Geomorphological Characterization of Rivers Using Virtual Globes and Digital Elevation Data: A Case Study from the Naryn River in Kyrgyzstan

Betz, F.,* Lauermann, M. and Cyffka, B.
Catholic University Eichstaett-Ingolstadt, Applied Physical Geography, Ostenstrasse 14, 85072 Eichstaett, Germany, E-mail: florian.betz@ku.de

Abstract:
In recent years, fluvial geomorphology included a range of new technologies for the characterization of riverine landscapes in the pool of methods. LIDAR, the analysis of drone imagery or satellite remote sensing improved the ability to analyze river systems in manifold ways. However, the high demand for (often expensive) data and processing skills limit the application commonly to smaller study reaches or to regions where data is already available. In contrast, a range of conceptual frameworks for the geomorphological characterization of river systems highlights the relevance of integrating the catchment scale context. Against this background, virtual globes such as Google Earth are cost-efficient alternatives as they make high resolution satellite imagery available almost worldwide. Merging the information mapped from virtual globes with digital elevation data allows the interpretation of riverscape attributes in the context of the longitudinal profile. In our study, we present the geomorphological mapping of the more than 600 km long Naryn River in Kyrgyzstan based on different virtual globes and the SRTM-1 digital elevation model. The experience from this mapping exercise suggests that the combination of virtual globe imagery and elevation data is a powerful and cost-efficient approach for river research and application in the context of data-scarce river corridors.

1. Introduction

In modern river science, it has become generally accepted to see rivers from a system point of view. This is a perspective which has also become popular as riverscape approach (Fausch et al., 2002). Over the past decades, a range of conceptual frameworks for the characterization of rivers has been proposed (see Gurnell et al., 2016b for a recent review). Despite the theory seeing rivers as hierarchical systems with various nested scales, empirical data has mostly been gained from either highly localized experiments or spatially loose studies (Marcus and Fonstad, 2008 and Fonstad and Marcus, 2010). More recently, technological progress allowed the acquisition of spatially consistent information on the catchment scale. While the visual interpretation of aerial imagery has already a certain tradition, the use of LIDAR, drones, and high resolution satellite imagery is a development of recent years (Tomsett and Leyland, 2019). Progress has been made for instance in the automated analysis of digital elevation models for river characterization (Roux et al., 2015 and Betz et al., 2020) but also in the processing of high resolution multispectral satellite imagery (Carbonneau et al., 2012). Even if these methods have an enormous potential for the analysis of riverscapes, the necessary datasets tend to be expensive as well as resource demanding in acquisition and processing. Especially in the context of developing countries they are often not available at all (Schmitt et al., 2014 and Betz et al., 2018, 2020). In such situations, the imagery available from virtual globes such as Google Earth can help to solve the issue of insufficient data availability. As early as 2006, Google Earth became available online and scientist started to discover the power of such virtual globes for studying the earth (Butler, 2006 and Tooth, 2006). While these early publications mainly focused on the educational potential of virtual globes, later research used such datasets for entire studies. For instance Fisher et al., (2013) used data from Google Earth to determine channel widths across a catchment. Perhaps the most sophisticated example of using virtual globe data for the study of entire rivers has been published by Large and Gilvear (2015) who assessed ecosystem services solely based on landscape attributes extracted by visual interpretation of Google Earth imagery. Beside the findings about the river ecosystem services they could successfully demonstrate how to get information about a riverine landscape from virtual globes.

The goal of this study is to develop a workflow for the characterization of riverscapes based on a combination of virtual globe imagery and digital elevation data. We test this framework at the example of the Naryn River in Kyrgyzstan and present an analysis of this more than 600 km long river. We discuss relevant theoretical issues related to the use of virtual globe data and suggest a cost-efficient and simple approach for the geomorphological characterization of rivers.

