

Dune preservation and microplastics distribution over time, River Waal, Netherlands

T.A.G.P. van Dijk *Department of Applied Geology and Geophysics, Deltares, Utrecht, Netherlands; and Department of Geology, University of Illinois at Urbana Champaign, IL, USA – thaienne.vandijk@deltares.nl*
J. Best *Department of Geology; and Departments of Geography & GIS, Mechanical Science and Engineering and Ven Te Chow Hydrosystems Laboratory, University of Illinois at Urbana Champaign, IL, USA – jimbest@illinois.edu*
S. Krause *School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, UK; and LEHNA–Laboratoire d’ecologie des hydrosystemes naturels et anthropiques, Villeurbanne, France – s.krause@bham.ac.uk*
U. Schneidewind *School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, UK – u.schneidewind@bham.ac.uk*
E. van Onselen *Department of Applied Geology and Geophysics, Deltares, Utrecht, Netherlands – erik.vanonselen@deltares.nl*
P. van Rijnsoever *Van den Herik, Slidrecht, Netherlands – paul.vanrijnsoever@herik.nl*
M. Karaoulis *Department of Applied Geology and Geophysics, Deltares, Utrecht, Netherlands – marios.karaoulis@deltares.nl*
L. Haverson *School of Geography, Earth and Environmental Sciences, University of Birmingham, Edgbaston, Birmingham, UK – l.haverson@bham.ac.uk*
M.G. Kleinhans *Department of Physical Geography, Utrecht University, Utrecht, Netherlands – m.g.kleinhans@uu.nl*
J. Stam *Van den Herik, Slidrecht, Netherlands – jaap.stam@herik.nl*

ABSTRACT: River valleys are major stores of sediments and plastics, providing archives of their accumulation. However, the temporal storage of sediments in river beds and the mechanisms of deposition and accumulation of microplastics within subsurface sediments remain poorly understood. This study aims to understand the links between dune dynamics, spatio-temporal sediment preservation and the patterns of microplastic accumulation in the subsurface. We collected short time series of bathymetric and sub-bottom profiler data in combination with 18 vibracores in the River Waal, Netherlands. Here, we explore linking the internal sedimentary structures to their formative bedforms, with the aim of establishing the date of formation with bathymetric records collected over the past two decades. Preliminary quantification of microplastics in one core reveals highest concentrations in the active dune, but also an occurrence of microplastics in underlying dune sets. These data will permit unprecedented insight into the development of the sedimentary architecture and its influence on the distribution of microplastics in riverine sediments.

1 INTRODUCTION

The sustainable management of lowland rivers requires a better understanding of spatio-temporal patterns of deposition and erosion of river beds. River dunes are

ubiquitous features in sand- and gravel-bed rivers and are key elements in bedload transport (Best, 2005; Zomer et al., 2021). Understanding the links between dune dynamics and the spatio-temporal patterns of sediment preservation (or reactivation) in

river beds is important to both system knowledge and the sustainable use of rivers.

Furthermore, river valleys are not only the conduits through which sediments and plastics are transported to the ocean, but also are major stores for plastics. Macroplastics have been found to accumulate in tidal river zones, rather than flowing out to sea (Van Emmerik, 2021) and pollute river banks, beds and water. For microplastics, recent modelling (Drummond et al., 2022) has indicated long residence times of microplastics in river beds (av. 2.5 hrs km⁻¹ to max av. 0.15 year km⁻¹ for microplastics <100 µm in the main stems of rivers). Through hyporheic exchange (i.e., surface water enters the river bed upstream and re-emerges at some point downstream, while potentially mixing with upwelling groundwater along its flow path, in which dunes also play an important role; e.g. Packman and Brooks, 2001; Frei et al., 2019), microplastics may be incorporated into the bed, re-entered into the water or transported into deeper layers (long-term burial) and into the surrounding floodplains, thereby affecting both riverine ecology and that in the surroundings.

