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Poyang and Dongting Lakes, Yangtze River: tributary lakes blocked by main-stem aggradation

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During its 6,300-km course from the Tibetan Plateau to the ocean, the Yangtze River is joined by two large lakes: Dongting Lake and Poyang Lake. We explain why these lakes exist. Deglaciation forced the ocean adjacent to the Yangtze mouth to rise ∼120 m. This forced a wave of rising water surface elevation and concomitant bed aggradation upstream. While aggradation attenuated upstream, the low bed slope of the Middle-Lower Yangtze River (∼2 × 10^{-5} near Wuhan) made it susceptible to sea level rise. The main stem, sourced at 5,054 m above sea level, had a substantial sediment load to "fight" against water surface level rise by means of bed aggradation. The tributaries of the Middle-Lower Yangtze have reliefs of approximately hundreds of meters, and did not have enough sediment supply to fill the tributary accommodation space created by main-stem aggradation. We show that the resulting tributary blockage likely gave rise to the lakes. We justify this using field data and numerical modeling, and derive a dimensionless number capturing the critical rate of water surface rise for blockage versus nonblockage.

alluvial river | lake | sea level rise | blockage | Yangtze

Significance

Tributaries of lowland rivers typically enter the main stem smoothly, without blockage. Rarely, however, the bed of the main stem forms a submerged step, creating a "blocked valley lake." The underlying cause is Holocene sea level rise, which drove main-stem aggradation. A blocked valley lake forms when the tributary does not have enough sediment to keep up. Examples such as Lake Murray in Papua New Guinea and the ria lakes of the Amazon Basin create extensive, ecologically valuable shallow water habitat. We show that the two largest lakes within China, Poyang Lake and Dongting Lake, are likely blocked valley lakes created by Holocene sea level rise.

Lakes may be formed by tectonic effects (e.g., Lake Baikal, Russia) and glacial gouging (e.g., Great Lakes, USA), and temporary lakes may be formed by flood overflow (e.g., Salton Sea, USA) and landslide and glacier damming (1). These lakes are bounded by solid boundaries (rock, debris, or ice). Here, we consider tributary blocked valley lakes (TBVLs), which are not only blocked by the aggrading bed of the main stem but also backwater driven by the rising base level. The phenomenon of blocked valley lakes along large, low-slope rivers was first recognized in Papua New Guinea. Fig. 1*A* documents a striking set of features on the Middle Fly-Strickland River system: each tributary forms a lake just as it joins the main stem (Fly or Strickland River). These lakes have been attributed to the effect of postglacial Holocene sea level rise (2, 3); i.e., ∼120 m over ∼12,000 y of sea level rise (Fig. 1*B*) forced rising water surface elevation up the 2 main stems. These channels, sourced in the Central Highlands, had enough sediment to aggrade in response to a rising water surface. The tributaries, which are sourced in the lowlands, did not. The main stems thus blocked the tributaries (4). The blockage is associated with a submerged step from the deeper lake to the shallower main stem (Fig. 1*C*). Such features were likely common when sea level stabilized (∼6,000 y ago). In Papua New Guinea, they persist today.

Here, we use the terminology TBVL to avoid confusion with river blockage due to, for example, landslides or glaciers. The mechanisms governing the formation of TBVLs are summarized in Fig. 1*D*, using the example of Bai Lagoon on the Middle Fly River (5). The main stem aggrades in response to the increase in water surface elevation. The tributary cannot keep up, and so a lake forms. When the floodplain water surface is higher than the main stem, nearly sediment-free water flows from lake to river. When the main stem is higher than the floodplain, sediment-laden water flows out of the main stem, forming a tie channel that connects the lake and the river (5). TBVLs can be found in other locations today, for example, the Amazon Basin (where they are called "ria lakes") (6) and South Africa (7).

Fig. 2 shows the two largest freshwater lakes wholly within China. Both are found on the Middle-Lower Yangtze River. Dongting Lake (upstream) and Poyang Lake (downstream) have surface areas of 2,623 km^2 and 3,860 km^2, respectively (8, 9), although these values can change rapidly and dramatically due to the shallow nature of the lakes. The Three Gorges Dam, which has been impounding water and regulating the flow of the Yangtze River since 2003, is a modern influence on the dynamics of the lakes through channel bed degradation and coarsening, for example (10–12). Extending previous arguments concerning the role of rising water level on river profiles (13, 14), here, we present a morphodynamic model that captures their formation.

