PlasticFreeDanube

PARAMETERS AND INDICATORS FOR PLASTIC ACCUMULATION PROCESSES

Report

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1. Introduction

One of the objectives of the project „PlasticFreeDanube“ is an analysis of the main sources, inputs and pathways of plastic waste in the Danube and on its river banks. Within the current activity 3.7 "Particle tracing and hydraulic characterization of plastic accumulation zones” it is aimed to describe fluvial processes related to plastic waste in river systems by the means of numerical simulation and particle tracing in particular. To simulate the particle pathways, a simplified numerical tracer model is applied. The areas selected for the investigation were defined according to the findings of activity 3.5 “Map of plastic accumulation zones”, where typical plastic accumulation zones were evaluated according to hydromorphological aspects. 2D and 3D numerical models were set up, described and analysed within activity 3.6 “3D hydrodynamic modelling of selected plastic accumulation zones” and build the basis for the application of particle tracing performed within this deliverable.

By defining and assigning the physical parameters of the macroplastic particles, the model predicts the motion paths in the flow. The calibration for the particle tracing is performed by measurements with floating objects in the river. Therefore, a field analysis of floating particles with attached GPS-trackers was performed within the current deliverable. Based on the knowledge gained about the behaviour of floating plastic particles in flowing waters, this allows a description of the hydraulic and morphological parameters of typical accumulation zones such as secondary flows, backwater, groyne shapes and angles, bank slopes etc. The resulting 2D and 3D information of particle flow and water age for different discharge conditions were basically plotted in maps and used for further analysis.

2. Project area

The study area related to numerical modelling covers the eastern Austrian section of the Danube, starting from Vienna to the Slovakian border. The Austrian Danube has an average gradient of about 0.4° (40 centimeters per kilometer). The average flow velocity varies between 1 and 3 meters per second. Floods caused by snowmelt are characteristic for this river mainly from late spring to the summer months, while floods due to precipitation events can occur all year round (Nationalpark Donau-Auen, 2017). Major regulation measures on the Danube took place in the 19th century, mainly to meet the requirements of inland navigation. Since then, the mainstream at many sections of the Danube, as also in the present study area, has been characterized by engineering structures such as groynes and guiding structures. At the same time, adjacent side arms have been successively cut off. The surrounding foreland of the considered Danube section is also a national park area, which consists mainly of floodplain forests and meadows and is administered by the Nationalpark Donau-Auen. The total length of the Danube river in Austria is about 350 kilometers, of which about 36 kilometers are flowing through the area of the national park. The main tributaries in the National Park are as follows: Schwechat, Fischa, Rußbach and March/Thaya. (Nationalpark Donau-Auen, 2017).

The study areas of the current activity 3.7 "Particle tracing and hydraulic characterization of plastic accumulation zones” are related to the numerical models set up in activity 3.6 “3D hydrodynamic modelling of selected plastic accumulation zones” and were selected according to the findings in deliverable D 3.5.1 “Map of plastic accumulation zones”. The modelling reaches are depicted in Figure 1 and cover:

- 3D model Haslau-Regelsbrunn: river-kilometer 1901 - 1903,5
- 3D model Haslau-Wildungsmauer-Witzelsdorf: river-kilometer 1903,5 1891,7 - 1895,2
- 2D model Vienna-Bratislava: river-kilometer 1907 - 1881,3
- 3D concept model

Figure 1 shows the defined model boundaries and the respective dimensions of the model. Detailed information on the location and dimensions of the concrete models can be found in the following subchapters.



Figure 1 Defined modelling reaches for 2D and 3D numerical simulation based on accumulation zones detected during site visits, expertise from Nationalpark Donau-Auen and GIs-bases analysis of the hydraulic structures of the Danube River

3. Methodology

Within activity 3.7. – "Particle tracing and hydraulic characterization of plastic accumulation zones" it is aimed to apply a particle tracing tool in order to describe hydraulic and morphological parameters of typical accumulation zones such as secondary flows, backwater, groyne shapes and angles, bank slopes etc. The used software is RSim (Tritthart, 2017), a detailed description of the numerical model is contained in the deliverable 3.6.1 "hydrodynamic flow models". In the following chapter an insight into the background and workflow of the implemented particle tracing tool is given.

3.1. Particle tracing

Since particle tracing plays a significant role in gaining knowledge about the transport and fate of macroplastics in streams, this chapter discusses in more depth the functionality and underlying equations of particle tracing in the RSim software.

