thus extremely challenging.

Catchment area (*A*) is in most cases hard to constrain accurately in ancient systems, due to erosional and tectonic modification. Systems with a marked topographic axis, such as in convergent and transpressive regimes, catchment size 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). In most other basin types, catchment area (A) and water-discharge (Q_w) are difficult to estimate.

This presents a problem, because application of the BQ_wART-model (Eq. 1) to ancient systems yields one equation and two poorly constrained unknowns, significantly hampering the usability of this method. In order to relate these variables, Syvitski and Milliman (2007) presented the following equation:

$$\textbf{Eq. 2: } Q_w = kA^m$$

, where Q_w is water-discharge, *A* is catchment size, *k* is an empirical constant set to 0.075, and *m* is an empirical exponent set to 0.8, providing a link between catchment area and river discharge. This equation is useful as it provides a simple way to relate sediment supply to parameters which are possible to estimate in the ancient (e.g. Sømme et al., 2013; Allen et al., 2013), and will in this paper be referred to as *Eq. 2*. However, this equation is clearly inadequate to accurately relate discharge and catchment size, because two equally large catchments in different climates will have very different water-discharge, owing to varying amounts of rainfall and evapotranspiration (e.g. Mu et al. 2007). In this paper, using global catchment data compiled by Milliman and Farnsworth (2011), it is demonstrated that using fixed values for the constant $k=0.075$ and exponent m =0.8 in *Eq. 2* for all systems regardless of climate is inadequate in many settings (Fig. 1).

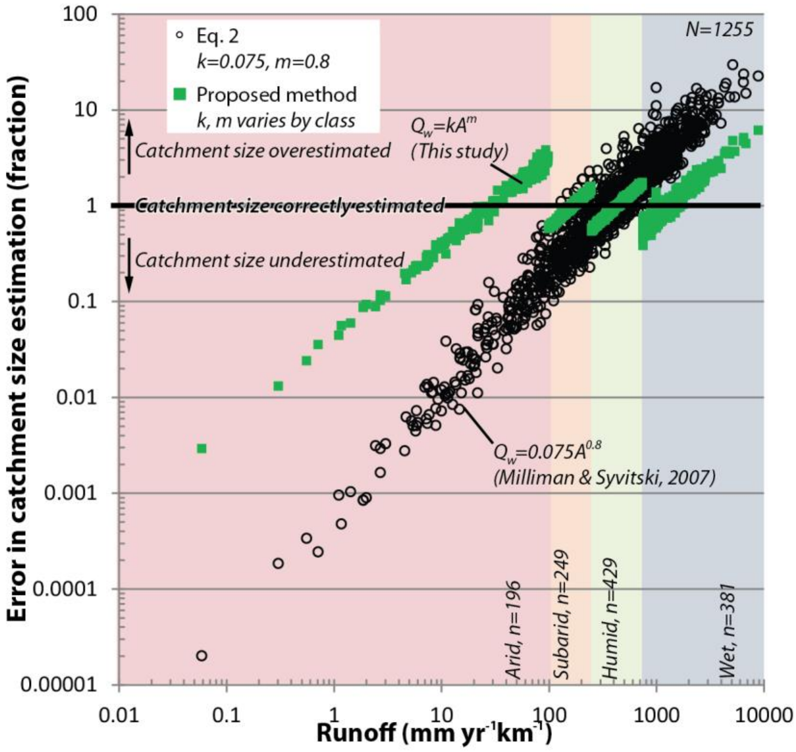

Fig. 1: Runoff and error in catchment size estimation using the Eq. 2 and the proposed method for 1255 modern catchments (Data from Milliman and Farnsworth, 2011). An error value of 1 indicates no error in the catchment estimation, and error values of 0.1 and 10 indicate a ten times under- and overestimation of catchment area, respectively. Note the large errors associated with wet and arid systems using Eq. 2 (circles), and how this improves significantly using the method proposed in this contribution (squares).

