Validation of Baer-Babinet's Law using modern Landsat retrievals

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Abstract

In this study, I use a modern river erosion dataset created by Langhorst and Pavelsky (LP) in 2023 (LP 2023) to validate the long-standing contention behind Baer-Babinet's Law (BBL). This law postulates that rivers preferentially erode the right bank of rivers in the Northern Hemisphere and the left bank in the Southern Hemisphere, as a result of the Coriolis Force. Albert Einstein also published on this work in 1926. Since then, some modern authors have argued this effect is small and that local factors dominate the preferential erosion of rivers.

The LP 2023 dataset, derived from Landsat observations, validates BBL, and thus Einstein's theory. Interestingly, preferential riverbank erosion is observed for both large and slow moving rivers as well as small and fast moving rivers. This is inconsistent with conventional Geophysical Fluid Dynamics (GFD) theory, assessed via the Rossby number. Instead, a new scaling law is derived. Tentatively named the Babinet-Baer-Einstein (BBE) number, this number captures that BBL is consistent across all problem scales in LP 2023. The BBE number modifies the Rossby number by incorporating the effects of river depth and meander wavelength. Analysis of BBE reveals that it can be reduced to being purely a function of latitude, and is nearly independent of streamflow. This analysis indicates preferential erosion only ceases for rivers within 1-2° of the Equator.

Plain Language Summary

Baer-Babinet's law postulates that rivers in the Northern hemisphere preferentially erode on their right banks, and that rivers in the Southern hemisphere preferentially erode on their left banks. This phenomenon is explained to be a consequence of the Earth's rotation, acting via the Coriolis force. Baer-Babinet's law has captured the imagination of many scientists since the original idea was put forth in 1850, including Albert Einstein. However, nobody has been able to definitively prove or disprove it due to lack of good global data.

In this paper, I use a modern satellite dataset of river erosion to confirm Baer-Babinet's law. As the Coriolis force is relatively weak, one may expect that large and slow-moving rivers may experience a stronger effect than small and fast-moving rivers. Instead, it is revealed that both scales of river experience this preferential erosion effect. A new quantity is derived that incorporates the effects of river depth and curvature that predicts this preferential erosion effect. This new quantity can be simplified to being purely a function of latitude, further supporting the scale-invariance of Baer-Babinet's law.

Key Points

1. A modern global satellite dataset of riverine erosion is used to validate Baer-Babinet's law and resolve the long-standing open question.
2. Further analysis reveals that preferential erosion occurs for both large and slow-moving and small and fast-moving rivers alike.
3. A new dimensionless number is derived that better captures these Coriolis effects for riverine systems, tentatively named the BBE number.

1. Introduction

Baer-Babinet's Law (BBL) derives from the work of Babinet in 1859 and Baer in 1860. It postulates that riverbanks preferentially erode on the right in the Northern Hemisphere (NH), while those in the Southern Hemisphere (SH) erode on the left bank. This is attributed to the Coriolis force, which causes fluid parcels in the NH to tilt rightward (Fairbridge, 1968). Another examination of this phenomenon was done by Albert Einstein in 1926, presented to the Prussian academy of sciences. He attributed this phenomenon to the formation of a secondary circulation within each river bend (Fairbridge, 1968; Yogananda & Einstein, 2000).

