Limited role of discharge in global river plastic transport

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Abstract

River plastic transport has been assumed to be driven by river discharge, although observational data does often not support this. We propose a new perspective that describes plastic transport as function of plastic availability and transport capacity. Plastic transport is under most circumstances driven by plastic availability, which is largely disconnected from river discharge. However, when river discharge is very low or very high, transport capacity becomes the dominant factor.

Main text

Plastic pollution in the environment is a wide-spread issue and has steadily gained traction in scientific community, the media, and the general public in the past decades. At the end of 2022 the United Nations Environment Programme (UNEP) adopted a resolution to limit plastic pollution and it intends to convert this to a binding treaty as soon as 2024 (UNEP 2022). Initially, the primary focus on this matter was directed towards marine litter, exemplified by discoveries such as the Great Pacific Garbage Patch (Derraik 2002, Li *et al* 2016). Later, this focus shifted more towards riverine plastic pollution when it was realised that rivers are an important transportation pathway, driving the spatial redistribution of land-based plastic and are likely an important of source of plastics in the world's oceans (Mai *et al* 2020).

Understanding how, how much and where this plastic is transported is needed to devise and implement effective prevention and reduction efforts. To this end, a range of models were introduced, with the goal of predicting the amount of plastic emitted from each river globally into the oceans. Although these models are quite different in nature, they broadly speaking use three different data categories to make the predictions: observations of plastic within the rivers, runoff or river discharge, and data describing the amount of plastic entering the river catchment. The models are designed to use assumed relationships between discharge, catchment plastic pollution, and the plastic found in the rivers and use these to predict the plastic transport flux in rivers without plastic observations. Examples are the models proposed by Lebreton et al. (2017), Schmidt et al. (2017), Mai et al. (2020) and Meijer et al. (2021).

The main assumption behind these models is that river plastic transport scales with discharge. Intuitively, this premise makes sense. In small rivers and creeks, the transport of large items is not typically expected, and if a river falls dry, all transportation comes to a halt. Larger rivers and higher discharges can carry very large amounts of plastic (Hurley *et al* 2018). Under flooding conditions even household items, vehicles, (parts of) infrastructure and buildings can be transported (Bayón *et al* 2024). Modelling the river plastic transport in this way is also in line with the conceptually similar and extensive literature on river sediment transport, where discharge and sediment mass transport are correlated, and heavier sediment requires higher discharge to be mobilised (Zhang *et al* 2021). However, observations of plastic in rivers show ambiguous results. Observations in many of the rivers in which plastic was monitored more than once did not show any significant relationship between discharge and plastic flux (e.g. Castro-Jiménez *et al* 2019, Schirinzi *et al* 2020, Van Emmerik *et al* 2022, Constant *et al* 2020).

Nevertheless, global riverine plastic models such as the one presented by Lebreton et al. (2017) show a good correlation between discharge and the plastic flux when comparing different rivers. The question is if this correlation is confounded with other factors that coincide with these river basins. By analysing the rivers that were at the base of the model in Lebreton et al. (2017), we found that besides the plastic transport (ρ=0.978), also the river basin population is correlated strongly to discharge (ρ=0.997) (using the data in the HydroATLAS, see Figure 2). This makes sense, as population centres are often connected to major rivers and streams for historical reasons (Best 2019). As the occurrence of plastic in the environment can be directly attributed to anthropogenic influence, riverine plastic is likely correlated to population (density), and it becomes impossible to infer cause and effect and therefore implicitly to validate model performance. In this paper we attempt to take a step back and provide a perspective on why the relation between discharge and riverine plastic observations show contradictory results and how this can be used in further measurements and model development.

