Supplementary Information
Rivers as witnesses of Titan's climate variability

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1 Validation of the selected values for transported sediment grain sizes

The grains size of the two rivers was inferred from the observations. However, this is the parameter on which we have the least observational constraints and we therefore had to make several assumptions. There is however a way to calculate this grain size and thus to confirm the chosen values. For this calculation, we must first assume that the threshold theory applies to both rivers. Assuming this is the case, we can compute a grain size with equations 3 and 4 in the main text:

$$W = \frac{\pi\theta_t(\rho_s - \rho_f)d_s}{S\mu_t\rho_f}, \tag{1}$$

Thus, we have:

$$ds = \frac{WS\mu_t\rho_f}{\pi\theta_t(\rho_s - \rho_f)}, \tag{2}$$

This calculation is independent of Equation 1, which is used to compute the discharge. It gives a range of values of 0.01-5 m for HLS and 0.005-0.04 m for the south pole. This is in agreement with the measured values (0.04-0.13 m and $>$ 0.022 m respectively).

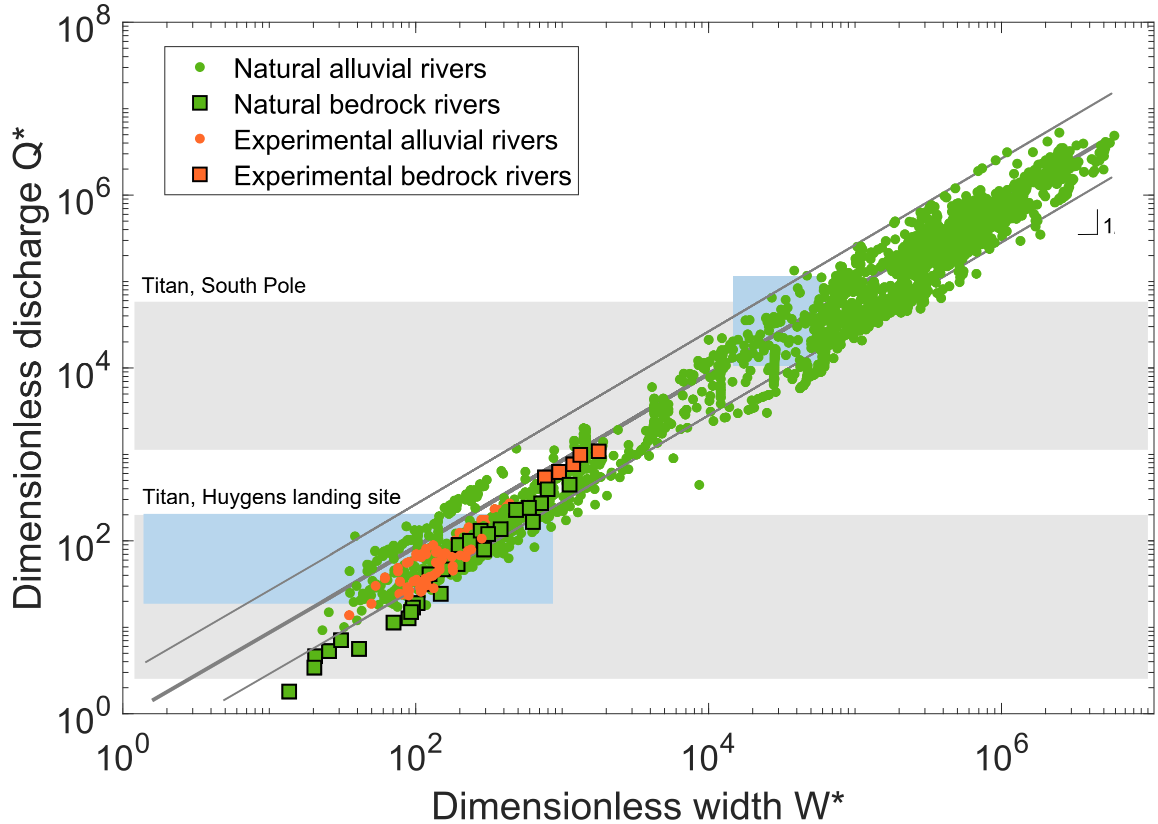

Figure S1: Loglog plot of the dimensionless discharge $Q^* = \frac{Q_w^{1/2}}{\sqrt{gds^5}}$ of terrestrial and Titan rivers as a function of their dimensionless width $W^* = \frac{W}{ds}\left(\frac{\rho_f - \rho_s}{\rho_f}\right)^{1/4}$. Orange color corresponds to laboratory data while green color corresponds to natural rivers. Dots correspond to alluvial rivers and squares to bedrock rivers. The broad gray line indicates the threshold theory (Equation 1) calculated with the parameters of Table 1 while the two thin gray lines represent the uncertainty in the calculation of the river width at threshold due to the intrinsic variability of the two dimensionless coefficients (c_f and μ_t) and the critical Shields number θ_t. The blue areas represent the estimated discharge at two Titan sites with their uncertainties (resulting from the uncertainties in drainage areas, river widths, and transported grain sizes) for the HLS and the south pole. The shaded bands represent the discharge estimates computed from GCM precipitation rates for the two study sites [4, 2, 7, 8, 6]. Uncertainties in these discharge estimates arise from both the variability between model predictions and drainage area estimates.