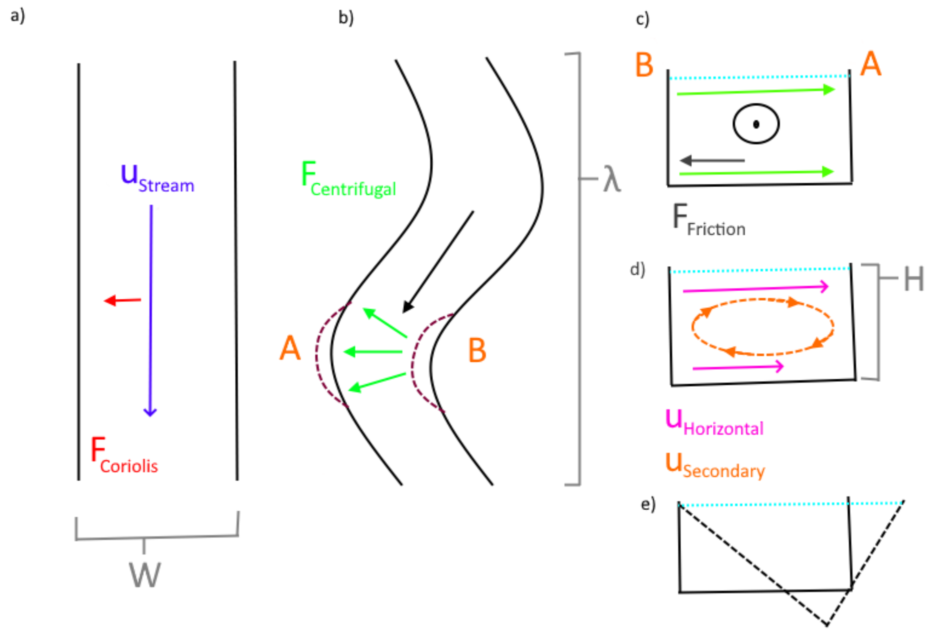

Figure 1. Definitions of variables used in text. 1a–e) Feedback process showing formation of meanders due to the development of a secondary circulation, as outlined in Einstein (1926).

Fig. 1a) shows a generic NH river flowing South. All NH fluid parcels are deflected to the right due to the Coriolis force, yielding F_{Coriolis}. Fig. 1b) shows the river after some time has passed, with the formation of meanders due to deposition of sediment at B and erosion at A. Regardless of the Coriolis force, parcels are accelerated during meanders outward by $F_{\mathrm{Centrifugal}}$. This induces a force through the length of the river, whose impacts are evident in the cross sections 1c–e). 1c) shows the forces acting over the river's cross-section, including F_{Friction} at the bottom boundary. This reduces the radial velocity at the bottom of the river compared to the top, resulting in $u_{\mathrm{Horizontal}}$ in Fig. 1d). To balance mass, this induces a secondary circulation in orange, $u_{\mathrm{Secondary}}$. Fig. 1e) shows the rough pattern of erosion this drives, leading to the black dotted profile. Einstein's theory is that F_{Coriolis} simply biases this existing secondary circulation feedback. However, other authors have argued that local processes are far more important to determine riverine erosion (Fairchild, 1932). Nonetheless, no author has been able to fully prove or disprove BBL, although alternative hypothesis have been suggested, such wind-driven aeolian processes (Goudie, 2004). This overall mechanism does not contradict modern river meander theory, which treats the formation of meanders as due to the growth of sinuous instabilities as a river erodes and accretes its banks (Seminara, 2006). These theories drop the Coriolis force a priori as the effective force is small for any individual river.

To celebrate 100 years of Einstein's original paper, I investigate BBL using modern river erosion data derived from Landsat by Langhorst & Pavelsky (2023) (LP 2023). With information from around 1.2 million river nodes, this dataset offers an unprecedented opportunity to statistically validate this classical conundrum in geomorphology. Matching BBL theory, I find that rivers in the NH preferentially erode on the right bank, while rivers in the SH preferentially accrete the right bank. Classical Geophysical Fluid Dynamics (GFD) defines the Rossby number as:

$$\mathrm{Ro} = \frac{u}{fW} \tag{1}$$

Which quantifies the ratio of inertial forces to the Coriolis force (Vallis, 2017). Here, u is the along-stream flow velocity, f is the Coriolis parameter, and W is the problem's length scale, taken here as the width along each cross-section of river . Conventionally, atmospheric and oceanic systems with $\mathrm{Ro} \ll 1$ are considered to be strongly affected by the Coriolis force. Ro is low for slow-moving and large-scale systems, like mid-latitude cyclones. However, the Rossby number is revealed to be a poor predictor of preferential river erosion, as even small-scale systems preferentially erode riverbanks in both hemispheres. Scale analysis reveals a new fluid mechanics number that explains the preferential erosion by correcting the Rossby number for river depth and meander wavelength. Tentatively called the Babinet-Baer-Einstein (BBE) number, it is defined as:

$$\mathrm{BBE} = \frac{uH}{fW\lambda} \tag{2}$$

Where H is the river's height (depth) and λ is the wavelength of the river if it were represented as a sinusoid.