The *runoff* (ratio of annual river discharge to catchment area) of rivers varies with climate. Runoff of rivers is commonly given in mm yr^{-1} km^{-1}, and is therefore easily compared to catchment-averaged rainfall. The *runoff efficiency* of a catchment is the ratio of runoff to catchment-averaged rainfall, and runoff efficiency is commonly lower in drier catchments due to higher evapotranspiration and infiltration, 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 a higher precipitation will lead to higher runoff due to both increasing the availability of water, but also due to increase in runoff efficiency.

Here, it is shown that discharge may be predicted from catchment area (and *vice versa*) at an acceptable level of precision and accuracy by choosing appropriate values for k and m in *Eq. 2* by classifying studied deposits into four runoff classes (arid, subarid, 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 input 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 for different climate types in modern environments, (2) 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. 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 and their sediment supply, such as relief, climate, location, and most importantly for this study, catchment area and water-discharge. These systems are investigated using simple cross plots and power law regression (Figs. 1 and 2), 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 the many of the rivers with pre-dam discharge values are well-known rivers with extensive water management systems (e.g. Murray-Darling, Nile, Colorado).

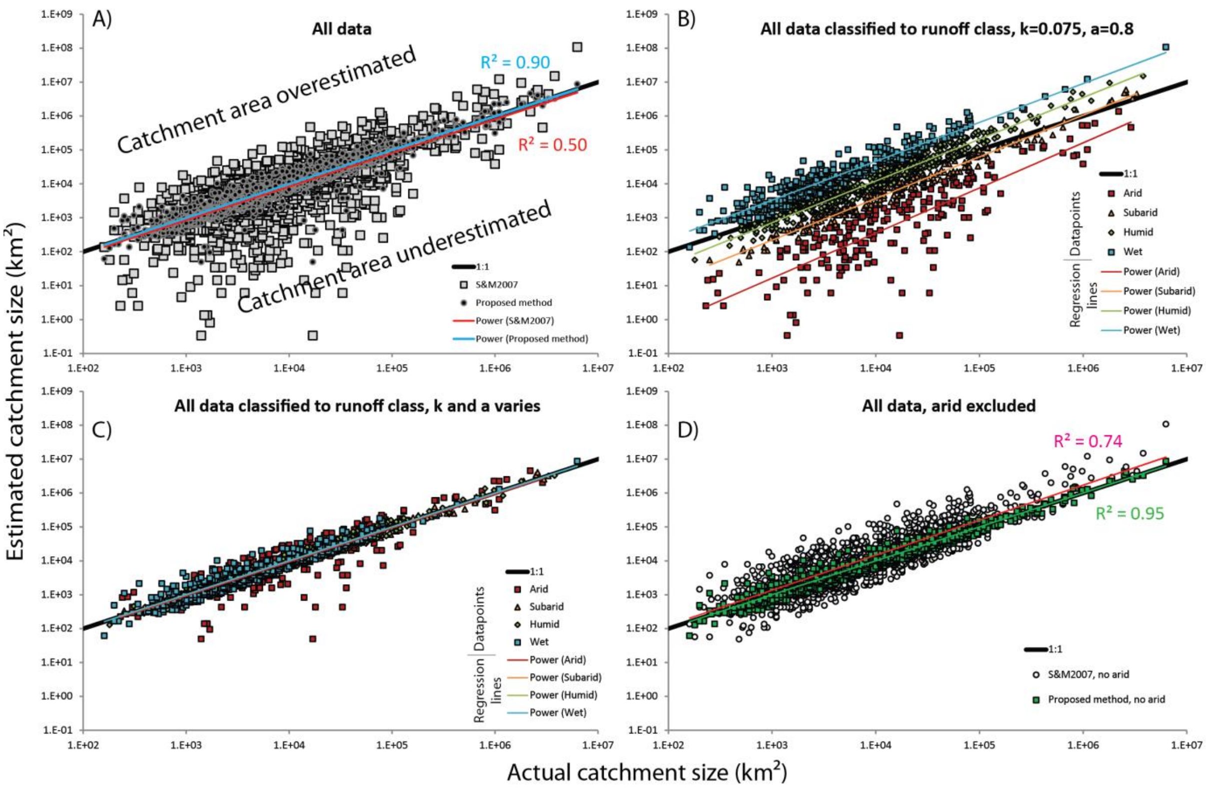

Fig. 2: Cross plots showing relationship between actual and estimated catchment size using different constants k and m. Data points are from the catchment database of Milliman and Farnsworth (2011), N=1255. A) Actual and estimated catchment size using all data and Eq. 2 (squares), compared to all data for the method proposed herein (circles). (B) Actual and estimated catchment size using all data and Eq. 2, color-coded by runoff class (arid, subarid, humid and wet). Note the systematic underestimation and large spread of errors in estimation of arid catchment area, and the systematic overestimation of wet catchment area. C) Catchment area estimated using different constant k and exponent m for each runoff class (see Table 1), color-coded by runoff class. Note the improved fit between actual and estimated runoff compared to (B), and note that errors are still large for

arid systems. (D) Comparison of Eq. 2 and the proposed method, for all data excluding arid systems. S&M2007, datapoints using Eq. 2 and k=0.075 and m=0.8 from Syvitski and Milliman, 2007.

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

Table 1: Runoff category limits, constants *k* and *m* and coefficients of determination for each of the populations plotted in Figure 2.