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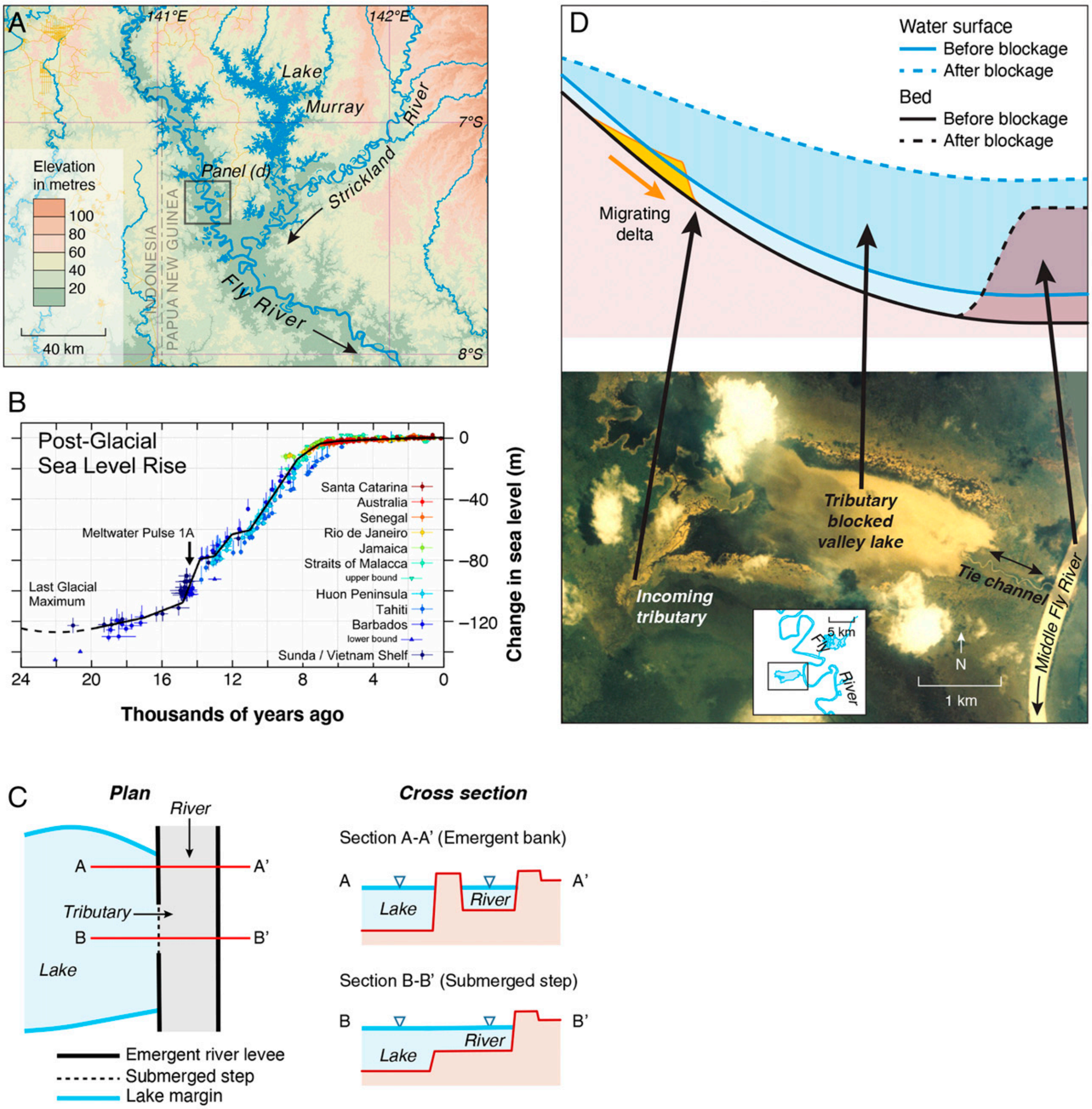