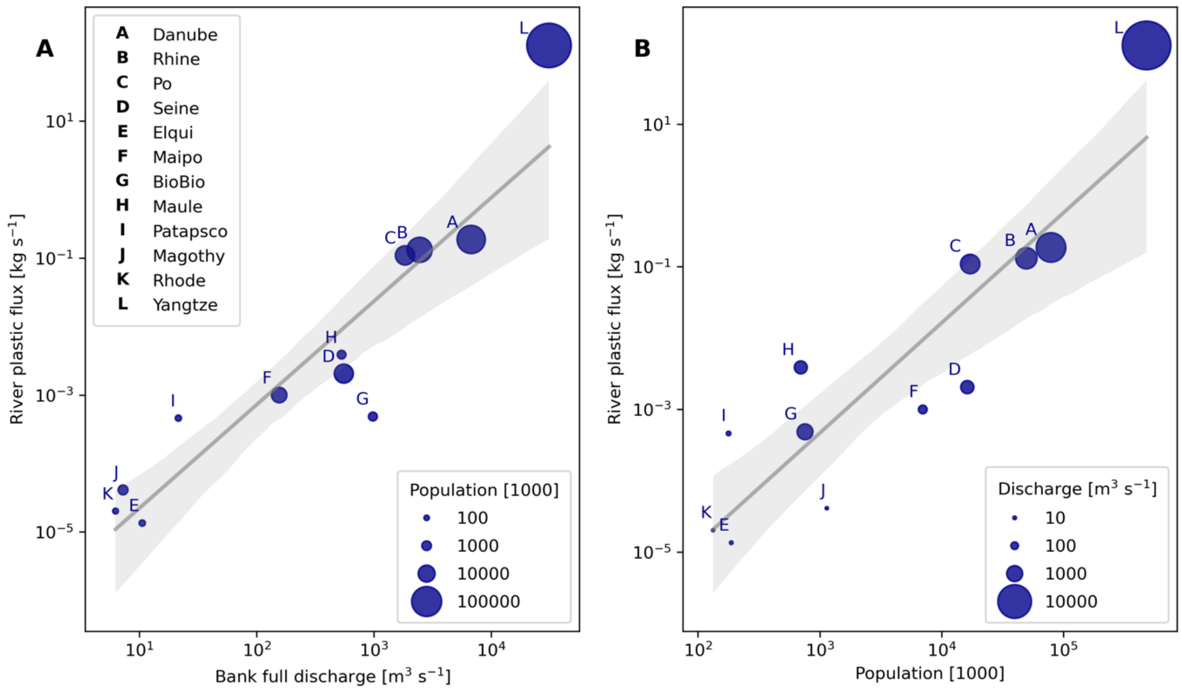

Figure 1: Correlation between plastic flux, population, and discharge. In panel (A) the relationship between bank full discharge and river plastic is presented, while (B) shows the correlation with population density. In panel (A) the population abundance is used to scale the points, while in panel (B) the discharge is used. The riverine plastic flux is highly correlated to both discharge and population, making causal inference impossible. The data for this figure was obtained by matching the records in the Lebreton et al. (2017) paper with the HydroATLAS database, which records basin polygons, population abundances and bank full discharge at the river mouth.

A unifying model for riverine plastic transport

Whereas global models do show a (possibly confounded) relation between discharge and the riverine plastic flux, many observations do not exhibit such a correlation under non-flood conditions. We propose to resolve this apparent paradox by reaching back to concepts used in the field of river sediment transport, splitting transport into two different components: the transport capacity of the river and the sediment availability for transport. Increasing discharge increases sediment transportation in almost all cases, constrained by the availability of sediments (Zhang *et al* 2021). We propose that the same concept can be applied to river plastic transport. Both the transport capacity and plastic availability are to some extent driven by or correlated to discharge (more on this below) but are fundamentally very different concepts. They can be encapsulated in the following equation:

$$P(Q) = \min(T(Q), A(Q))$$

Where P(Q) is the river plastic transport, T(Q) the amount of plastic that can be transported by the river (transport capacity) and A(Q) the available plastic for mobilisation, at discharge Q. The plastic flux is equal to the most constraining factor. This concept is graphically represented in Figure 2. Transport capacity grows exponentially at low discharges (as in sediment transport (Zhang *et al* 2021)), possibly being limited by stream characteristics in larger rivers (possible trajectories are drawn in light grey). Plastic availability remains approximately constant for a given river (fluctuations around this line are expected due to specific human activities) below a certain threshold (shown as T2), after which it can increase stepwise. These steps represent activations of additional reservoirs or sources of plastic, such as when a river overflows its banks at high discharge events (Liro *et al* 2020). The discharge at which the plastic flux switches from being transport capacity (or discharge) limited to plastic availability limited is denoted with T1. Below this threshold, such as in small streams and intermittent rivers, a positive correlation between the observed plastic flux and discharge could be found. Between T1 and T2, plastic availability is the limiting factor, but does not change with discharge, which yields no correlation. At high discharges (above T2), a positive correlation can again be found between plastic and discharge. Finding a statistically significant correlation between discharge and the plastic flux in observational studies depend on where the observations fall in this discharge plastic domain. Below we discuss transport capacity and plastic availability more in depth, describing the transitions and trends in Figure 2.

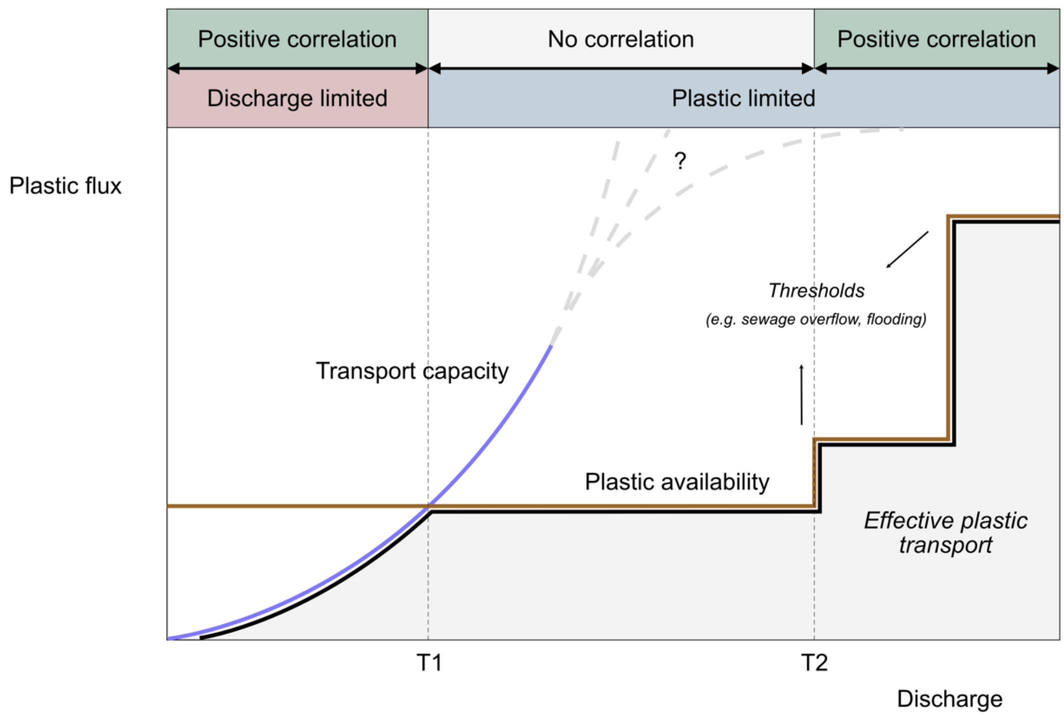

Figure 2: Conceptual model of the relationship between river discharge and plastic flux. The plastic availability is largely unrelated to discharge, except when thresholds are exceeded, such as during a sewage overflow or a flood exceeding the riverbanks. Threshold T1 describes the point where plastic availability becomes the main limiting factor in describing the riverine plastic transport instead of the transport capacity of there river. Threshold T2 highlights the point in which discharge starts playing a role in the availability of plastic for transport.

Transport capacity

The plastic transport capacity of a river is mainly determined by discharge - which expresses the force of the water to move objects - and river morphology as well as by the characteristics of the plastic items. Together they determine if the stream has the capacity to mobilise the item and if the item is transported at the surface of the water, in the water column or as bedload transport. Transport dynamics depends on the stream characteristics. In strongly vegetated streams for example, transport capacity can be reduced (Przyborowski *et al* 2024). These processes are physically driven but can be altered by anthropogenic factors. By the introduction of weirs or other flow control structures (Hoellein *et al* 2024), local deposition can be favoured over transport. A limited transport capacity is the cause of transportation halting when a stream falls dry. Determining the transport capacity can be studied with experiments and comes conceptually closest to the global river plastic flux model formulations described above.