To date, dune dynamics have often been analysed using multibeam echo sounder (MBES) time series, but the spatio-temporal sediment preservation of dune sediments in the subsurface remains poorly understood. Moreover, the mechanisms of deposition and accumulation of microplastics within river sediments are still largely unknown, since present empirical studies merely include water samples and bed (surface) sediments. Vitally, observations must cover the spatial patterns and temporal dynamics of microplastics as related to sedimentary heterogeneity.

This paper presents a preliminary analysis (around selected cores) of dune preservation and microplastics distribution in the bed of the River Waal, a branch of the River Rhine in the Netherlands. The near-3-D dataset that we acquired provides a comprehensive archive of accumulation, in which times of deposition can be dated using bathymetric

records. Future quantification and characterisation of microplastics within the preserved sediments will offer a unique opportunity to derive and explain the presence, type and abundance of microplastics in the sedimentary record. These data will permit unprecedented insight into the development of the sedimentary architecture and its influence on the distribution of microplastics in riverine sediments.

2 METHODS AND DATA

In three areas of the River Waal, Netherlands (Figure 1), with varying longer-term bed dynamics (Van Dijk et al., 2015) and varying grain size (Ten Brinke, 1997), we collected simultaneous MBES and sub-bottom profiling data in time series (Table 1). These data were combined with 18 vibracores down to depths of ca. 5 m.

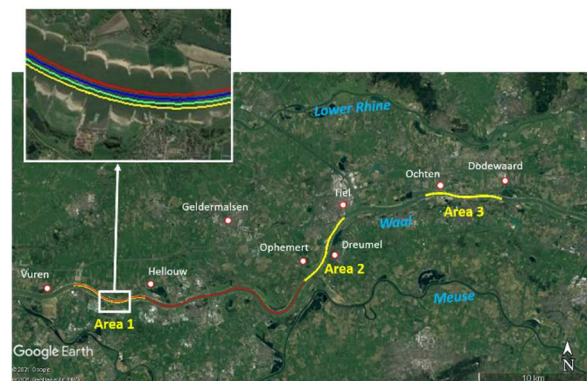


Figure 1: Locations of the three survey areas in the River Waal, Netherlands (yellow). The enlarged inset map of Area 1 shows the four survey lines. In addition, one track line (red in main figure) was surveyed to connect the most western Areas 1 and 2. Flow is from east to west.

2.1 Geophysical surveys

High-resolution MBES (for both bathymetry and backscatter) and sub-bottom profiler data (parametric echo sounder, PES) were recorded simultaneously, as to guarantee their ultimate correspondence in space and time. In each area, four 7 km-long lines were surveyed in the navigation channel (Figure 1), thus creating a near-3-D dataset, sailing in the upstream direction in order to limit the sailing speed to 5 km h⁻¹ and provide excellent spatial data resolution.

Surveys were conducted by Van den Herik aboard the ‘Sprinter’, a small survey boat equipped with RTK, GPS and motion sensor. MBES data were recorded using a Teledyne RESON SeaBat T20-P at full swath (512 beams, $-70/70^\circ$), 400 kHz and 50 pings s^{-1} , resulting in 50-200 observations m^{-2} . Sub-bottom profiling data were recorded with an Innomar Standard SES2000 Parametric Echo Sounder (PES), which was linked to the on-board GPS and motion sensor (Applanix) for optimal processing. The advantages of PES are that the echo sounder emits two primary frequencies, thereby creating two new secondary frequencies (a sum [high] and difference [low] frequency; Sambrook Smith et al., 2013), which results in a good return of the bed whilst preserving a good penetration at ca. 0.10 m vertical resolution. After testing for optimal settings, we used a low and high frequency of 8 and 100 kHz, respectively, ca. 43 pings s^{-1} (system-controlled) and we manually varied the start depth during surveying in order to obtain the optimal subsurface results.

Bathymetric data were gridded into 0.25 m resolution DEMs. PES data were processed to correct for vertical offsets, to convert to horizontal coordinates (i.s.o. ping $^{-1}$) and to suppress noise/to bring out reflectors, using auto-gain, and cleaning the water column.