Fig. 1. (*A*) Middle Fly-Strickland River System, Papua New Guinea. The largest of the numerous tributary blocked valley lakes is Lake Murray, which drains into the Strickland River. Many others are found along the Middle Fly River. (*B*) Holocene postglacial sea level rise curve. The sea level rose ∼120 m worldwide over ∼12,000 y. From Wikimedia Commons, sourced in the Global Warming Art project (https://commons.wikimedia.org/wiki/File:Post-Glacial_Sea_Level.png). The Yangtze River and its tributaries were subject to this increase, which would have attenuated upstream. (*C*) Schematic diagram with plan and cross-section of main stem and tributary lake denoting the elevated step. (*D*) Bai Lagoon on the floodplain of the Fly River, Papua New Guinea, is a characteristic TBVL (5). It is connected to the main-stem Fly River by a bidirectional tie channel. Tributary aggradation has not kept pace with main-stem aggradation, leading to the formation of a blocked valley lake. The migrating delta at the upstream end of the lake is a response to base level stabilization.

More specifically, we demonstrate that the formation of the two large lakes was driven by main-stem base level rise, which in turn can be associated with Holocene sea level rise (3).

Morphodynamic Model of Formation of Tributary Blocked Valley Lakes

What is the specific formative mechanism of TBVLs? One can model the pattern of water surface rise and bed aggradation in response to sea level rise along the entire main stem of a river (e.g., the Fly-Strickland River System) (15). We do this for the case of the Middle-Lower Yangtze River in the *SI Appendix*, Text S3. This is not necessary, however, for a first morphodynamic model of the formation of TBVLs themselves. Here, we model a generic single tributary along a reach of the Yangtze River, with its mouth at the outlet of Poyang Lake (Fig. 2). We impose a range of rates of water surface rise b at the downstream end of the tributary, corresponding to the main stem. (As shown in the *SI Appendix*, Text S3, in the case of the Yangtze River, b can be loosely approximated by the rate of sea level rise at the mouth of the main stem.) We show that if this rate is small relative to tributary sediment supply, then bed aggradation along the tributary can keep up with base level rise. If this rate is large enough, however, tributary aggradation cannot keep pace, and a TBVL forms.

Our morphodynamic model has two key parts: the one-dimensional (1D) constant-width backwater equations of shallow water flow and the Exner equation of sediment conservation. The

