Horizontal Visibility Graphs as analysis tool for river runoff dynamics

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Introduction

River runoff time series are available at daily resolution since decades from thousands of gauges. We analyze 150 daily runoff series from Brazil obtained between 1931 and 2015 (average length 65 years). All gauges are influenced by water regulation (dam construction; Fig. 1), but the series have been corrected ("natural" flow). The catchment sizes vary between 248 km^2 and 989000 km^2. The accuracy of the records is limited to 1 m^3/s, leading to *tied values*, especially for the smaller catchments.

Figure 1. The Itaipu dam of the Paraná at the border between Brazil and Paraguay, the largest hydroelectric plant worldwide in terms of power generation. Photo: International Hydropower Association

Analysis method: HVGs

The dynamics of the river runoff is investigated using Horizontal Visibility Graphs (HVGs; Luque et al. 2009). The method constructs a network from a time series, where every value is a node, and two nodes are linked when there is no higher value between them (they "see" each other) (Fig. 2). The *degree k* of a node is the number of links attached to it. From the HVG, network properties can be derived; here, we analyze the degree distribution.

Degree distributions

In HVGs, each node has a minimum degree of k = 2 (its directly adjacent neighbors). For uncorrelated random series, the mean degree is $k_{mean} = 4$, and for any process, $2 \leq k_{mean} \leq 4$. For infinitely long white noise series, the degree distribution is an exponential $P(k) = \frac{3}{4} e^{-\lambda_c k}$ with the critical value $\lambda_c = \ln\left(\frac{3}{2}\right)$. For some correlated noise processes, $\lambda > \lambda_c$; for some deterministic chaos, in general $\lambda < \lambda_c$ (Lacasa and Torral, 2010).

Research Questions for the runoff series

- Are degree distributions exponential?
- If yes, is the estimation of λ reliable?
- What is the influence of ties and seasonality?
- What is the effect of water regulation?