2.1.1 Data in time series

Repeat surveys were near-exactly overlapping with the navigation lines of the first survey (S1). One repeat survey was conducted after 4 days in Area 1 (S1-R), and 3 weeks after the first survey in all three areas (S2; Table 1). The time in between the surveys was based on previous analyses of dune migration rates (Wilbers & Ten Brinke, 2003; Van Dijk et al., unpublished), so that dune migration between S1 and S2 would have resulted in dune displacement of half a wavelength of a large dune. The period of 4 days was just to be sure, in case dynamics were higher.

2.2 Vibracores

To link PES data to sediment characteristics, 18 vibracores were taken by Marine Sampling Holland (MSH) during

Table 1: Survey overview

	Area 1	Area 2	Area 3
MBES & PES			
S1	31 May	1 Jun	2 Jun 2021
S1-R	3 Jun	.	.
S2	21 Jun	22 Jun	23 Jun 2021
VCs (S2)	22 Jun	23 Jun	24 Jun 2021

survey S2, one day after the MBES and PES data for each of the three areas (Table 1). Core locations were based initially on the PES data from S1, to include clear internal active dune cross-stratification as well as sedimentary structures in the subsurface. Where dune migration dictated, based on inspection of the PES data of S2 (on the same day), core locations were refined. All vibracores penetrated to 5.9 m into the bed (often down into the multiple), but recovery was between 3.9 and 5.5 m, due to rodding.

Sediment cores were split in the laboratory and described (according to NEN 5104 guidelines), whereby grain size was estimated using a comparative microscope. In addition, we made lacquer peels from the cores in order to bring out sedimentary structures, such as fine lamination.

2.3 Microplastics analyses

Cores were subsampled in the laboratory (using the 100 Plastic Rivers project laboratory protocol; UoB, 2019) throughout the depth of the cores and samples were analysed for microplastics (< 5 mm) at the University of Birmingham, using established methods (Nel et al., 2020). First, organic matter was digested (using H_2O_2 , below $55^\circ C$) and density separation (using $ZnCl_2$ at $1.5 g cm^{-3}$) was done to separate

microplastics from the sediment and to reduce false positive inclusion. Staining samples with Nile Red enabled fluorescent microscopy (lower size limit here is 64 μm) to count and measure putative plastic particles. μFTIR (micro-Fourier Transform Infrared Spectroscopy) will be performed on select samples (lower size limit is 20 μm) to identify polymer types. Herein, only plastic particles were counted in one core, but future analyses will be extended over the whole area and include particle size and polymer type data. Organic matter content was determined by loss on ignition (LOI).

2.4 Sediment grain-size analyses

Samples were analysed for grain-size distributions, using laser diffraction (Malvern Mastersizer) for the finer sediments and dry-sieving for the coarser sediments.

3 RESULTS

3.1 Morphology and sedimentary structures

Both the bathymetric and PES data show large dunes with superimposed small dunes. The PES data reveal internal sedimentary structures of the active dunes, exhibiting foresets of large dunes and smaller structures where superimposed small dunes descended along the lee slope of large dunes (Figure 2; Galeazzi et al., 2018). In nearly all data, the active large dunes have distinct horizontal reflectors at their base.

As revealed by the PES data, the sedimentary structures immediately below the active dunes and in the deeper subsurface, exhibit foresets of older dune sets (especially Area 1) or display larger-scale horizontal or concave reflectors.

The sediment cores showed large variations, comprising recent dune sediments to Pleistocene deposits. For example, core 2 (Area 1; west) comprised stacked sets of cross-bedded sand and gravel beds, whereas some cores in Area 3 (east) contained an organic clay layer and Pleistocene aeolian sands. In most sediment cores, the recent