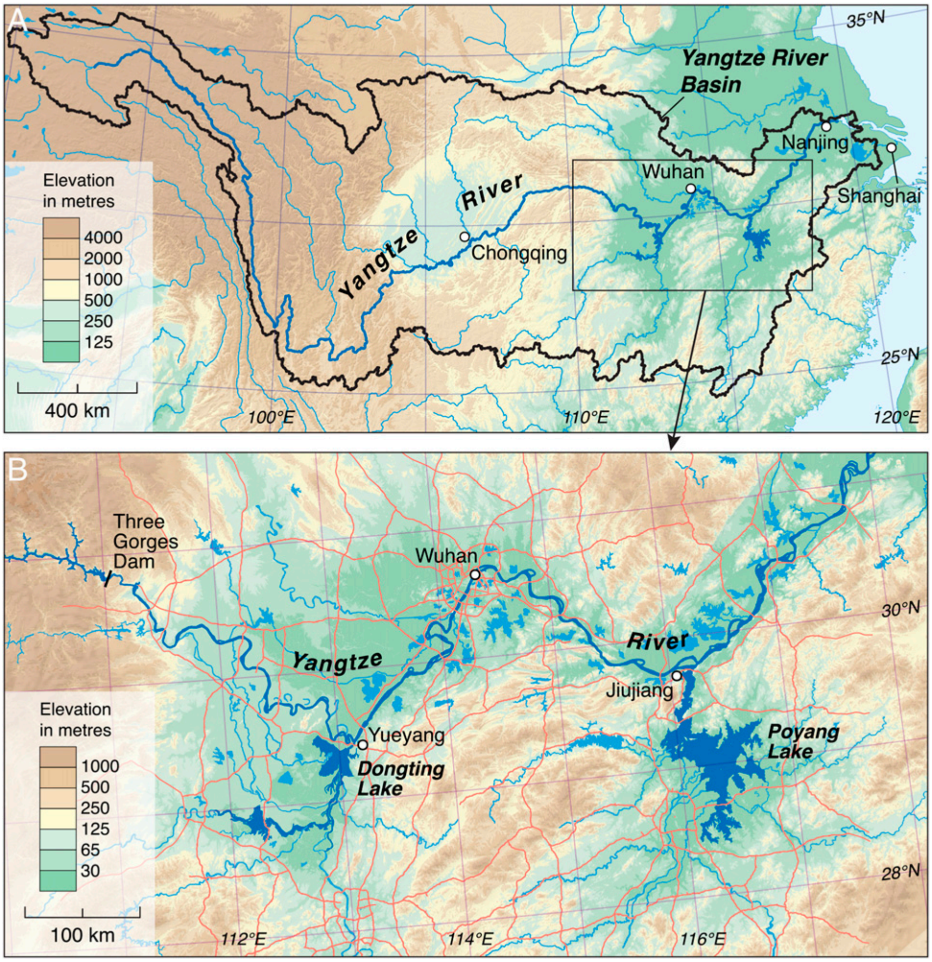

Fig. 2. (*A*) Drainage basin of the Yangtze River, China. (*B*) Dongting Lake and Poyang Lake.

backwater formulation is given in *SI Appendix*, Eqs. **S1** and **S2** of Text S2). The key parameters are as follows: streamwise distance x, time t, flow depth H, bed slope S, friction coefficient C_f, bankfull water discharge per unit width q_w, gravitational acceleration g, bed elevation η, water surface elevation $\xi = \eta + H$, L = reach length such that x = L denotes the downstream end of the reach, rate of main-stem water surface level rise b (specified in the downstream boundary condition), and Froude number $Fr = [q_w^2/(gH\ (3))]^{1/2}$. The dimensionless Chezy coefficient of resistance is Cz, where $C_f = (Cz)^{-2}$.

The backwater formulation is coupled to morphodynamics in terms of the Exner equation of sediment conservation (*SI Appendix*, Eqs. **S3** and **S4**). It involves the following parameters: q_s = volume sediment transport rate per unit width, q_{sf} = sediment feed rate upstream, λ_p = bed sediment porosity, and I_f = flood intermittency factor (16) (as explained in *SI Appendix*, Text S6). The sediment transport equation for predicting q_s is a calibrated version of the Engelund-Hansen formulation (17) (i.e., *SI Appendix*, Eq. **S5**). The key parameters are D = characteristic grain size, R = sediment submerged specific gravity, and β = calibration coefficient estimated in *SI Appendix*, Text S4.

In performing the calculation, we lump the Poyang feeder channels into a single tributary with a bankfull discharge per unit width q_w, which is some fraction of that of the main stem q_{wm}. We assume constant width, use discharge per unit width rather than total discharge because our calculation is 1D. Insofar as $q_w = Q_w/B_w$ and $q_{wm} = Q_{wm}/B_{wm}$, where Q_w and Q_{wm} are tributary and main-stem bankfull discharges, respectively, and defining B_w and B_{wm} as tributary and main-stem bankfull widths, respectively,

$$\frac{q_w}{q_{wm}} = \frac{Q_w}{Q_{wm}}\frac{B_{wm}}{B_w} \qquad [1]$$

Relations for hydraulic geometry for sand-bed rivers (18) can be used to show that $B_w \sim Q_w^{0.669}$, $B_{wm} \sim Q_{wm}^{0.669}$, and thus

$$\frac{B_w}{B_{wm}} = \left(\frac{Q_w}{Q_{wm}}\right)^{0.669}, \quad \frac{q_w}{q_{wm}} \equiv \varphi = \left(\frac{Q_w}{Q_{wm}}\right)^{0.331} \qquad [2a, 2b]$$

The drainage area A_{dp} for Poyang Lake is 1.62×10^5 km^2 based on the data at Hukou hydrological station (19), which is at the outlet of Poyang Lake. The drainage area A_{dyup} for the Yangtze River upstream of Poyang Lake is approximately 1.49×10^6 km^2 based on the data at Hankou hydrological station (19), which is near Wuhan. Assuming bankfull discharge to scale as area, we obtain the estimate

$$\varphi = \left(\frac{A_{dp}}{A_{dyup}}\right)^{0.331} = 0.480 \qquad [3]$$

The flow of calculation is as follows: for a given bed profile and rate of downstream base level rise, the backwater equation is solved upstream from the mouth. Then, the bed is allowed to deform in time, but satisfying the boundary condition of a set sediment feed rate q_{sf} upstream.