2. Materials and Methods

The data used for this manuscript is entirely derived from LP 2023 (Langhorst & Pavelsky, 2023). LP 2023 contains data for river "nodes", sections of river roughly 200 meters long. Each node has information regarding river properties, including flow rate, coordinates, river width, and erosion properties on each bank. We filter for nodes with `n_chan_mod = 1`, i.e. rivers which are not branching. River erosion on the right bank was calculated as:

$$\begin{aligned}\text{Right Bank Change (RBC)} = &(\text{Right Accretion Rate} \times \text{Accretion Direction}) \\ &- (\text{Right Erosion Rate} \times \text{Erosion Direction})\end{aligned} \tag{3}$$

Yielding RBC in m/year. The Coriolis parameter, f, is calculated as:

$$f = 2\Omega \sin(\phi) \tag{4}$$

Where Ω is Earth's rotation rate of $7.2921 \times 10^{-5}\ \mathrm{s}^{-1}$, and ϕ is Earth's latitude. Rivers within the deep tropics (5°S–5°N) are not included in this analysis as their Rossby and BBE numbers approach infinity. River height/depth is estimated as per Leopold & Wolman (1960):

$$H = 0.27 \cdot Q_{\mathrm{Med}}^{0.4} \tag{5}$$

Where Q_{med} is the median flow rate at that node. The Q_{Med} is chosen over Q_{Mean} to avoid the effects of extreme events. Calculating H allows flow velocity in m/s to be determined as:

$$u_{\mathrm{Stream}} = \frac{Q_{\mathrm{Median}}}{H \cdot W} \tag{6}$$

This, combined with other data provided in LP 2023, allows for a Rossby and BBE number to be calculated for each node. The above pre-selection yields ~1,000,000 nodes in the NH and ~200,000 nodes in the SH. The BBE number's form was inspired by dimensional analysis, as described in the Results and Discussion section. Once a given dimensionless number is calculated, I filter out the node entries corresponding to the top 0.975 and bottom 0.025 percentile of data for that number, as extreme events may bias the scale analysis performed here. I then calculate the RBC while filtering for data between certain data-informed values of the dimensionless number, analogous to a bar plot, with non-overlapping intervals. Increasing each of the dimensionless numbers used here corresponds to decreasing the length scale and increasing stream flow. Error in RBC is estimated as:

$$\mu_{\mathrm{RBC}} \pm t_{\mathrm{stat}}(\mathrm{Sig} = 0.99,\ N_{\mathrm{df}} = N_{\mathrm{eff}}) \cdot \frac{\sigma_{\mathrm{RBC}}}{\sqrt{N_{\mathrm{eff}}}} \tag{7}$$

Where N_{eff} is estimated as $N/3$. This is a conservative estimate due to the strong autocorrelation present in the nodes. The assumption here is that knowledge of one node provides full knowledge of the nodes ahead of and behind that node. The resultant degrees of freedom are a third what one may expect from uncorrelated data. I then fit a log-transformed linear regression to understand the response of RBC to the variable at hand. I correlate RBC (y) with data binned by the chosen dimensionless number (Rossby or BBE, x-axis). Small values of the dimensionless number indicates river nodes with slower flow, higher latitude, and longer length scales. For the BBE number, small values also imply more shallow and rivers with longer meanders. Significance of this slope shows if there is a trend across problem scale, with the following hypothesis test:

- Null: There is no slope in RBC with respect to the chosen dimensionless number. Thus, problem scale has no impact on preferential right bank erosion.
- Alternate: There is a slope in RBC with respect to the chosen dimensionless number. Thus, the chosen dimensionless number captures that larger problem scales enhance preferential riverbank erosion.

The signed interpretation for the hypothesis test is different for the Northern Hemisphere (NH) and Southern Hemisphere (SH). In the NH, we would expect the slope to be negative, implying rivers erode less on the right bank for smaller problem scales. The opposite is true in the SH. Meanwhile, the intercept shows the typical response across all tested velocity-length scales. In the NH, we would expect the intercept to be positive, implying right banks preferential erode. Once again, the opposite is true in the SH.