Model	**Class**	**Runoff** (mm yr^{-1} km^{-1})	***K***	***m***	**r^2**
Eq. 2 (Syvitski and Milliman, 2007)	**All data**	**>0**	**0.075**	**0.8**	**0.50**
	All data, arid excluded	>100	0.075	0.8	0.74
Proposed method (this study)	Arid	0-100	0.0005	1.0633	0.72
	Subarid	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**

3. Results

Figure 1 presents the runoff of all systems in the database (Milliman and Farnsworh, 2011), plotted against the error of the catchment size estimation. Catchment size estimation is dependent on runoff, and is thus systematically greatly underestimated in arid systems (median error: 0.01x), systematically underestimated in subarid systems (median error: 0.4x), correctly estimated for humid systems, and systematically overestimated for wet systems (median error: 4x).

Plots of actual versus estimated catchment size (using Eq. 2 and the coefficients from Syvitski and Milliman 2007) also demonstrate this relationship (Fig. 2B): catchment size is underestimated for arid systems, and overestimated for wet systems. Furthermore, Eq. 2 leads to large (four orders of magnitude) variation in error of estimation of catchment areas for arid systems (Fig. 2B). Subarid, humid and wet systems generally show little variation in error and generally constrain the input with reasonable accuracy (within 30x).

In order to obtain new coefficients and exponents for each of the 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 coefficients of determination (R^2) are presented in Table 1. Plots of actual versus estimated catchment size using the proposed model are presented in Fig. 2C. These show a significant improvement compared to Eq. 2, but also large variations for arid systems. Eq. 2 and the proposed model are compared in Figures 2A and 2D, including and excluding arid systems, respectively. This shows that estimates of catchment size are significantly improved using the proposed method. However, catchment size estimation appears to be too variable to be useful in arid catchments.

4. Discussion

4.1. Recognition of runoff classes in ancient deposits

Defining runoff class of ancient deposits makes estimations of river discharge and catchment area more accurate (Fig. 2, Table 1). This is possible because runoff is related to features which are preserved in sedimentary systems (Fig. 3) and observable in the geological record (Table 2). The key assumption in this work is therefore that the runoff classes defined in this study would correspond to geologically observable factors, such as the presence of calcretes, coals, particular palaeosol types and features (e.g. Mack and James, 1994; Bestland, 1997), aeolian dunes, plant communities (Paterson et al., 2015), 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 provenance area (e.g. 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.