2 Drainage area calculations

Drainage areas for both rivers are needed to infer the rainfall rates from discharge values. The two study sites have different types of data. The Huygens Landing Site (HLS) site provides the most resolved Digital Terrain Model (DTM) on Titan's surface with a spatial resolution of 18 m whereas, the DTM of the south pole (SP) site has a spatial resolution of 875 m. Because of this difference in resolution, the drainage area is computed differently for the two sites.

One way to extract the drainage area is to calculate the routing on the DTM. This is a method commonly used in hydrology to determine the natural path taken by a liquid over a given topography. It calculates the direction of flow at a single angle taken as the steepest downslope on the eight triangular facets centered on the DTM pixel[9]. It also calculates the ”upslope area”, which is the number of pixels drained into a cell. If a threshold is applied to the number of drained cells, it provides a hydrographic map of the study area (see Figure S1.b).

A routing calculation has already been performed on the HLS DTM in a previous study [3] to ensure that the DTM was correctly leveled. At this site, it generally follows the same path as the river seen in the images. However, we do notice some differences, particularly on the tributaries of the river (Figure S3a), that could affect the routing calculation. Assuming that the flow path remains unchanged, it should follow exactly the same path as the rivers. This problem is caused by the high sensitivity of the routing calculation to variations in the scalar elevation field. The presence of noise in the DTM can therefore bias the predicted flow directions for the fluid. This bias is common in terrestrial applications where highly accurate DTMs are available. Additional river information is then used to condition the DTM, adjust the routing and thus produce hydrographic maps in better agreement with river networks [5, 10]. Several manual operations are then required on the DTM to ensure the generation of quality hydrographic maps such as those derived from the HydroSHEDS database [1], developed from the SRTM (Shuttle Radar Topography Mission) DTM. The DTM is then said to be hydrologically conditioned.

We decided to use the same process on the HLS site by slightly modifying the DTM in order to reorient the routing and thus improve the hydrographic map on the studied area. These supervised modifications must remain below the uncertainties of the DTM[3]. Concretely, our approach aims at manually increasing or decreasing the altitude of the pixels located in the areas where the routing does not follow the river well on the image, to compute the routing, and then to visually check that it has been reoriented. 7% of the DTM pixels were modified to obtain a hydrographic map in agreement with the observations. This procedure results in a hydrographic map that agrees with the observations for the study river (Figure S3).

We then used the routing to calculate the drainage area. By multiplying the upslope area of the most downstream pixel of the river by the DTM ground sampling, we then obtained the drainage area of the river. The uncertainties in the drainage area are calculated by varying the DTM elevations from the uncertainty map. This gives us a minimum and maximum drainage area.

For the SP site, the river is not discernible on the DTM because it is undersampled: the river is 500-850 m wide and the DTM has a ground sampling of 850 m/px. Thus, we cannot estimate the drainage area with the routing on this region. Instead, we use the orthoimage and hand-draw the limit of the maximum and minimum drainage areas (Figure S2). The drainage area is then determined by calculating the number of pixels in the area and multiplying them by the image ground sampling.