3. Results and Discussion

3.1 Rossby Number Analysis

Fig. 2 shows the Right Bank Change (RBC), the net change between erosion and accretion on the right bank, for rivers in the NH and SH respectively. Each data point represents the mean RBC binned to by the Rossby number as given in the x-axis ticks. Conventional GFD theory would suggest that preferential RBC would be increased for smaller Rossby numbers. This would be evident as a negative trend in the fitted line for the NH.

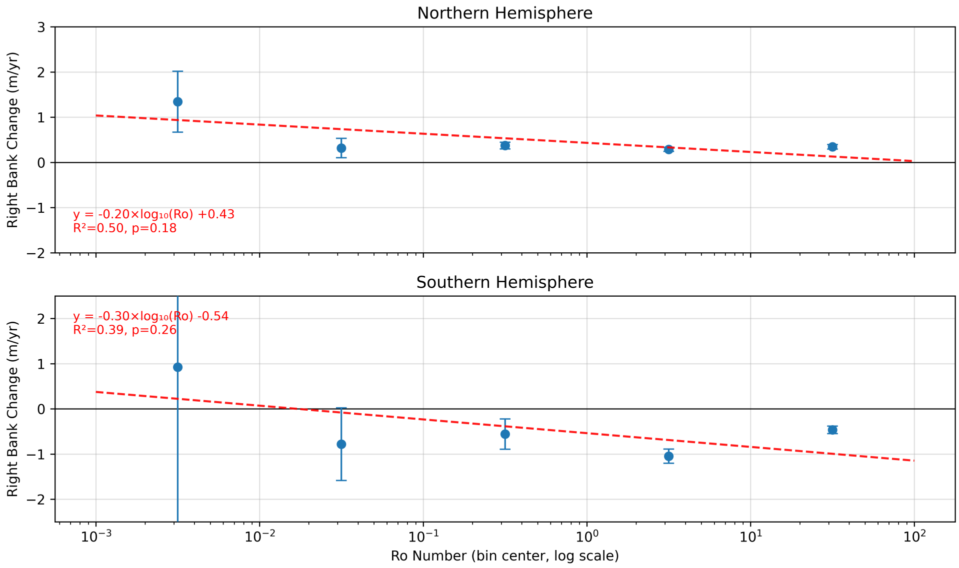

Figure 2. Right Bank Change (RBC) in m/yr (meters per year) as a function of binned Rossby number. Bins are centered with respect to x-axis ticks. Positive RBC implies erosion of the right bank, while negative RBC implies accretion of the right bank. 2a) RBC in the Northern Hemisphere, for data binned until Rossby number on the x-axis. 2b) Same as 2a), but for data in the Southern Hemisphere.

The fitted data confirms BBL, as the intercept is positive in the NH and negative in the SH. This indicates preferential erosion of the right bank of rivers in the NH and accretion of the right bank in the SH. However, there is a weak but non-significant negative trend present in the NH, indicating that Coriolis drift may weaken slightly for smaller and faster-flowing rivers. The negative trend in the SH is likely an artifact of the large errors present here, due to fewer rivers in the SH to average over. However, these slopes have p-values that are greater than the chosen significance level of 0.01, indicating that conventional Rossby dynamics are insufficient to explain these trends. Further, Fig. S1 reveals that the majority of preferential erosion in the NH occurs over high-latitude Siberian rivers, which may bias these results. Such rivers are not well-sampled in the SH due to the distribution of landmasses in the SH.

3.2 BBE Number Analysis

Motivated by dimensional analysis, I introduce the BBE number, which can be considered as a modification of the Rossby number:

$$\mathrm{BBE} = \mathrm{Ro} \cdot \frac{H}{\lambda} \tag{8}$$

This adjustment was not derived via analytical solutions of the Navier-Stokes equations. Rather, it is a dimensional analysis conducted via the Rayleigh method (Kurth, 1972). The relevant physical variables for this system were identified as stream width (m), stream depth (m), flow velocity (m/s), Coriolis parameter (s^{-1}), and meander wavelength λ (m). With five variables and two fundamental dimensions, Buckingham's π theorem implies there are $5 - 2 = 3$ dimensionless parameters that can be constructed to represent this system. The Rossby number is one such group, alongside the pure length ratios of W/λ and H/W. The BBE number is a combination of these dimensionless groups, collapsing Ro and the two pure length ratios into one variable. The BBE number was selected as it is is supported by the results that follow. Other dimensionless groups, such as using λ/H for the BBE number were attempted but did not yield consistent results. The physical interpretation of BBE is as follows: The strength of the secondary circulation should weaken for deep rivers, implying a multiplicative adjustment to Ro. The idea here is the strength of the secondary circulation is proportional to the gradient in radial velocities:

$$u_{Secondary} \sim \frac{du_{Horizontal}}{dz} \sim \frac{u_{Horizontal,Top} - u_{Horizontal,Bottom}}{H} \tag{9}$$