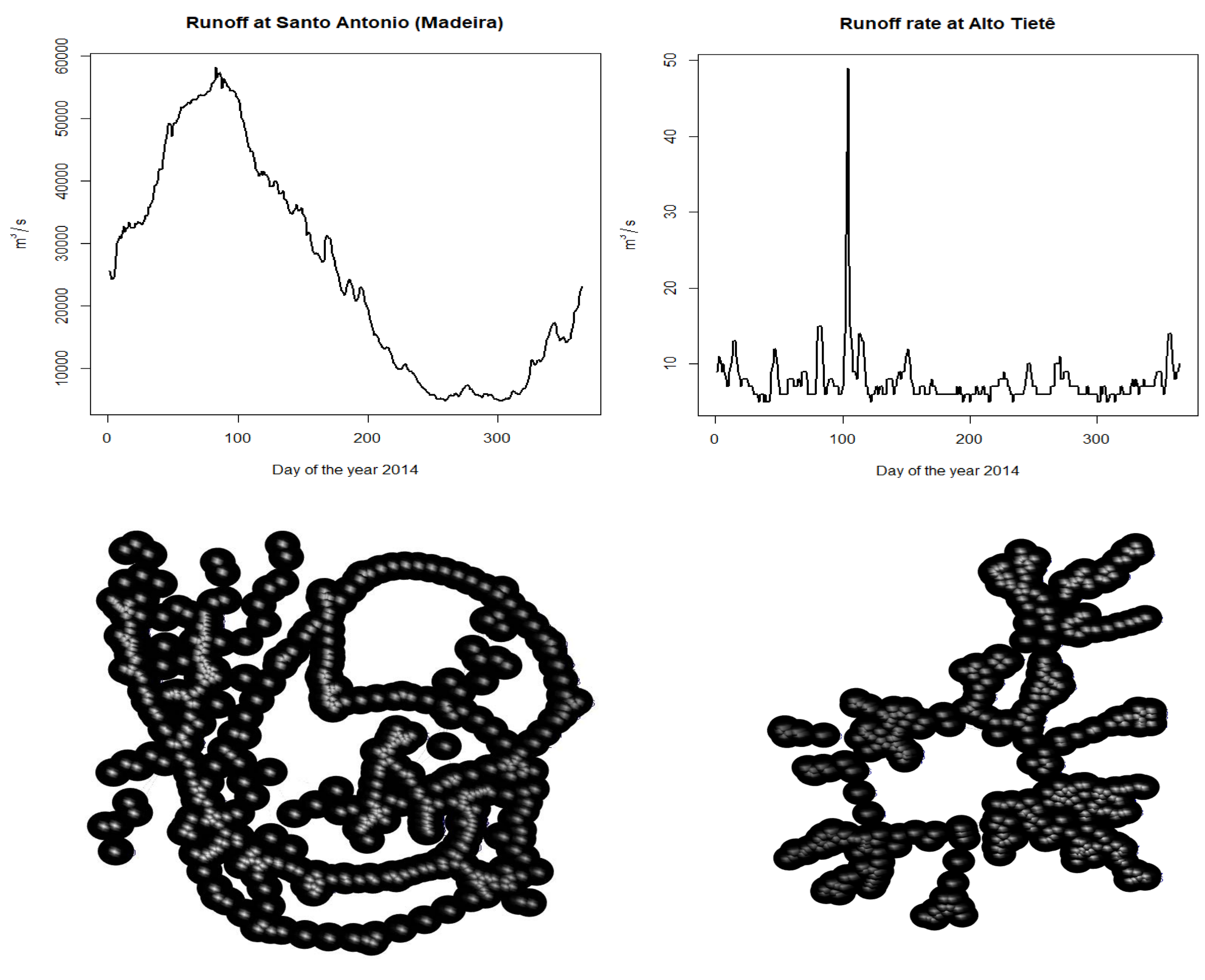

Figure 2. Upper part: One year (2014) of runoff time series for the largest (left) and the smallest (right) catchment. Ties have been removed by adding red noise with very small amplitude. Lower part: The corresponding HVGs. Note the very different topology.

Influence of seasonality and ties

We remove seasonality by subtracting mean flow values μ_i and normalizing by the standard deviation σ_i for given calendar days i. The two parameters are estimated within moving average windows of length ρ. The choice of ρ has a strong influence on the degree distribution, especially if there are many ties (Fig. 3).