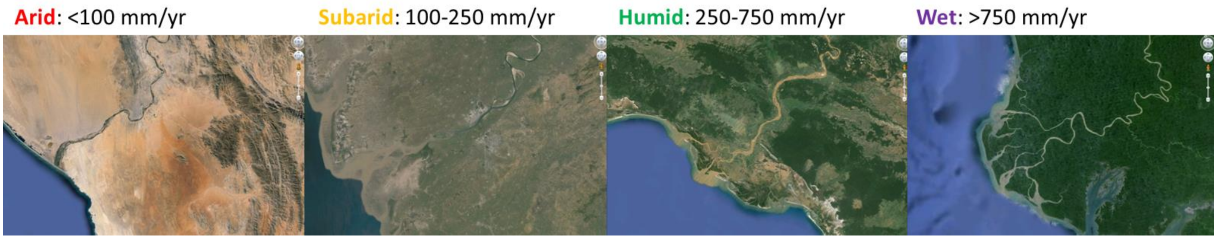

Fig 3: Satellite images of systems in the four categories, showing clearly different landscapes that would be expressed in detectable geological indicators. A) Orange River, Namibia. Runoff = 4.5 mm km^{-1} yr^{-1}. B) Narmada River, India. Runoff = 230 mm km^{-1} yr^{-1}. C) Grijalva River, Mexico. Runoff = 460 mm km^{-1} yr^{-1}. D) Rajang, Indonesia. Runoff = 2 150 mm km^{-1} yr^{-1}. Image data are © Google 2016.

Table 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	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	-	-	-	-	-

4.2. Comparison to Eq. 2

The comparison of errors in catchment size estimation for Eq. 2 (Eq. 2; Syvitski and Milliman, 2007) and the proposed method shows that Eq. 2 performed well in runoff ranges 200-800 mm/km yr (Fig. 1), 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 Eq. 2 (Fig. 1). Wet systems would commonly be characterized by perennial rivers and abundant gleysols or coal deposits. Furthermore, this study shows that it is hard 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 a factor of 100. Finally, this study shows that water-discharge and catchment area can be related with a high degree of confidence if the runoff class of the system can be determined, with the exception of arid systems.

4.3. Human influence and validity of equations

The majority of world catchments have some degree of human influence. In the database (Milliman and Farnsworth, 2011), 72 of the 1254 catchments also have data about pre-dam discharge. 21% of these are classified as arid based on runoff, 29% are sub-arid, 31% are humid and 11% are wet. Post-dam discharge decrease in 71 of the 72 catchments, and the reduction ranges from 11% (Tapti, India) to 99% (Colorado, USA), and no correlation between the amount of decrease and runoff or catchment size exists. This indicates that post-dam discharge reduction is mainly determined by water management strategies and water demand.

It is also worth noting that the rivers with pre-dam discharge-data in the database often represent highly populated catchments with well-known and large water management projects, such as the Nile, Orange, Los Angeles, Colorado and Huanghe. It may therefore be speculated that discharge from catchments without pre-dam discharge data generally is less affected by human intervention than catchments with pre-discharge data. Thus, it is estimated that the coefficients presented here, which are conditioned to post-dam river discharge, might underestimate final discharge to some degree. However, further research would be needed to constrain this amount.

5. Conclusions

When reconstructing ancient source-to-sink-systems, estimates of water-discharge (Q_w) and catchment area (A) are crucial to apply mass-balance models. Here, it is demonstrated that the previous method (Q_w=0.075$A^{0.8}$) works reasonably well in in subarid and humid settings, but that it yields a significant overestimation of catchment size in wet systems, and a significant underestimation of catchment size 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 modern systems. However, arid systems show too high variability to be reliably predicted in this way.

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7. Captions

Fig. 1: Runoff and error in catchment size estimation using the Eq. 2 and the proposed method for 1255 modern catchments (Data from Milliman and Farnsworth, 2011). An error value of 1 indicates no error in the catchment estimation, and error values of 0.1 and 10 indicate a ten times under- and overestimation of catchment area, respectively. Note the large errors associated with wet and arid systems using Eq. 2 (circles), and how this improves significantly using the method proposed in this contribution (squares).

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