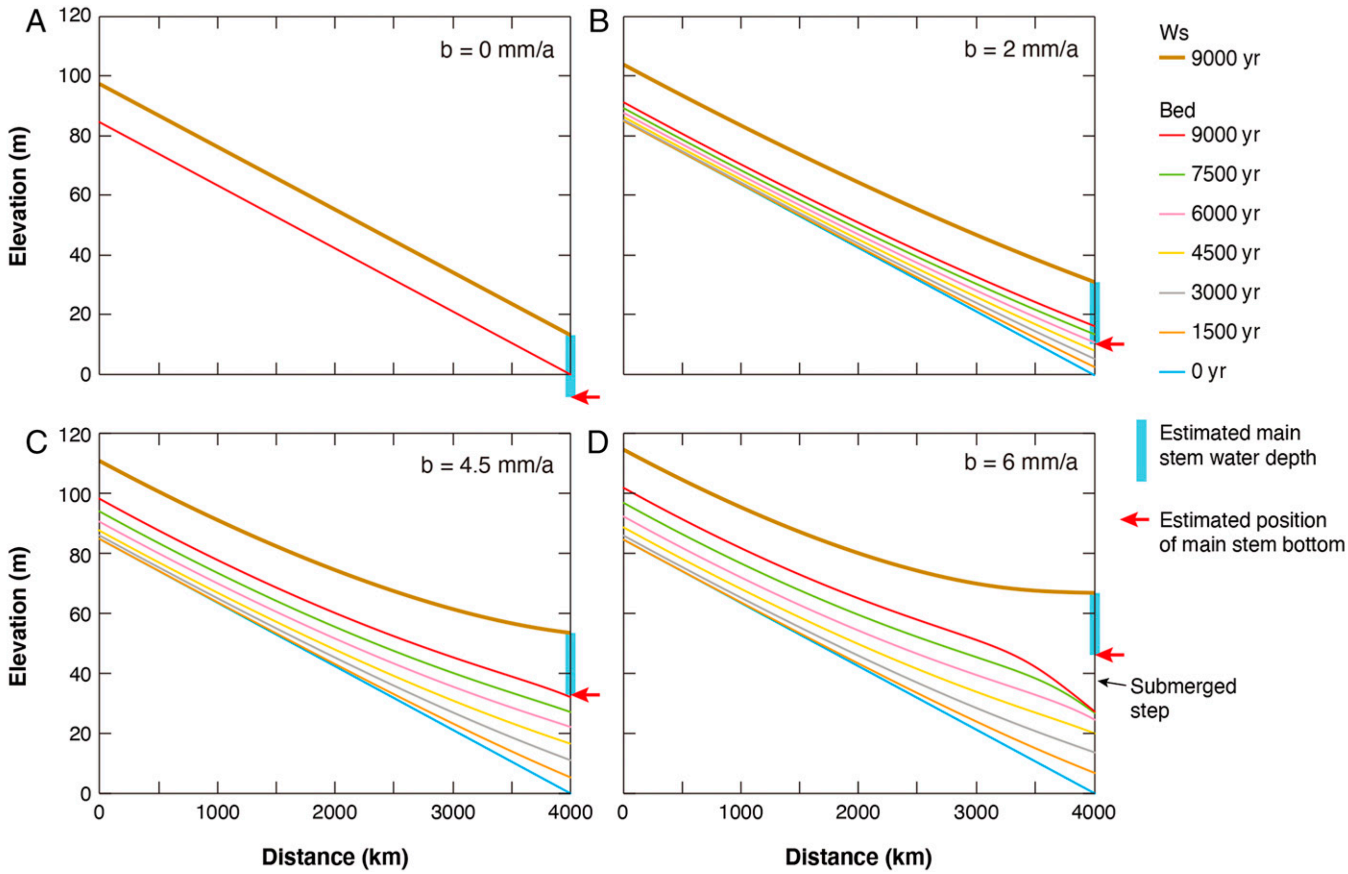

Fig. 3. Calculational results for 4 cases of base level rise: (*A*) b = 0 mm/y; (*B*) b = 2 mm/y; (*C*) b = 4.5 mm/y; and (*D*) b = 6 mm/y. A tributary blocked valley lake clearly forms for *D*, whereas the tributary is able to keep up with base level rise for *A* and *B*. *C* is slightly above the critical condition for blocked valley lake formation. The red arrow denotes the estimated position of the main stem after 9,000 y. Note that for b = 6 mm/y, the bottom of the main stem forms a submerged step 18.5 m above the adjacent lake bed.