More often than not, transport capacity is not the factor that effectively limits the transport of plastic, hence the non-correlation between discharge and plastic in field surveys. To demonstrate this, we ran a simple (numerical) experiment. To quantify the plastic transport capacity of a river, we assumed it being covered with a layer of buoyant plastic spheres with a diameter of 2.5 centimetres, and calculated how many could be transported in a given period of time. We applied this method to ten rivers, from three continents and spanning almost five orders of magnitude in discharge, where floating plastic items were observed and counted from bridges with a standardized protocol (Van Emmerik *et al* 2023, Meijer *et al* 2021, González-Fernández *et al* 2021, Van Emmerik *et al* 2020). The bank full discharge and river characteristics were taken from the HydroATLAS database (Linke *et al* 2019) (Figure 3). We found that none of the rivers used more than 0.1% of the estimated transport capacity, with the largest rivers (Danube and Rhone) showing a six orders of magnitude difference between observations and transport capacity. Additionally, we found that even the highest plastic observation count, that happened under flood conditions in the Meuse River (The Netherlands) and in the Motagua river in Guatemala, could be transported in the 30-meter-wide Fiumicino canal (HydroATLAS) (Rome, Italy) under average flow conditions. With this amount of plastic, the transport capacity of the Fiumicino canal would still only be utilised to 4 percent. This quantification of plastic transport capacity is only a very rough and conservative estimate as plastic items can be smaller than 2.5 centimetres and transported in stacked layers as represented by the arrows in Figure 3. Additionally, this is only a very small subset of all global rivers. Nevertheless, this calculation shows that plastic transport capacity, and therefore discharge, is not the main determinant of the plastic flux. Most rivers under non-flood conditions would fall between the T1 and T2 threshold in Figure 2, where no correlation is expected to be found between discharge and the riverine plastic flux.