Which is stronger for shallower rivers. The interpretation of λ in the denominator is more complicated. Larger λ implies BBE should increase for straighter rivers. Further, λ is related to a given node's radius of curvature by the relation $R_c \approx 4.7\lambda$. Thus, greater lambda yields a larger radius of curvature (Langbein & Leopold, 1966). Gentler curves or a straighter river likely allow the Coriolis force to exert a stronger influence as the centrifugal force is weaker. Using λ in the BBE number is preferred over R_c as λ is directly reported in LP 2023 while R_c would be a derived quantity. Dividing by λ also ensures the BBE number is dimensionless.

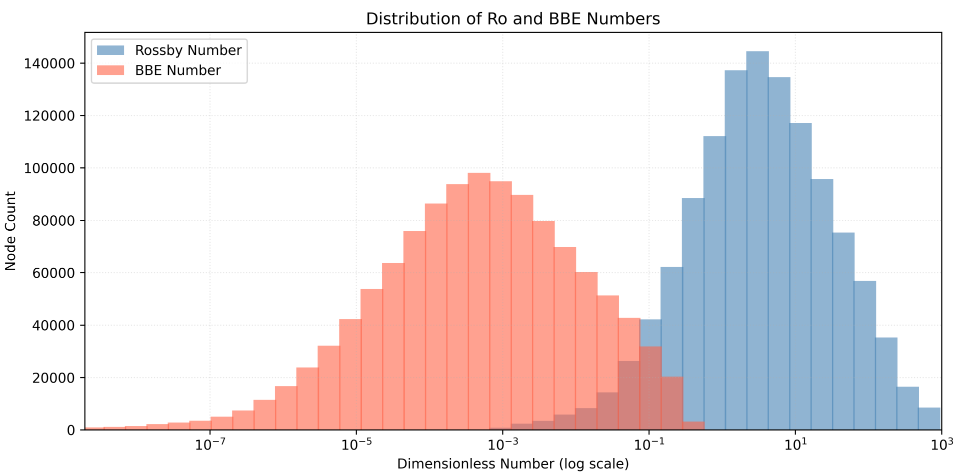

Figure 3. Distribution of Rossby and BBE numbers over the nodes in LP 2023

When calculated for the nodes in LP 2023, the BBE number is revealed to be systematically smaller than the Rossby number (Fig. 3). Assuming the interpretation of the BBE number is the same as the Rossby number, smaller BBE numbers should correspond to greater tendency of preferential riverine erosion due to the Coriolis force. Fig. S2 is an analogue of Fig. 1, but using the BBE number and more appropriate axis bounds. Data binned using the BBE number reveal preferential erosion of the right bank in the NH and preferential accretion of the right bank in the SH (Fig. S2a, S2b). There is no trend across problem scale for this phenomenon. Error bars also shrink considerably as compared to similar analysis for the Rossby number in Fig. 2. The predictive value of the BBE number is further supported by Table S1, which shows the RBC for data filtered by Ro or BBE. Preferential riverbank erosion in the NH is revealed to be roughly $+0.33\pm0.03$ m/yr and -0.53 ± 0.06 in the SH. In the NH and SH, increasing the Rossby number filter does not reduce the preferential erosion effect, as per Fig. 2. However, increasing the BBE filter highlights rivers with markedly weaker preferential erosion in both hemispheres. These results imply that the right banks of all rivers in the NH, regardless of length or flow velocity, erode just slightly more than the left banks, at least over the length-velocity scales observed by LP 2023.