This set q_{sf} is not user specified, but is computed as follows: the bed material and initial bed slope of the tributary are chosen, for simplicity, to be equal to those of the main stem, as would be expected in a broad lowland river valley. With the specified slope and discharge per unit width, depth and water surface elevation can be computed for normal flow conditions. Then, the value of q_{sf} is computed as the sediment transport rate associated with this normal flow condition. The effect of base level rise is to force the system out of equilibrium; we do this while keeping q_{sf} constant. This means that when the rate of base level rise b is zero, the tributary remains in grade, as shown in Fig. 3*A*. In this way, we isolate the rising base level as the only mechanism driving disequilibrium.

Specification of the sediment feed rate in this way ensures that the ratio of tributary sediment concentration to main-stem concentration drops nonlinearly as φ decreases below unity. This captures the condition that the tributary has a lower sediment supply than the main stem, becoming substantially lower as $\varphi \rightarrow 0$. It is this condition that lowers the ability of the tributary to compete with the main stem as the base level rises. The issue is explained in more detail in the *SI Appendix*, Text S5.

Basic Data

To implement the calculation, we used the following basic data (see also Table 1).

Calculational Examples. Here, we consider the case $\varphi = 0.480$, corresponding to our estimate for the Yangtze and lumped Poyang feeder channel bankfull discharges. Calculational examples with different values of φ are given in the *SI Appendix*, Text S7. The duration of the calculation is 9,000 y, so as to scale with the 12,000-y duration of Holocene sea level rise at 10 mm/y (25). A shorter duration, however, is sufficient to determine whether a TBVL forms (see below). The calculational domain is 4,000 km long, an overlong value purposely set to study asymptotic behavior. Shorter domains can also be considered. The downstream boundary condition corresponds to a fixed rate b of base level rise of the main stem at the tributary junction (not the sea).

Fig. 3 *A* and –*D* show calculations for rates of base level rise b = 0, 2, 4.5, and 6 mm/a, respectively. As noted above, in the case of b = 0, the tributary slope has been set so that it is in grade with the tributary (Fig. 3*A*). In the three following cases, the initial slope is the same as in case b = 0, but base water surface elevation is set to rise at ever-increasing rates, forcing the bed out of grade. For the case b = 2 mm/a (Fig. 3*B*), the bed is everywhere upward-concave over the 9,000 y of simulation.

The incipient condition between nonblockage and blockage is the borderline between a bed slope at the downstream end that decreases downstream (no blockage) and increases downstream (blockage):

$$\left.\frac{\partial S}{\partial x}\right|_{x=L} = 0 \qquad [4]$$

Beyond this point, the tributary river spreads out as a lake, and our 1D model is no longer accurate. Nevertheless, we show

Table 1. Basic Data for the Yangtze River near Wuhan

Parameter	Value
Bankfull discharge Q_{bf}	38,500 m^3/s (20)
Bankfull depth H_{bf}	21 m (20)
Bankfull width B_{bf}	1,250 m (20)
Bed slope S	2.12×10^{-5} (20)
Characteristic grain size of bed D	0.17 mm (20)
Porosity of bed sediment λ_p	0.4
Flood intermittency factor I_f	0.73
Mean annual sediment load Q_{smean}	402.2 Mt/y (21)
Mean annual bed material load $Q_{sbm,mean}$	90.1 Mt/y
Dimensionless Chezy resistance coefficient C_z	22.22
Drainage area, Poyang Lake	1.62×10^5 km^2
Drainage area, Yangtze River upstream Poyang Lake	1.49×10^6 km^2

The dimensionless Chezy resistance coefficient is calculated via bankfull characteristics; $Cz = [q_w^2/(gH^3S)]^{1/2}$. The sediment load includes 2 modes of transport: bed material load, which corresponds to the part of the sediment load that exchanges with the bed (and thus contributes to morphodynamics), and washload, which corresponds to the part of the sediment load that is transported through without exchange with the bed. Based on a measured bed surface grain size distribution, 62.5 µm can be used as the cutoff size for washload (22). The fraction of load that is bed material load is then estimated (23). Using the mean annual sediment load and the fraction of bed material load, we then computed the mean annual bed material load. Flood intermittency factor is estimated based on the data for daily water and sediment discharge of the Middle Yangtze River (24). The method for computing it is outlined in the *SI Appendix*, Text S6.

ponding predicted by our 1D model for illustrative purposes. For the conditions of Fig. 3, the incipient condition is reached for a value of b slightly below 4.5 mm/y (Fig. 3*C*); The formation of a zone of ponded water is clear when b = 6 mm/y (Fig. 3*D*).