By means of particle tracing, the trajectories of imaginary particles can be determined, on the basis of which statements can be made about eddy structures and main flow paths in groyne fields. The trajectories can be used, in particular, to visualize the time course of successive flow phenomena (Octavian, 2010). The trajectory line of the imaginary particle is based on the following equations in the three spatial directions, where the calculation of the particle in the respective spatial direction at time t is performed for the time step t + Δt (Tritthart et al., 2009):

$$x(t+\Delta t) = x(t) + \bar{u}(t)\Delta t + u'(t)\Delta t$$

$$y(t+\Delta t) = y(t) + \bar{v}(t)\Delta t + v'(t)\Delta t \quad (1)$$

$$z(t + \Delta t) = z(t) + \overline{w}(t)\Delta t + w'(t)\Delta t$$

$\overline{u}$, $\overline{v}$, $\overline{w}$ … average flow velocities as a result of the Reynolds equations

u‘, v‘, w‘ ... Flow velocity fluctuations in the Cartesian coordinate system

Due to the explicit procedure used in equation (1), the time step Δt must satisfy the stability condition, also known as the Courant-Friedrichs-Levy condition:

Δt ... discrete time step [s]

Δx ... discrete location step [m]

U ... flow velocity [m/s]

h ... water depth [m]

c ... wave velocity [m/s]

Groyne fields are often characterized by deterministic streamlines in the form of a closed circulation or elliptical shape, which does not allow the particle to leave this predefined path. Furthermore, a deterministic approach neglects velocity fluctuation, which is why a stochastic approach was implemented in RSim to additionally account for velocity fluctuations. (Tritthart et al., 2009)

However, unlike the mean flow velocities, the random fluctuations are not calculated from the Reynolds equations, but are derived from the turbulent kinetic energy k. The formula for this is as follows (Tritthart et al., 2009):

$$k = \frac{1}{2}(\overline{u}'^2 + \overline{v}'^2 + \overline{w}'^2) \quad (2)$$

Since the vertical velocity fluctuation w' is relatively small compared to the other directions, it can be neglected and the following applies:

$$\overline{u}'^2 = \overline{v}'^2 = \overline{U}'^2 \quad (3)$$

From equation (2), we also obtain the mean value of fluctuation at a given point.

$$\overline{U}' = \sqrt{k} \quad (4)$$

This condition applies to a normal distribution of the fluctuation in the range of ±2√k, within which span the particle can randomly move forward, backward, and sideways from the deterministic path line. This random-based approach, also known as the random walk method, thus solves the closed circulation or elliptical streamline problem of the deterministic approach (Tritthart et al., 2009). The random fluctuation is thus determined as follows:

$$\begin{aligned} u'(t) &= 2Z_1\sqrt{k} \\ v'(t) &= 2Z_2\sqrt{k} \\ w'(t) &= 0 \end{aligned} \quad (5)$$

Z_1, Z_2 ... random variables with values between ± 1

However, in this previously described random-based motion approach, particles tend to move to regions of lower diffusivity. To avoid this tendency, an additional advection term is introduced, also called noise-induced drift. (Tritthart et al., 2009)

$$\Delta y_n = \frac{\partial D_n}{\partial n}\Delta t \tag{6}$$

n … Normal coordinate to the particle path

Δy_n … Additional translation along this coordinate

D_n … Turbulent diffusion coefficient

Substituting the equations (5) with

$$v'(t)\Delta t = Z\sqrt{2D_n\Delta t} \tag{7}$$

the turbulent diffusion coefficient D_n is obtained, with which equation (6) can be solved

$$D_n = 2k\Delta t \tag{8}$$

3.1.1. Residence time and transit time of particles

To calculate the residence time of particles, a Monte Carlo simulation is used in which multiple particle paths are calculated for each particle released at a given point in the control volume. The travel time of a particle at each of these paths is calculated by multiplying the duration of each particle path by the time step Δt. The calculated travel times represent an average over all calculated particle paths to obtain the mean residence time of the particle in the control volume. (Tritthart et al., 2009)

3.1.2. Water age

Water age is defined as the time it takes a virtual particle to travel from the edge of the control volume to its current position (Tritthart et al., 2009).

3.1.3. Possible variation options

RSim offers the possibility to perform particle tracing based on the results of hydrodynamics in 2D or 3D. In the 2D calculation of particle paths, particles are locked vertically in the selected layer and thus can only travel in the x and y directions. This allows particles with a density lower than water to be simulated, in this case particles floating on the surface. In the 3D calculation, the virtual particle starts in the specified level and can move in all three spatial directions. When leaving the original level, the particle path is color-coded. Accordingly, dark red would represent the water surface, while dark blue would represent the water bottom (Tritthart et al., 2009). This allows a general subdivision into floating and water-like particles.