2. Material and Methods

2.1 Study Area

The Naryn River is located in Kyrgyzstan within the Tian Shan Mountains (Figure 1). The segment we focus on in this study begins in the uppermost headwaters of the Naryn in an elevation of 5133 m. On the first approx. 266 km it is still named Big Naryn before its confluence with the Small Naryn in an elevation of 2300 m. From there, the river is officially named "Naryn" and flowing to the west towards the Toktogul Reservoir where the first dam is located. At the dam, our area of interest is ending. Along this 752 km long river segment, the Naryn River is in a natural state without embankments or relevant modifications of the discharge regime (Betz et al., 2018 and Chymyrov et al., 2018). The climate is highly continental with mean annual summer temperatures up to 25 °C and winter averages below -25 °C. The precipitation has an average annual amount of 300 mm and reaches a maximum in May and June. Due to these climatic conditions, the Naryn River is highly dependent on water supply from the glacier melt (Kriegel et al., 2013). This leads to a glacial discharge regime with a single peak in July. Mean annual discharge at the station Naryn City is 92.12 m^3/s increasing to 323.33 m^3/s at the inflow of the Toktogul Reservoir.

The entire region is highly influenced by the active tectonics of the Tian Shan. Several faults cross this mountain belt causing an interplay of mountain ranges and basins in the region with an east-west strike direction (Thompson et al., 2002). The Naryn Basin – the central part of the Naryn Catchment – is the biggest basin in the Kyrgyz Tian Shan. During the Pleistocene and Quaternary, terraces have formed in this basin with a height up to 20 m (Thompson et al., 2002). Even if their geological history is not fully understood, they are an important geomorphological feature. Further downstream, the Naryn is turning northwards. Here, the river is leaving the Naryn Basin and passing a water gap towards the Toktogul.

2.2 Data Analysis

First step of our data analysis is the extraction of a channel network from the SRTM-1 DEM. This dataset has a spatial resolution of 1 arc second resulting in a pixel size of 24.05 x 24.05 m when projecting to UTM. We use the r.stream toolkit implemented in Grass GIS (Jasiewicz and Metz, 2011). Beside the channel network extraction, this toolkit allows also the computation of the stream order and the subsequent extraction of the main river course (Hack order = 1). The resulting line is than split into segments fitting to the cells of the SRTM-1 elevation model and attribute fields for the desired mapping attributes have been added. This line was than loaded to QGIS which allows the integration of various virtual globe imagery via the QuickMapServices plug-in (www.qgis.org).

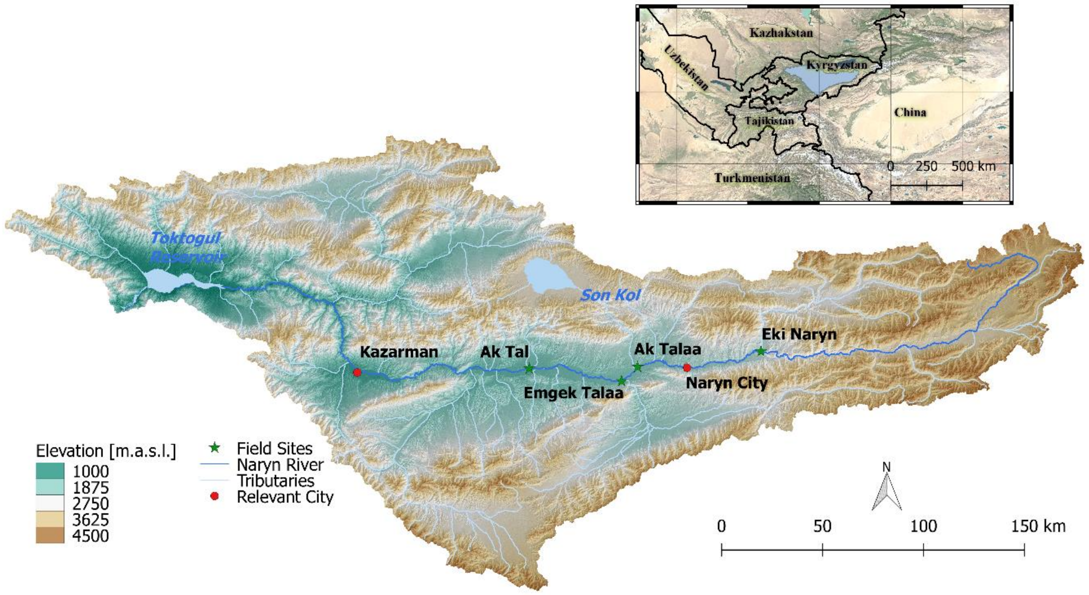

Figure 1: Overview over the study area; the light blue area in the inlet map gives the Naryn catchment