The calculations show that a lumped tributary similar to the sum of those that flow into Poyang Lake and Dongting Lake is sensitive to even modest rates of base level rise. As noted above, Holocene sea level rise can be approximated as 10 mm/y for 12,000 y (25). Although this rate should have attenuated upstream of the mouth of the Yangtze River, even values corresponding to less than half of this rate would be enough to block our model tributary. We conclude that Poyang Lake, and by implication, Dongting Lake, are likely TBVL lakes.

A point deserves clarification. The analysis presented here is 1D, whereas lakes are 2D. This is not a problem, as long as we search for the incipient condition for blockage, up to which the channel remains 1D and does not overflow. Below this condition, the tributary can construct a floodplain, and thus maintain a distinct channel flowing into the main stem. Above this condition, bed morphodynamics detach from water surface change, and the flow can spread laterally to form a wide lake. We do not model this lateral spread here.

Dimensionless Rate of Rise of Main Stem for Tributary Blocking

The above analysis for the incipient formation of TBVL can be cast in dimensionless, and therefore, quasi-universal form. Details are given in the *SI Appendix*, Text S8. The key dimensionless numbers are as follows: blocking number **Bl** and blocking time $\mathbf{T_b}$, characterizing the dimensionless rate of main-stem water level rise and dimensionless blocking time, respectively.

$$\mathbf{Bl} = \mathrm{F}(\mathbf{T_b}); \quad \mathbf{Bl} = \frac{(1-\lambda_p)bH_n}{q_{sf}S_nI_f}; \quad \mathbf{T_b} = \frac{t_b q_{sf} S_n I_f}{(1-\lambda_p)H_n^2} \qquad \textbf{[5a, 5b, 5c]}$$

where t_b is the dimensional time for incipient blockage, and subscript n denotes values under normal flow conditions. It is seen from Fig. 4 that when the blocking number is high (e.g., 0.8), the time to blocking is short ($\mathbf{T_b}$ ~0.58–0.78 for the range $\mathbf{Fr_n}$ = 0.05–0.8). The time to blocking increases as the blocking number decreases, and reaches infinite time to blocking as $\mathbf{Bl} \to 0$. For reference, a line corresponding to $\mathbf{Bl} = 0.11$ is shown in Fig. 4. This corresponds to $\mathbf{T_p} = 50$; for the case of Poyang Lake, it translates to 40 ka of sea level rise—far longer than the period of Holocene sea level rise associated with the end of the last glaciation. In the *SI Appendix*, Text S9, we conduct a Froude scaling analysis to explore the dependence of time to incipient lake formation on spatial scale.

Discussion

We have performed the analysis above using a single bed grain size to characterize the bed. In *SI Appendix*, Text S10, we have generalized to the case of a mixture of bed sediment sizes, using the transport relation designed for mixtures of sand (26). The results using a mixture prove to be very similar to those using a single grain size.

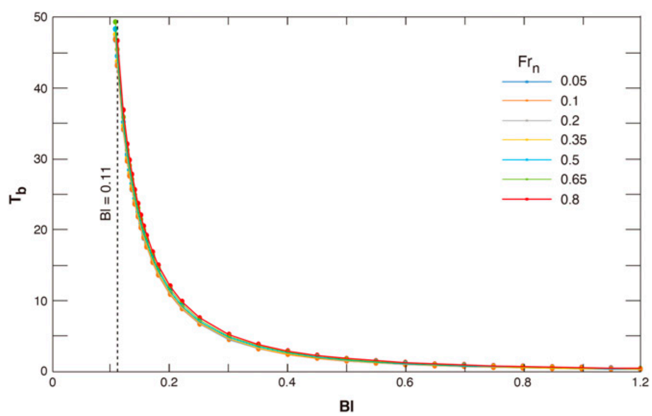

Fig. 4. Dimensionless relation between dimensionless main-stem rate of water surface rise **Bl** and dimensionless time for the incipient of blockage $\mathbf{T_b}$. The results collapse over a wide range of tributary Froude numbers at normal flow $\mathbf{Fr_n}$ (i.e., when the tributary is in grade with a main stem that is not subject to base level variation). When the blocking number **Bl** reaches the value 0.11, the dimensionless time to blockage takes the value 50. In the case of Poyang Lake, this corresponds to 40 ka of sustained sea level rise (i.e., far longer than the observed postglacial value).