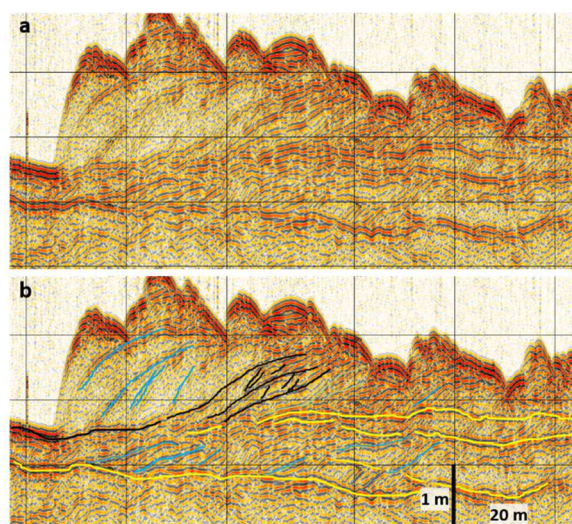


Figure 2: Example of sub-bottom profiler data (parametric echo sounding, PES), showing dune morphology, internal structures of the active dunes and reflections of older dune sets below. **a.** raw data. **b.** preliminary interpretation plotted on raw data.

deposits of the active dunes were clearly distinct units with sharp basal boundaries.

3.2 Dune dynamics

Both the bathymetric and parametric echo sounding in time series, acquired during these surveys, record dune morphology and dune dynamics. The high-resolution bathymetry data is best used for quantitative morphometric and morphodynamic analyses, such as dune migration celerity. Quantitative analyses still have to be completed, but an initial estimate of average dune celerity based on one dune is 3.6 m day^{-1} in June 2021. Note that the PES data in time series are not only useful for determining sediment reactivation in the subsurface by dune movement, but also for identifying sedimentary structures to larger depths (i.e., where reflectors were within the signal multiple during one survey, they appeared in the other survey, by dune migration).

3.3 Dating of the sedimentary structures

By linking the bathymetry to the PES data, the more recent sedimentary structures can be dated accurately, thereby allowing for the reconstruction of depositional and erosional episodes. Dating the sediments is not only essential for future quantification of the spatio-temporal preservation of sediments in

the river bed, but also for the historic record of microplastics within these sediments and understanding the depositional processes and potential distribution of microplastics by hyporheic flow. In addition, a 2-weekly bathymetric time series over the past 16 years (2005-present) and a half-yearly time series (1999-2011) are available from Rijkswaterstaat, which provide a unique opportunity to date the dune structures. However, initial analyses of a selection of bathymetric profiles show a ‘spaghetti’-plot, where dune migration causes a rapid and repeated replacement of dune deposits (active dune level). Moreover, a preliminary analysis of dune preservation, (i.e., exploring the riverbed built-up using bathymetric profiles – i.e., 1D – over time; Figure 4), revealed that dune migration has not only caused little preservation since 1999, but in some places the river bed has eroded into the 1999 bed. This implies that at these locations, recent dune deposits will directly overly pre-1999 sediments. This has also led to the finding that older pre-1999 bathymetric datasets (e.g. single-beam data) will be needed to date the sedimentary structures below the active dunes in the PES data.

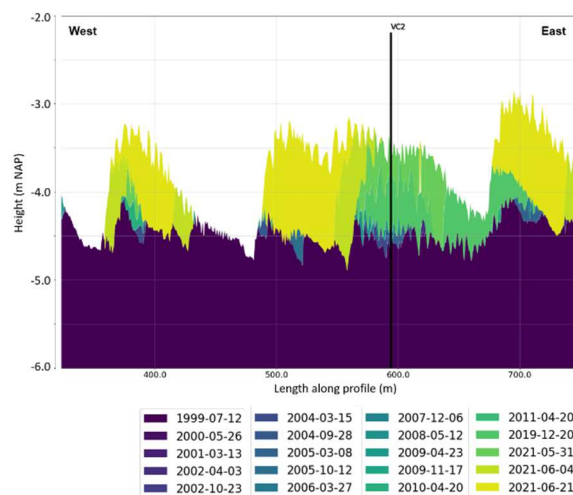


Figure 4: Exploring the analysis of dune preservation (example around core 2) for a small selection of bathymetric profiles between 1999 (purple) and the surveys in this study in 2021 (yellow and yellowish-green).

Additional indicators of the ages of the sediments are the occurrence of *Corbicula fluminea*, an invasive species of freshwater clam that was first recorded in the Rhine

system in the Netherlands in 1987 (Den Hartog et al., 2007), and the geological model GeoTop of TNO Geological Survey of the Netherlands.