Table 1: Attributes used for characterizing the Naryn River

Characteristic	**Specification**	**Distinguishing Attribute**
Valley Setting	Confined	Majority of the channel hits the valley margin or the terrace
	Partly confined	A minor share of the channel hits the valley margin or the terrace, often on just one side
	Laterally unconfined	The channel is not in contact with the valley margin or the terrace
Floodplain	No floodplain	No floodplain is present
	Discontinuous floodplain	Floodplain is only present along one river bank
	Continuous floodplain	Floodplain is abundant on left and right bank
River Type	Gorge	Bedrock confined valley setting
	Straight	Low sinuosity with no extensive instream features and absent or discontinuous floodplains
	Braided	Low sinuosity with extended gravel bars or islands, clearly identifiable main channel
	Braided-anastomising	Low sinuosity with multiple channel; single channels show characteristics of braided rivers with extended bars and islands
	Steep headwater	Low sinuosity with confined valley setting; instream geomorphic features like bars or islands as well as floodplains are widely absent

We used imagery from Google Earth, Bing Maps and Yandex Maps for mapping riverscape attributes of the Naryn River. Using images from different virtual globes ensured the availability of cloudless high resolution imagery throughout the entire area of interest. This was not achievable by any of the single virtual globes mentioned above. Based on the river type, we discriminated also single reaches defining a reach boundary as a change in the river type. This reflects the assumption that there is a clear linkage between the controlling processes and the resulting river type (Fryirs and Brierley, 2013).

For the mapping itself, we base upon the Riverstyles Framework (Brierley and Fryirs, 2005) and assess confinement and the abundance of floodplains. Furthermore, we assign a river type as interpretation of the planform. Table 1 gives an overview of the attributes used during the mapping procedure. To integrate the elevation data in the interpretation of the mapping results, we computed a longitudinal profile from the extracted main river stem and the SRTM-1 DEM. As the profile shows some noise and errors probably resulting from radar scattering, we smooth the profile using constrained quantile regression smoothing (Schwanghart and Scherler, 2017 and Betz et al., 2020). This smoothed profile was also used to calculate average channel gradients for the different reaches. In addition to the profile and the gradients, we extracted also the flow accumulation along the longitudinal profile which can be used as proxy for the discharge. All analysis except the mapping have been performed using R (R Core Team, 2015) along with GRASS GIS.

3. Results

3.1 Planform Mapping

Probably the most intuitive result for fluvial geomorphologist is the river type as this classification already includes a lot of interpretation. Figure 2 shows the distribution of river types along the entire Naryn River as well as for 4 selected sections. Based on the river type, we could discriminate 121 reaches with a median length of 2.25 km. In the uppermost part of the catchment upstream from the confluence of Big and Small Naryn, steep headwater reaches dominate as shown in Figure 2a. Here the valley setting tends to be confined, floodplains are widely absent. Further downstream, there is an interplay of straight and braided reaches, also the valley setting changes between confined and partly confined. Floodplains are absent or occur in a discontinuous form (Figure 2b). Further downstream, braided and braided-anastomising become the dominant river types (Figure 2c). In this setting, the valleys are likely to be unconfined, floodplains are mostly continuous. Another important feature of the lower part of the investigated catchment are two gorges with an entire length of more than 150 km. Figure 2d shows a part of the longer gorge. Within the gorges, the valley setting is confined, floodplains exist only in form of isolated pockets. Right downstream of the longer gorge, the Toktogul Reservoir begins. This river section has to be considered as heavily modified by human activities. Consequently, the valley setting as well as the floodplain abundance for the river type "reservoir" have been classified as "anthropogenic".