In the interest of obtaining a global perspective, it is useful to compare the surface areas of Poyang Lake and Dongting Lake with those of other TBVLs outside China. As noted above, Poyang Lake and Dongting Lake had the respective surface areas of 3,860 km^2 as of 1998 (9) and 2,623 km^2 as of 1995 (8). The corresponding area of Lake Murray, the largest blocked valley lake in Papua New Guinea, has been reported to be 647 km^2 (27). In the Amazon Basin, these lakes are known as ria lakes (28). In *SI Appendix*, Text S1, we performed a remote-sensing analysis of the areas of the seven large Amazon ria lakes between 2007 and 2016; the largest area we found was 2,225 km^2. Such lakes should have been much more common at the end of the Holocene sea level rise, but have since filled with sediment. In *SI Appendix*, Text S11, we show examples of ancient TBVLs in southern Illinois, USA.

The status of the Poyang and Dongting Lakes is, however, in jeopardy. Channel degradation of the Yangtze River associated with the Three Gorges Dam, extensive dredging that has partially removed the submerged step, occasional lake drying, and encroachment by farmers have taken a toll (29–31). In addition, ecosystem services are being lost as the lakes degrade (32). One legacy of the last ice age is being lost in the Anthropocene. The importance of these lakes is also emphasized by the fact that Poyang Lake reached its highest stage on record in July 2020, during historic floods on the Yangtze River. Future sea level rise at rates estimated to be 7–11 mm/y may cause expansion of the lakes, or at least may mitigate lake shrinkage due to anthropogenic factors (33). Our model could be coupled with a model of bed degradation and a model of main-stem response to sea level rise (34) to address this question.

Conclusions

The 120-m Holocene sea level rise has left legacies around the world in terms of TBVLs. These lakes can be found in Africa (KwaZulu Natal), South America (Amazon River Basin), Papua New Guinea (Fly-Strickland River Basin), and East Asia (Yangtze River Basin). They exist because the main stem has responded to water surface level rise by aggrading, but the tributaries have not, due to the relative unavailability of sediment. As the main stem has aggraded, the river has forced backwater up tributaries, and the river bed has formed steps that block the tributaries and create lakes. Here, we develop a general numerical model to describe tributary blockage via main-stem base level rise and apply it to the formation of Poyang and Dongting Lakes, China. We conclude as follows:

- Although several authors have inferred that Poyang and Dongting Lakes were caused by sea level rise, we offer a morphodynamic model that specifically explains the mechanism of formation of these and other TBVLs around the world.
- In the case of Poyang Lake, a base level rise of 4.5 mm/y is sufficient to force the formation of a TBVL; this is considerably smaller than a mean sea level rise of 10 mm/y for 12,000 y, and represents the attenuation of the effect of sea level rise in the upstream direction.
- Our analysis shows that if the tributary is forced to have the same initial bed slope as the main stem (as would be expected in a broad lowland river valley), then it will in general fail to have the sediment supply necessary to keep up with main-stem bed aggradation.
- The problem of incipient TBVL formation can be characterized universally with three dimensionless numbers: blocking number $\mathbf{Bl}$, dimensionless blocking time $\mathbf{T_b}$ and Froude number $\mathbf{Fr}_n$. The influence of the Froude number is weak.
- If a sufficiently long amount of time passes, then the TBVL is eventually filled with sediment. This has not yet happened in the case of Poyang and Dongting Lakes.

The only limiting factor in the application of the model to other TBVLs, such as those on the Fly River, Papua New Guinea, and the ria lakes of the Amazon River, Brazil, is a lack of input data. The model can also be used to study postglacial blocked tributaries that have subsequently filled with sediment.

Materials and Methods

Numerical analysis of morphodynamics was carried out using a standard backwater calculation and an Euler time step method applied to the Exner equation of sediment conservation. Analysis of remotely sensed images was used to characterize planform characteristics of lakes.

Data Availability. Data applied in the analysis of this paper, including hydraulics and sediment transport in the Yangtze River, were obtained from the published literature (19, 24). The codes used in the analysis are available in the GitHub repository at https://github.com/acg08/Blocked_Valley_Lake_Poyang. All other study data are included in the article and/or *SI Appendix*.

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