3.4 Microplastics (core 2)

The concentration of microplastics in core 2 was highest in the top 1 m of the core (see Figure 3, chart on the right). Nevertheless, small amounts of microplastic particles were found down to a depth of 3 m.

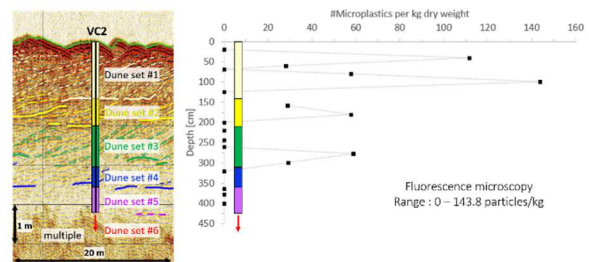


Figure 3: PES raw data with interpreted sedimentary structures around core 2, interpreted dune sets in core 2 and number of microplastics kg^{-1} per sample. The PES data are plotted on a vertically exaggerated scale, so the angles of lee slopes are steeper than in reality.

3.5 Interpretation around core 2

Core 2 is in the western part (lower reach) of the River Waal, where aggradation rates were expected to be largest. On the PES data, six dune sets were identified down to a depth of 5 m. The recovery depth of core 2 of 4.20 m captures five of these dune sets (Figure 3). The high content of microplastics in the top 1 m of the core corresponds to the active dunes (dune set #1). The occurrence of microplastics in the two older dune sets below (yellow and green in Figure 3) suggest active accumulation in older dunes or possible injection within hyporheic exchange.

4 DISCUSSION & FUTURE RESEARCH

The highest abundance of microplastics in the active dune set may confirm their recent deposition, simultaneously with the dune deposits. However, the occurrence of microplastics in the two older dune sets below suggests accumulation during deposition from older dunes (pre-1999) and/or inflow through hyporheic flow.

Although those older dune sets still need to be dated, these may potentially be pre-plastic era in age: if this is the case, hyporheic flow becomes the only mechanism for microplastic introduction into these lower dune sets. For the interpretation of microplastics within the sediments, it is thus crucial to assess the age of the sediments.

Using older (pre-1999) bathymetric data may help in determining the age of the dune sets below the active dune set. However, single-beam echo soundings may not go back in time far enough. In this case, linking the PES data to the Dutch geological model will provide crude depositional epochs of the Late Pleistocene and Early Holocene deposits.

At present, we have analysed the concentration of microplastics in core 2. Although this concentration was small, it is in the order of concentrations found in other rivers (i.e., to date, literature merely reports surface samples of the top 5 cm). Future analyses of all cores will provide the spatial distribution of microplastics (concentration, size and polymer type from FTIR) from surface samples and their vertical distribution in the subsurface of the River Waal.

For the geological context, future interpretation of the full MBES and PES datasets will present a near-3-D record of the sedimentary architecture. In combination with the 2-D bathymetric time series (surfaces rather than profiles) and vibracores, this is a unique 3-D dataset, which will allow quantification of dune dynamics and sediment preservation over time, identifying potential time gaps in the sediment cores and providing insight into the depositional processes of microplastics and hyporheic transport within these sediments. We can then start to link the spatio-temporal sediment storage to depositional events (e.g. floods). To date, creating such a dataset was only possible in flumes, whereas the field record presented herein may contribute to future data-driven morphodynamic modelling.

5 CONCLUSIONS

Dune stratification of active dunes, as revealed on the sub-bottom profiles in the River Waal, Netherlands, comprise foresets of large dunes and occasionally of superimposed small dunes. The combination of high-resolution bathymetry and simultaneously recorded PES data in time series allows for the quantification of spatio-temporal sediment preservation in the last two decades. The dune sets below the active layer may be dated using older bathymetric data.

Microplastics were more abundant in the active dune layer, but were present to a depth of 3 m, corresponding to two older dune sets. Future analyses of microplastics in all cores will provide the 3-D spatial distribution of microplastics in the subsurface. Combining these data with quantification of the sedimentary architecture leads to insights that permit explanation of processes that deposit and redistribute microplastics in river beds.