3.2 River Characteristics along the Longitudinal Profile

Often, the analysis of riverscape attributes along the longitudinal profile gives more insights than the planform interpretation alone. Figure 3 shows three major characteristics of the Naryn River along the longitudinal profile derived from the SRTM-1 elevation model. Along the uppermost 266 km, the river is dominated by steep headwaters with reach averaged gradients up to 0.063 m/m. Despite the headwater character two plateaus with lower gradients exist within this river section. In the steep headwater reaches, floodplains are widely absent, only within the braided river sections on the lower gradient plateaus discontinuous floodplains exist. Downstream of the confluence of the Big and Small Naryn, there is a 157 km long section characterized by an interplay of straight and braided reaches. The gradients are less steep compared to the steep headwaters and range from 0.0035 to 0.0043 m/m. For the majority of this section, the Naryn is partly confined by fluvial terraces. Floodplains exist mainly in a discontinuous form. Further downstream, the gradient becomes less steep with an average of 0.003 m/m. Dominant river types are braided and braided-anastomising. The Naryn is widely unconfined, only a minor share is partly confined. Floodplains are also abundant in a continuous form along the majority of this section. After this section, the Naryn flows into a short, 48 km long gorge with bedrock confined valley setting and absent floodplains before entering another section with braided river reaches. After this braided section, the Naryn enters another 115 km long gorge with occasional floodplain pockets before entering the Toktogul Reservoir. Within the gorges, the gradient is higher compared to the other river sections and reaches values up to 0.01 m/m.