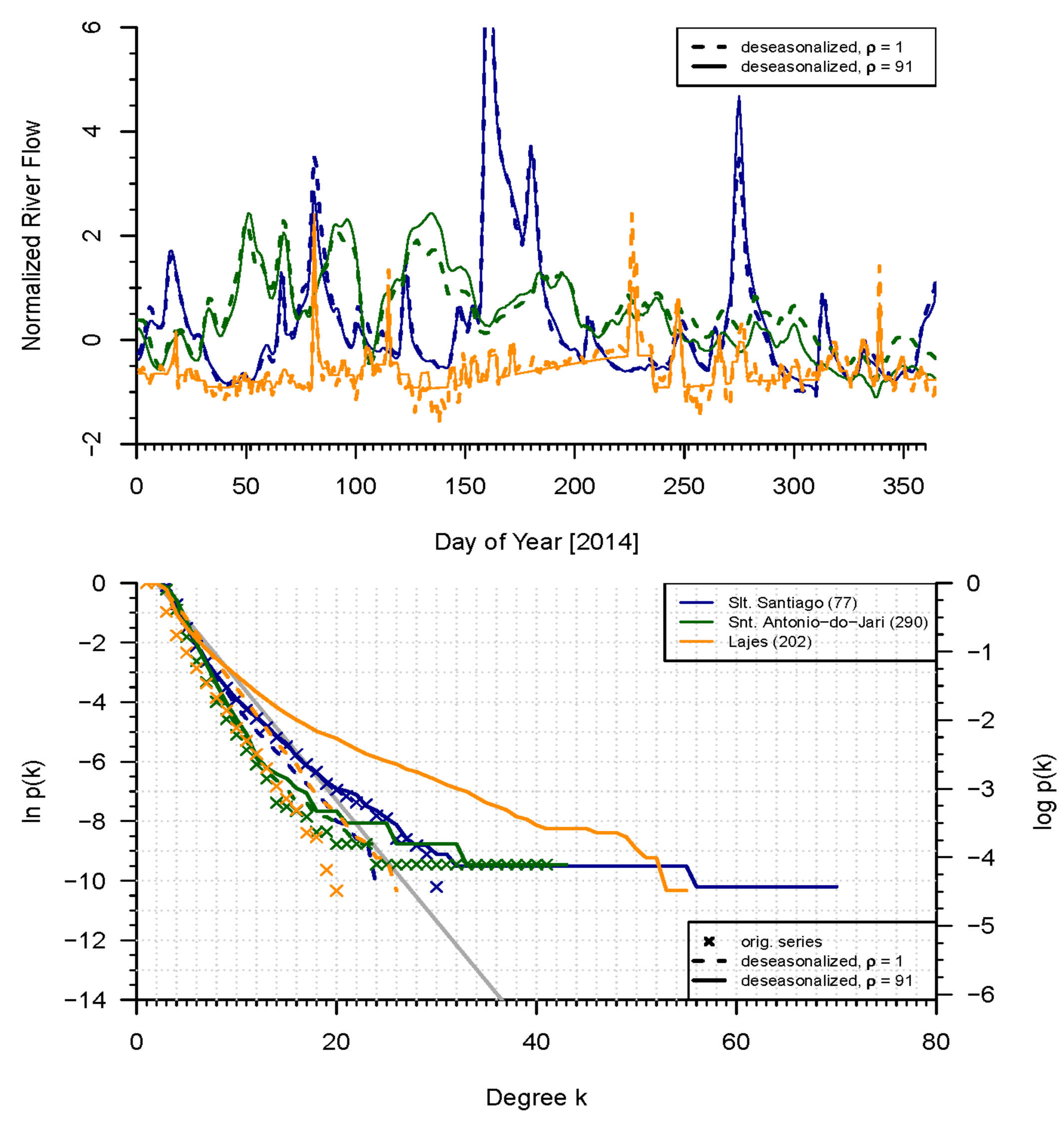

Figure 3. Alternative deseasonalization schemes change the slope of the degree distribution. The gauge Lajes contains 50% ties. The grey line is the white noise result.

The different deseasonalization schemes and the ties explain the discrepancy between claims that for runoff, $\lambda > \lambda_c$ for Brazilian data (Braga et al. 2016), but $\lambda < \lambda_c$ for US data (Serinaldi and Kilsby 2016). Choices of small ρ induce series that appear like $\lambda > \lambda_c$, while a smoothed seasonal cycle (high ρ values) induces "long tails" in the degree distribution, seen as $\lambda < \lambda_c$, most prominent for series with many ties.

Conclusions

- HVGs are analytical tools suitable to characterize the dynamics of runoff series.
- Preprocessing requires great care and might induce severe changes to the derived empirical degree distribution.
- Management of water resources is demonstrated to change the dynamics even if «natural» flow is reconstructed.

Are degree distributions for runoff exponentials?

The Generalized Pareto Distribution (GPD) contains the exponential as a special case for shape parameter $\xi = 0$. Independent of preprocessing, Brazilian runoff

HVG-degree distributions have long tails with $\xi > 0$ (Fig. 4).