6 ACKNOWLEDGEMENT

This research was funded by the Dutch Topconsortia Knowledge and Innovation (TKI) base funding through Deltares (DEL107), and co-funded by Van den Herik Slidrecht, Rijkswaterstaat (Rivers2Morrow programme) and Deltares's Strategic Research programme. Bram van der Kooy and Erik Roos (Van den Herik Slidrecht) are thanked for their skilled help in linking the PES to on-board systems and with survey logistics.

7 REFERENCES

- Best, J.L., 2005. The fluid dynamics of river dunes: A review and some future research directions. *Journal of Geophysical Research* 110, F04S02. doi:10.1029/2004JF000218
- Den Hartog, C., van den Brink, F.W.B., van der Velde, G., 1992. Why was the invasion of the river Rhine by *Corophium curvispinum* and *Corbicula* species so successful? (opinion article) *Journal of Natural History* 26, 1121–1129. doi: 10.1080/00222939200770651
- Drummond, J.D., Schneidewind, U., Li, A., Hoellein, T.J., Krause, S., Packman, A.I., 2022. Microplastic accumulation in riverbed sediment via hyporheic

- exchange from headwaters to mainstems. *Science Advances* 8. doi:10.1126/sciadv.abi9305
- Frei, S., Azizian, M., Grant, S.B., Zlotnik, V.A., Toundykov, D., 2019. Analytical modeling of hyporheic flow for in-stream bedforms: Perturbation method and implementation. *Environmental Modelling and Software* 111, 375-385. doi:10.1016/j.envsoft.2018.09.015
- Galeazzi, C.P., Almeida, R.P., Mazoca, C.E., Best, J.L., Freitas, B.T., Ianniruberto, M., Cisneros, J., Tamura, L.N., 2018. The significance of superimposed dunes in the Amazon River: Implications for how large rivers are identified in the rock record. *Sedimentology* 65, 2388–2403. doi: 10.1111/sed.12471
- Nel, H.A., Sambrook Smith, G.H., Harmer, R., Sykes, R., Schneidewind, U., Lynch, I., Krause, S., 2020. Citizen science reveals microplastic hotspots within tidal estuaries and the remote Scilly Islands, United Kingdom. *Marine Pollution Bulletin* 161, doi:10.1016/j.marpolbul.2020.111776
- Packman, A.I., Brooks, N.H., 2001. Hyporheic exchange of solutes and colloids with moving bedforms. *Water Resources Research* 37, 2591-2605. doi:10.1029/2001WR000477
- Sambrook Smith, G.H., Best, J.L., Orfeo, O., Bardy, M.E. and Zinger, J.A., 2013. Decimeter-scale in situ mapping of modern cross-bedded dune deposits using parametric echo sounding: A new method for linking river processes and their deposits. *Geophysical Research Letters* 40, 3883-3887. doi:10.1002/grl.50703
- Ten Brinke, W.B.M., 1997. *De bodemsamenstelling van Waal en IJssel in de jaren 1966, 1976, 1984 en 1995*. Rijkswaterstaat RIZA, ISBN 9036950562
- University of Birmingham, 2019. 100 Plastic Rivers – a global investigation. Unpublished, 8 pp.
- Van Dijk, T.A.G.P., Van der Mark, C.F., Doornenbal, P.J., Menninga, P.J., Keppel, J.F., Rodriguez Aguilera, D., Hopman, V., Erkens, G., 2012. *Onderzoek Meetstrategie en Bodemdynamiek*. Deltares report, 1203749-000-BGS-0006.
- Van Emmerik, T., 2021. Macroplastic research in an era of microplastic (editorial). *Microplastics and Nanoplastics* 1, doi:10.1186/s43591-021-00003-1
- Zomer, J.Y., Naqshband, S., Vermeulen, B., Hoitink, A.J.F., 2021. Rapidly migrating secondary bedforms can persist on the lee of slowly migrating primary river dunes. *Journal of Geophysical Research: Earth Surface* 126. doi:10.1029/2020JF005918