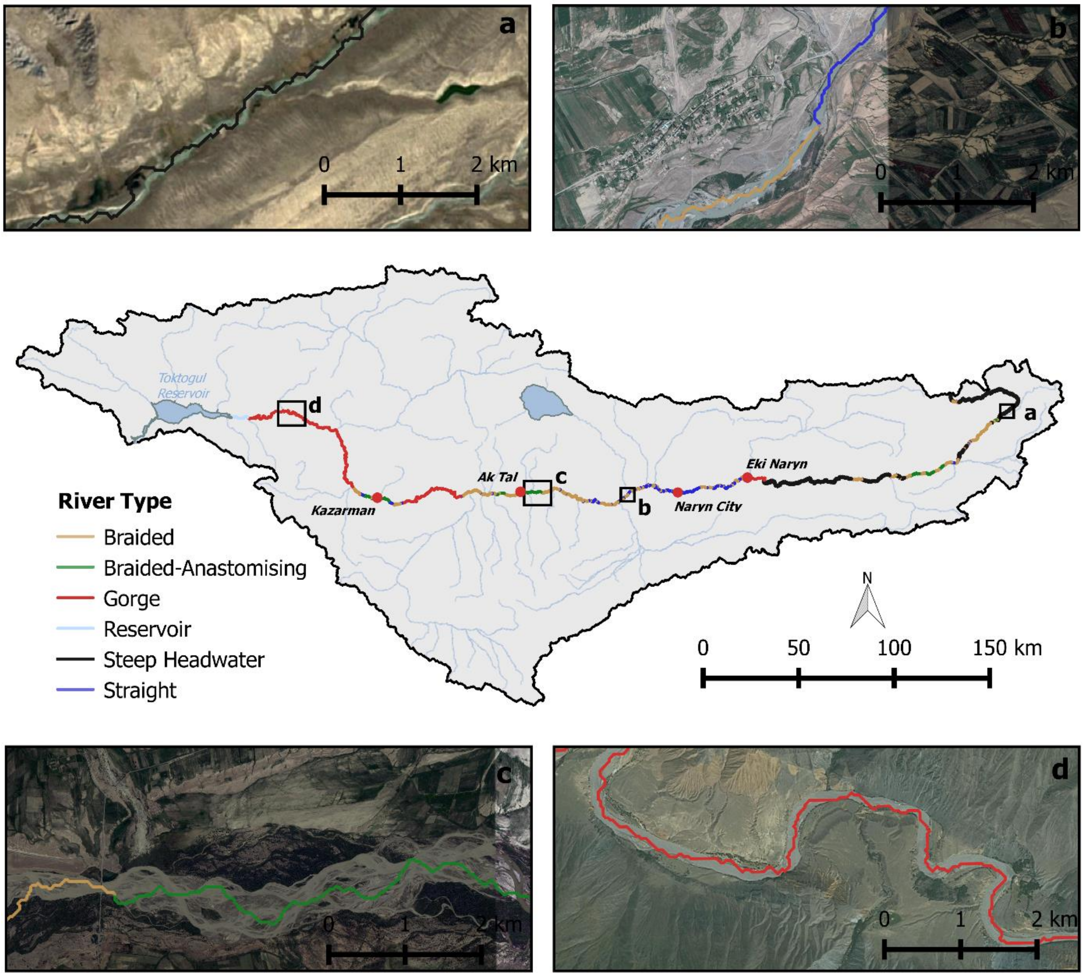

Figure 2: River types along the Naryn River

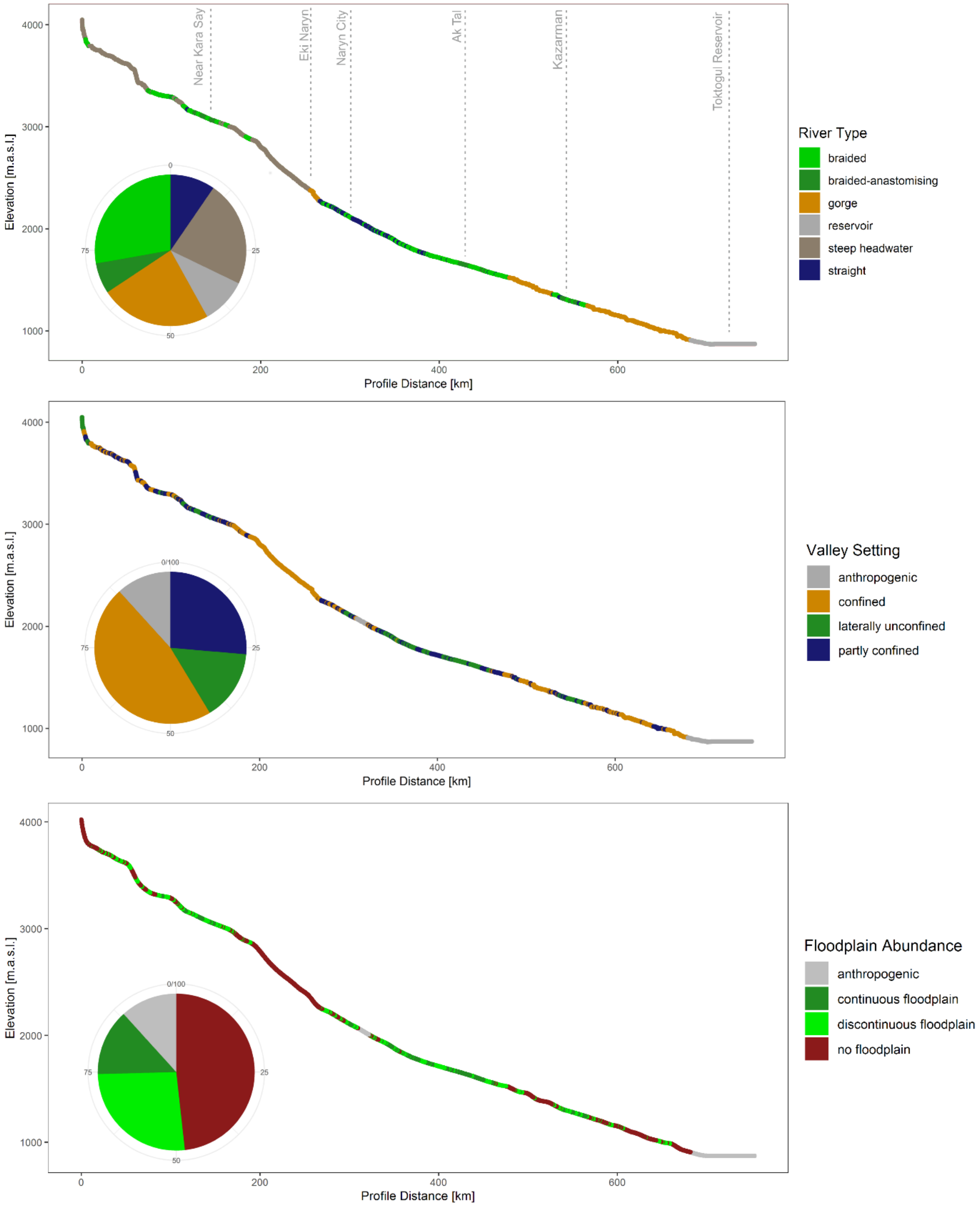

Figure 3: Major geomorphological characteristics along the Naryn River; the pie chart give the relative share of the respective riverscape attribute in percent