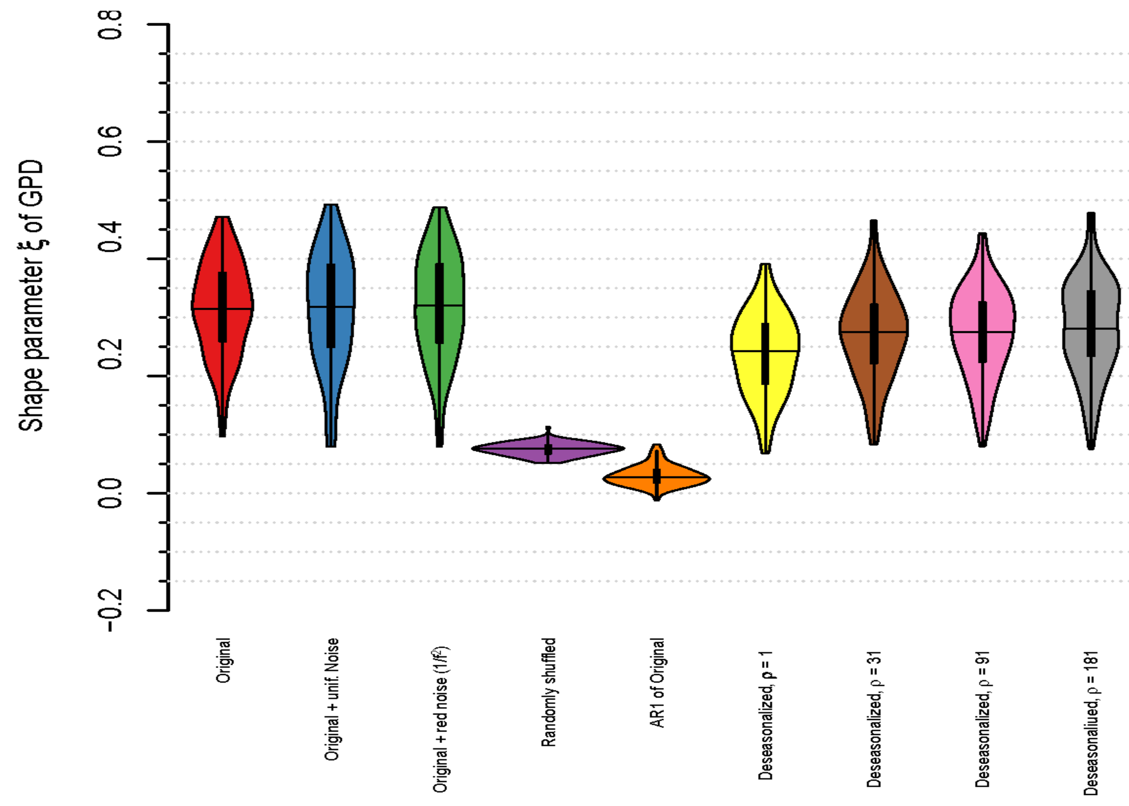

Figure 4. GPD fits to all degree distributions obtained from the Brazilian runoff data. Long tails with $\xi > 0$ are a robust property of the series.

Influence of the dam construction

Where possible, we calculated degree distributions for 20 year windows before and after the dam was built. In most cases, the dam increases λ, away from the random case (Fig. 5).

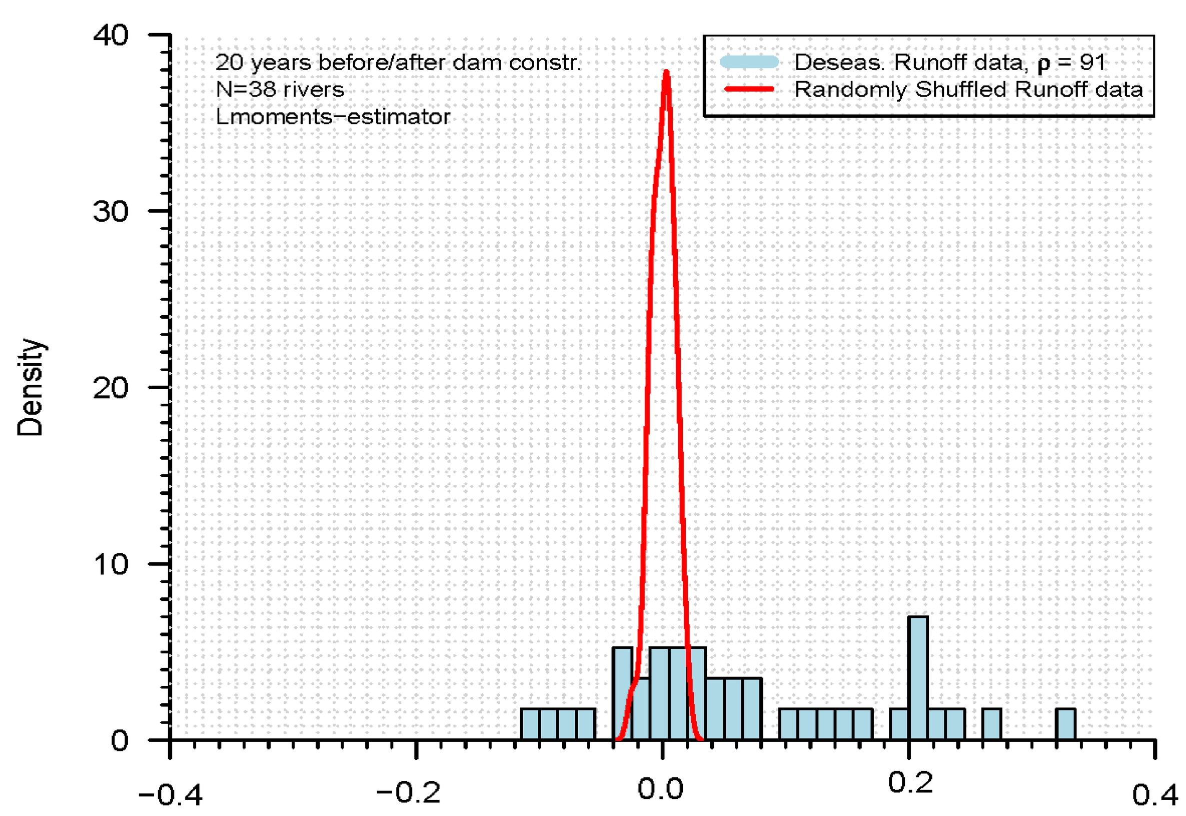

Figure 5. Differences between slopes for degree distributions after and before a dam was built at the site.

References

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