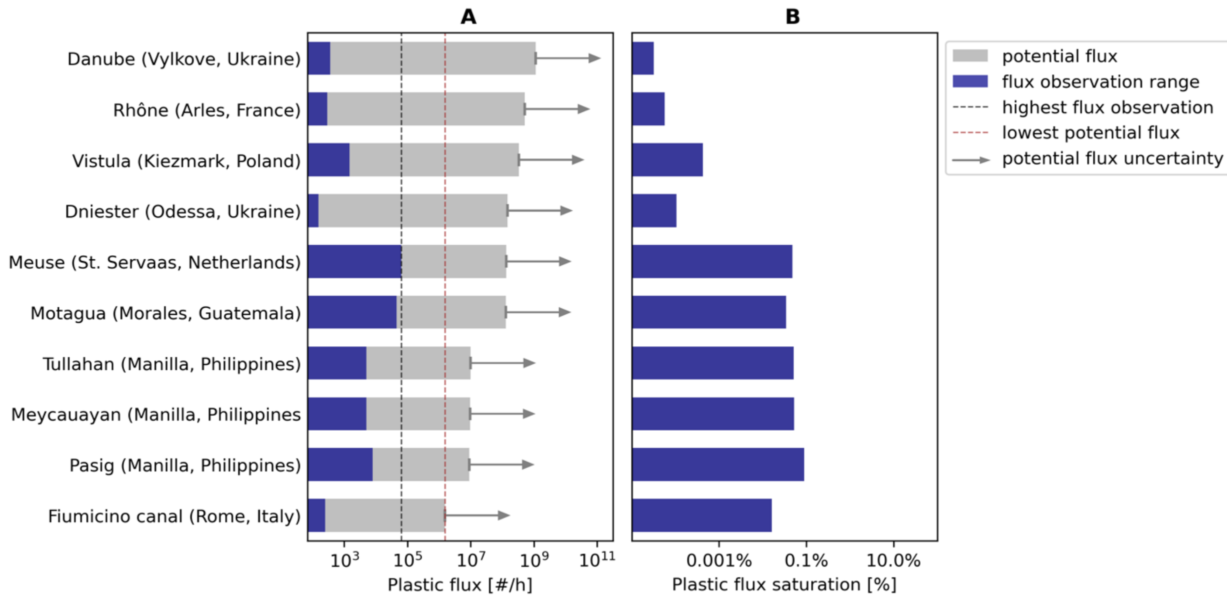

Figure 3: Plastic flux observations in relation to the potential flux and transport capacity. Panel (A) shows the potential flux in items per hour, while panel (B) shows the saturation, as percentage of the transport capacity that is utilised. The highest observations (Meuse and Motagua) are lower than the transport capacity of the smallest river in this dataset (Fiumicino canal).

Plastic availability

As shown above, the plastic availability is, in most cases, the factor that limits the actual transport of plastic in rivers. It is mostly driven by human drivers, ranging from behaviour, waste management and hydraulic infrastructure. It is also a much more stochastic process (Cowger *et al* 2022). In some cases, however, plastic availability can be influenced by, or correlated to, discharge. If river water level rises (and discharge increases), a larger surface area is inundated by water. Plastic not previously within the reach of the river can be mobilised under such circumstances (Roebroek *et al* 2021b). In extreme cases, where rivers exceed their riverbanks, large amounts of additional plastic can be transported (Roebroek *et al* 2021a, Hurley *et al* 2018, Van Emmerik *et al* 2023). However, once the available plastic is mobilized, local plastic transport may again decrease, even if discharge further increases, because of decreasing availability (Cowger *et al* 2022).

Other scenarios in which discharge might be correlated to the river plastic flux come from anthropogenic factors. One example is combined sewage overflow. Under conditions of excess rain, some sewage systems are designed to release some of their content into open water (Gooré Bi *et al* 2015, Hauk *et al* 2023). Depending on the design of the system, this could convey plastic into a river. At the same time this excess in rain is likely to cause increased discharge, which would lead to a positive correlation being present between discharge and the river plastic flux. Something similar could occur during storms with wind mobilising plastic and transporting it into the river channel, paired with large amount of rain which makes the discharge increase (Roebroek *et al* 2021b).

Discussion

By describing the riverine plastic transport as a function of plastic availability and transport capacity, we can explain the apparent paradox of the plastic observations in rivers not being correlated to the discharge in many field surveys. To improve our ability to model the riverine plastic transport realistically – and increase our capacity to implement global plastic pollution reduction measures – more data and different approaches are needed. Increased availability of river plastic observations (González-Fernández *et al* 2021), allow for better calibration and validation of the models that we develop. However, this kind of data does not provide us with any insight in how plastic actually *reaches* the river, which is needed to effectively extrapolate information to unsampled catchments. To adequately do this, we would require data collection on e.g., human behaviour, infrastructure, waste collection and sewage systems (González-Fernández *et al* 2023). On top of this, we need data on the plastic storage on land, floodplains, and riverbanks, and how much of this plastic is available for transportation into rivers. Not only by using waste statistics and population density, but also by starting and harmonising global field data collection on land.

In summary, discharge is not always correlated to the riverine plastic transport for good reason. In most cases the most limiting factor to plastic transport in rivers is the amount of plastic available for transportation, not the amount of plastic that the river could physically transport. This means that simple regression-based models using only discharge as a proxy for all transport processes cannot accurately capture the true mechanisms of the riverine plastic flux. Our conceptual model points especially to the importance of understanding and quantifying the plastic availability, as this would in most circumstances determine the riverine plastic transport. This paper highlights the need for additional data on anthropogenic factors, and underscores that to reduce the plastic transport, most of the leverage lies in reducing the plastic availability for transport.

Data availability

The data used in this study are openly available. The plastic observations are available as supplements to the original papers and an the HydroATLAS is available online: https://www.hydrosheds.org/hydroatlas.

Author contributions

The concept was devised by CTJR together with TvE. The analyses were performed by CTJR. Interpretation of the results was done by all co-authors. The manuscript was written by CTJR, under supervision of AJT, MJvdP, DGF and TvE.

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