4. Discussion

4.1 Disentangling the Geomorphology of the Naryn River

Interpreting the heterogeneity of the Naryn River requires the analysis of the driving forces of the riverscape development. Besides the gradient, also discharge is considered as control of the river channel processes. To explore thresholds in the riverine landscape development, Church (2002) placed different channel types in the context of gradient and discharge. Figure 4 shows the river type in the context of gradient and flow accumulation in a similar manner as in the seminal paper of Church (2002).

Steep headwaters are clearly associated with smaller flow accumulation (discharge) and high gradients while the Toktogul is clearly associated with the highest flow accumulation and the lowest gradient. The other river types are very close together in this plot indicating that there is a more complex control on the river type as just the available flow energy alone, a phenomenon being well-known also from other rivers in the world (Wohl, 2013). As a consequence of this complexity, the Naryn River shows a high diversity along the longitudinal profile. Despite this heterogeneity, 5 major segments can be discriminated (Figure 5).

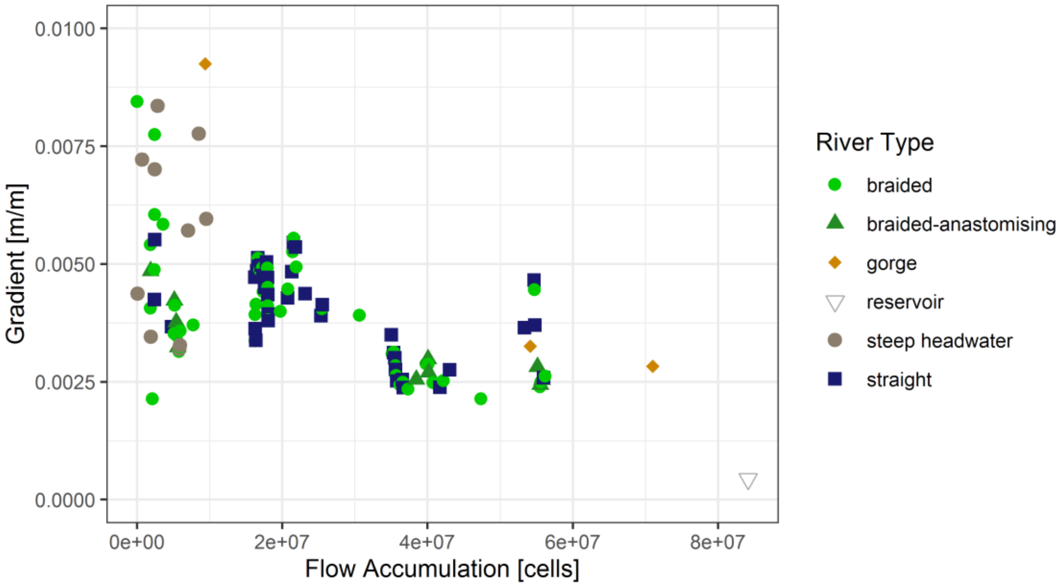

Figure 4: Relationship between channel gradient and flow accumulation as proxy for the discharge