References

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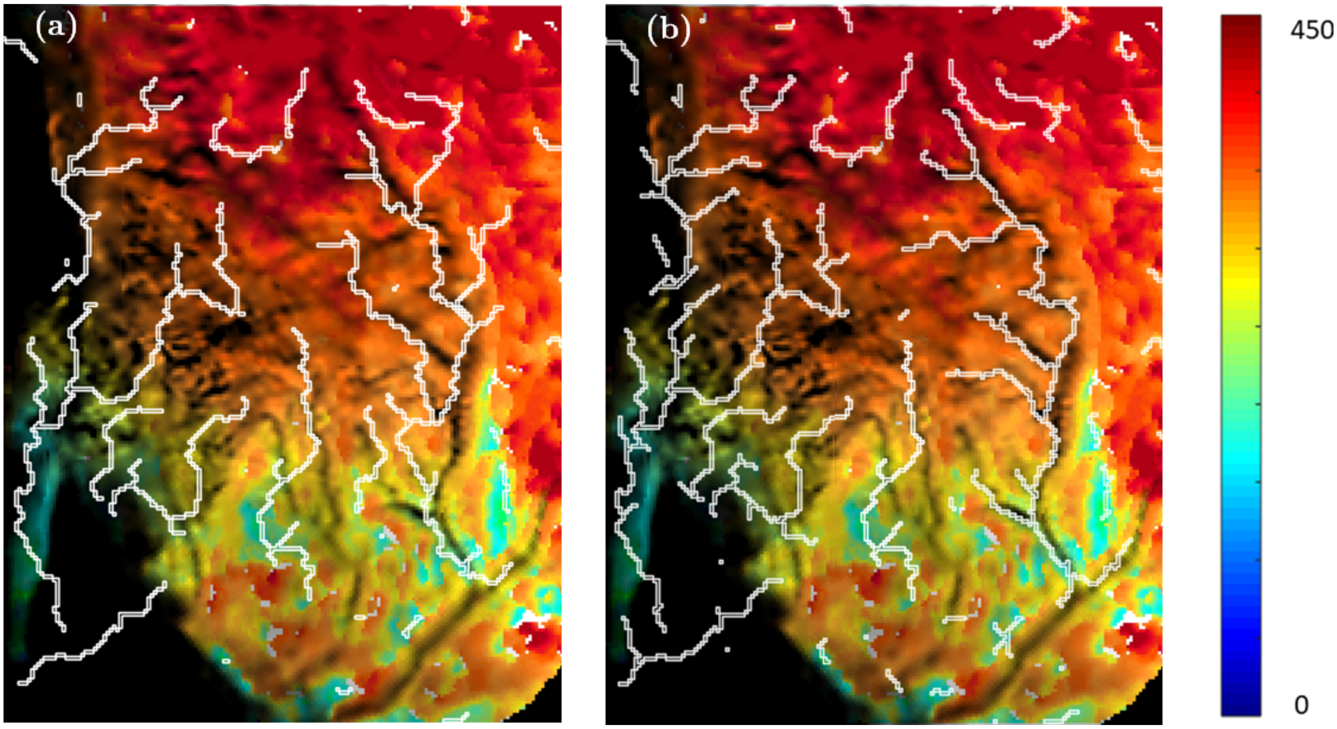

Figure S2: Orthorectified image draped over the DTM with shown in white (a) the initial routing and (b) the routing redirected by hydrological conditioning. The colorbar indicates the DTM elevation (in m).

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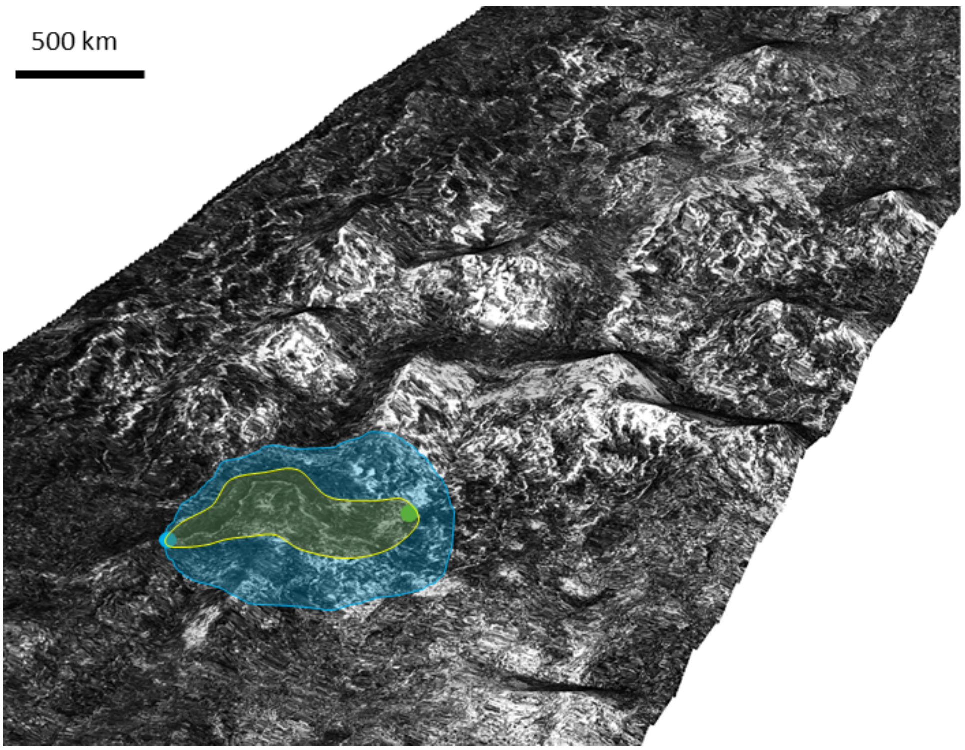

Figure S3: Orthoimage draped on the DTM of the south pole drainage basin. The DTM is derived from the Radar swath stereo pair T55 and T56[1]. The hand-drawn drainage areas are indicated in yellow for the smallest and in blue for the largest.