3.3 Further Analysis of BBE Number

The constituent components of the BBE number, including river depth, width, flow rate, and meander wavelength, are not truly independent. Rather, they can all be expressed as functions of the riverine flow rate, as per Leopold & Maddock (1953); Leopold & Wolman (1957):

$$W = aQ_{Med}^{b} \tag{10}$$

$$H = cQ_{Med}^{f} \tag{11}$$

$$u = kQ_{Med}^{m} \tag{12}$$

$$\lambda \approx 36Q_{Med}^{1/2} \tag{13}$$

Where W H and u are related by mass conservation, such that $b + f + m = 1$ and $a \cdot c \cdot k = 1$. For a given station (i.e. node), $b = 0.26, f = 0.4, m = 0.34$. The parameters a, c, and k must be determined per-node. For the LP 2023 dataset, a was approximated as $a = W/Q_{Med}^{b}$. While its value shows considerable variability, its median value is roughly $O(100)$. The 95th percentile range of a ranges from ~50 to ~5000. All these results are order of magnitude approximations for river erosion processes, meaning that they only hold when averaging over a large number of rivers. Applying these substitutions to the BBE number, one obtains:

$$BBE = \frac{Q_{Med}^{0.5-2b}}{36fa^2} = \frac{1}{3.6 \cdot 10^5} \cdot \frac{Q_{Med}^{-0.02}}{f} \tag{14}$$

Which shows very weak dependence on Q_{Med}, whose term ends up being $O(1)$ for data from LP 2023. This implies the BBE number is primarily dependent on the f rather than streamwise flow rate. This supports the scale-invariance hypothesis: preferential riverbank erosion occurs for all rivers, small and fast-moving alongside large and slow-moving alike. Expanding f, setting a to 100, and dropping $Q_{Med}^{-0.02}$ for unity, one obtains:

$$BBE = \frac{1}{3.6 \cdot 10^5} \cdot \frac{1}{2 \cdot \Omega \sin\phi} \approx \frac{0.02}{\sin\phi} \tag{15}$$

Thus, BBE only depends on geographic location, and must be large only for rivers in the deep tropics. Indeed, BBE only crosses 1 when ϕ is less than 0.02 radians or ~1.15°. If a is set to 50, this increases to 0.08 radians or ~4.5°. On the other hand, ff a is set to 5000, then this drops to near-zero. As such, preferential erosion of riverbanks likely only fails to occur in the very-near equatorial region, which was excluded from the Rossby and BBE number analysis as the dimensionless numbers approach infinity. Table S2 shows riverbank erosion in the deep tropics, revealing a NH mean RBC of -0.17±0.05 m/yr and a SH mean RBC of -0.28±0.08 m/yr. As such, preferential erosion fails to occur in the NH but may still be active in the SH for nodes in LP 2023. Future research should focus on this key region where BBL likely breaks down. These results strongly indicate that rivers of all scales show preferential erosion of the right bank in the NH, and the opposite in the SH, but only outside of the deep tropics.

4. Conclusions

In this work, I used the LP 2023 dataset to validate the long-standing contention behind BBL. I find that the LP 2023 dataset confirms BBL, with preferential riverbank erosion in the NH being +0.33±0.03 m/yr and −0.53±0.06 m/yr in the SH. It is possible that these results may be biased due to the majority of the NH trends being dominated by high-latitude rivers located in Siberia. No such biases exist in the SH, although high-latitude rivers there are poorly sampled due to the relative distribution of landmasses in the NH vs. SH. Scale analysis revealed that conventional Rossby dynamics are insufficient to explain this phenomenon. Instead, the BBE number, a modification of the Rossby number, is derived, and is shown to better capture the key dynamics behind BBL, including scale-invariance. Detailed analysis of BBE reveals that it can be simplified to a pure function of latitude, further supporting the scale-invariance of BBL. Analysis reveals BBL likely only breaks down in the near-equatorial region. Future analysis may point towards fundamental laws regarding river curvature, the Coriolis effect, and erosion processes. Analytical solutions of the Navier-Stokes equations or long-running numerical simulations of riverine systems may also reveal if these simple scaling results hold under greater scrutiny.

5. Availability Statement

The LP 2023 dataset was downloaded from Langhorst & Pavelsky (2022). All research code used for data analysis and visualization is publicly available on Zenodo at Manapat (2026).

6. Acknowledgments

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7. Conflict of Interest

The author declares there are no conflicts of interest for this manuscript.

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