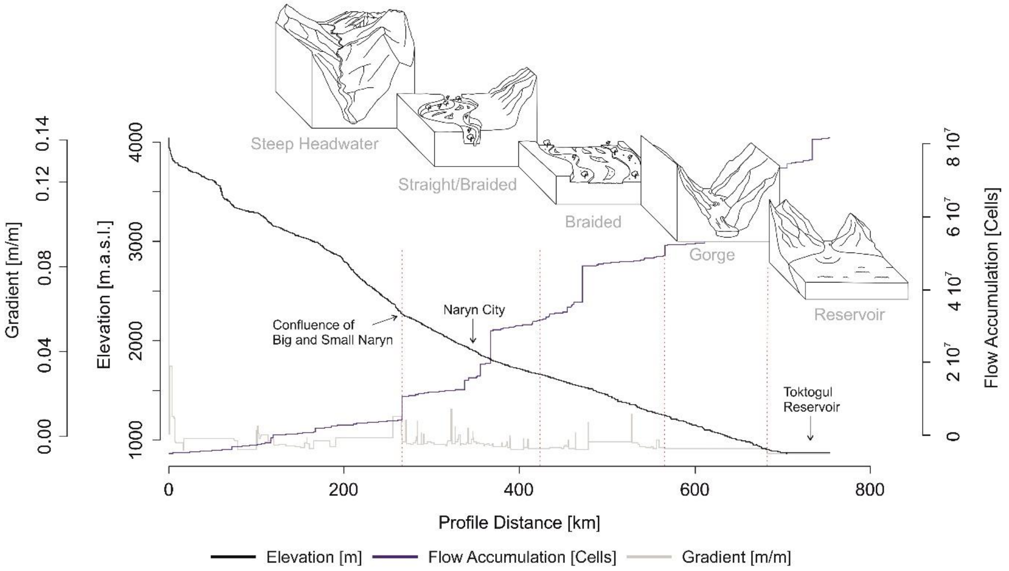

Figure 5: Generalized geomorphological structure of the Naryn River

The first segment is dominated by steep headwaters with a mainly confined valley setting without floodplains. Exceptions are two plateaus, where more gentle gradients allow the deposition of sediment and thus the formation of gravel bars and floodplains. In an overall interpretation, these headwater reaches can be seen as high energy system. Despite the available energy, the potential for lateral channel adjustment is low due to the confinement. Also other planform adjustment is not likely to happen as no instream features such as bars are abundant (Fryirs and Brierley, 2013). In the segment downstream from the confluence of Big and Small Naryn, the river flows into the Naryn

Basin. The channel gradients become smaller due to this tectonic situation. As a consequence, sediments can be deposited and instream features like bars and islands develop. Also floodplains become abundant even if mainly in a discontinuous form. This segment is characterized by a deep incision of the Naryn in Quaternary sediments. The resultant terraces form a partly confined valley. Within the area actively shaped by the Naryn River, an interplay of straight and braided reaches dominate the riverscape. While for the confined, straight reaches we cannot expect extended planform changes, the braided reaches and their floodplains have a high potential for changes of the instream features as well as the channel margins. Further downstream, the channel gradient is getting gradually lower. Straight reaches do not occur anymore and braided as well as braided-wandering are becoming the dominant river types. This low gradient is leading to an extensive sediment deposition resulting in bars and islands as well as a wide, continuous floodplain in an unconfined valley setting. In this segment, the river has a high ability for planform adjustment as there is no confining margin for the majority of the flow length. In this setting, we can expect the riparian vegetation to be the main control of planform evolution as it has been demonstrated in various studies from other rivers (Gurnell et al., 2016a). In the downstream end, this segment has a sharp boundary where the Naryn River is leaving the Naryn Basin to the North and flowing into a 115 km long gorge. Within the gorge, floodplains as well as bars or islands are mostly absent even if occasional floodplain pockets are occurring. Consequently, planform adjustment is not likely to happen. Directly downstream from that gorge, the Toktogul Reservoir begins. Since the completion in 1971, the natural fluvial dynamics have been heavily modified by humans. Thus, the reservoir marks the end of the near natural part of the Naryn River.

From the context of gradient and flow accumulation (Figure 4), we see that these factors representing the flow energy of the river are not the only control over the river type. The local geology like e.g. the bedrock confinement in the gorges is the second important factor. Flow energy seems to be the primary control only within the tectonically formed Naryn Basin, where the straight, braided and braided-wandering reaches dominate. Straight reaches have higher gradients than the braided and braided-wandering reaches. However, all reaches are within a similar range. Thus, we can expect a certain sensitivity to change from one type to another as response to only small changes in discharge or sediment supply (Church, 2002). However, further monitoring is necessary within the reaches in the Naryn Basin as also other factors like for instance the riparian vegetation or local grain-size variations might be controlling factors.

Interpreting the riverscape of the Naryn from a sediment dynamics perspective, we have full lateral and longitudinal connectivity under the current conditions. First barrier is the Toktogul Reservoir acting as sediment trap. While the steep headwaters with their connected hillslopes are likely to be a sediment source zone, the landforms of the braided segments in the central part of the catchment suggest sediment storage and re-distribution over shorter distances. In the gorge segment, we cannot expect extensive sediment storage, it is assumed to be a transfer zone.

4.2 Virtual Globes as a Tool for Riverscape Characterization

A wide range of information can be derived from virtual globes. However, there are several issues related to this data source. First, the data behind the imagery is not accessible for automated remote sensing approaches due to the web mapping service character of this data source. Therefore, visual interpretation is required what leads on the one hand to a high work load for the analyst. For instance, Fisher et al., (2013) used Google Earth for digitizing channel margins and report that they were able to digitize 10-25 km river length per hour while we have been able to map approx. 100 km per day applying our classification scheme. On the other hand, even if using well designed interpretation schemes, a certain degree of subjectivity is associated with the visual interpretation of imagery (Tadaki et al., 2014). Furthermore, there is no control of the imagery availability, an issue what was also recognized by Large and Gilvear (2015) for their ecosystem service based study. Especially for remote areas like the rural Kyrgyzstan where the overall interest in high quality satellite imagery is low, there exists not always up-to-date imagery. As a consequence, the mapping – at least over larger scales – has often to be performed on imagery from various dates in various seasons. An additional issue arises from imagery with different resolution. Thus we argue that it is necessary to focus on robust parameters widely independent from the acquisition date and the image resolution if the imagery source is not consistent across the entire area of interest.

Thus, even if Large and Gilvear (2015) could successfully demonstrate the derivation of manifold riverscape attributes from Google Earth, quantitative parameters are a critical issue when using virtual globes over larger areas. A simple example is the channel width. Here, it matters if the image is taken during a flood event with bordfull channels or in a low flow stage. Consequently, we suggest that a qualitative, interpreting approach (or in the sense of Brierley et al., 2013 “Reading the Landscape”) is an appropriate method to avoid pitfalls arising from inconsistent imagery when applied by a trained fluvial geomorphologist. A combination of the information obtained from virtual globes with digital elevation data is a powerful combination to gain deeper insights into riverscapes. The possibility to place river attributes in the longitudinal profile or to see them in the context of channel gradient and flow accumulation as direct proxy for the discharge allows to evaluate potential flow energy thresholds in the river system. Despite the advantage of almost global availability, open access digital elevation data has limitations regarding resolution and accuracy. Thus, working with this kind of data requires some caution and results should be carefully evaluated.

5. Conclusion

Virtual globes make high resolution imagery available for almost any place in the world. This makes them a powerful tool for fluvial geomorphologist as they provide a vast quantity of data for no cost. Their high resolution allows to obtain a degree of detail not achievable with common medium resolution satellite data like pansharped Landsat (15 m) or Sentinel-2 data (10 m). The fusion of the information from virtual globes with digital elevation data allows deeper insights in riverscapes as an interpretation of river attributes along the longitudinal profile becomes possible. Also further DEM derivations such as the channel gradient can be included in the analysis. However, there are clear limitations. Virtual globes do not allow to control the acquisition date of the imagery. Thus, quantitative analysis of morphometric parameters is limited due to the inconsistent base data. The same issue makes also a comprehensive analysis of change impossible.

Despite these limitations we could successfully demonstrate the geomorphological characterization of the Naryn River in Kyrgyzstan based on a qualitative mapping of riverscape attributes and the fusion of the resultant information with derivations from digital elevation data. This combination allows to expand our view on the riverscape of the Naryn from the plot or reach scale to the entire longitudinal profile. This gives interesting insights into the structure and functioning of this unique river system. Of course, virtual globes are not the exclusive tool for all kind of riverscape analysis and will never be able to substitute more sophisticated, quantitative methods. Nevertheless, they allow to move our view on rivers beyond the plot scale with simple methods and at low cost.

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