Time steps of 0.05 s (20 Hz) are required to capture the correct time scales of the turbulent structures of the Danube (Tritthart, 2018). If a virtual particle has not left the control volume within the specified time (timeout), it is not considered in the calculation of mean values (Tritthart et al., 2009). If the function "Random walk" is deactivated, the calculation of the particle paths follows the deterministic concept. In addition, both the particle path and the particle runtime can be plotted. A particle can be released either individually over "Pick start point", or it can be

generated for each computation point within a specified polygon. It is also possible to generate points with specified coordinates in the model space from a text file. Via "Unsteady hydrograph" the calculation of the particle paths can also be done unsteadily – see Figure 2.

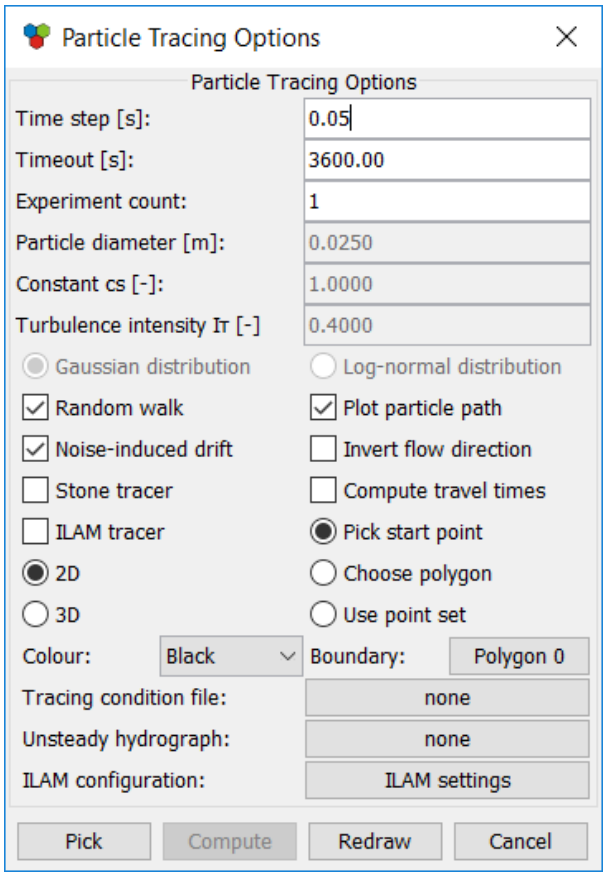


Figure 2 Particle tracing options in RSim3D

3.2. Application of particle tracing

3.2.1. 3D numerical models

3.2.1.1. 2D Particle tracing

By means of 2D calculation of particle tracing, those macroplastics could be represented which have a lower density than water and therefore float on the water surface. The 2D particle tracing was mainly applied at the orographically right bank of the river sections. The reason for this is the morphology of the groyne fields with the largely shallow bank areas. 2D particle tracing is presented at the near-surface layer (level 5) of the groyne fields in order to show the hydraulic characteristics within this layer.

The particle paths were calculated using time steps of 0.05 s (20 Hz), over a period of 3600 s (1 hour) and a number of experiments of 10. In addition, random walk was activated. To generate the particle paths, the area in which the particles are to be released was first delimited by means of a structure polygon. The release of virtual particles thus took place both in the main stream and within the groyne fields.

In addition, for the regulated low flow (RNQ), individual particles were situated within the groyne field in order to better represent the phenomenon of a lowering of the water level. The defined settings regarding time step, time restriction and number of experiments were the same as mentioned before.

3.2.1.2. 3D Particle tracing

In addition, 3D particle tracing in a depth-averaged layer (level 2) was applied in this work to show whether the transported particles remain in that layer or also move within the water body. In this way, the secondary currents could also be better identified. Here also time steps of 0.05 s, a time limit of 3600 s, and a number of 10 experiments were chosen, with active random walk at the same time.

3.2.1.3. Nets / particle count

In order to be able to make a more precise statistical statement in addition to the optical evaluation of the particle tracing paths, virtual nets, which are able to detect crossing particles were implemented in the 3D concept models. The virtual nets represent a model extension for particle tracing module implemented in the RSim-3D program. The arrangement of virtual nets used in the 3D concept model is displayed in Figure 3.

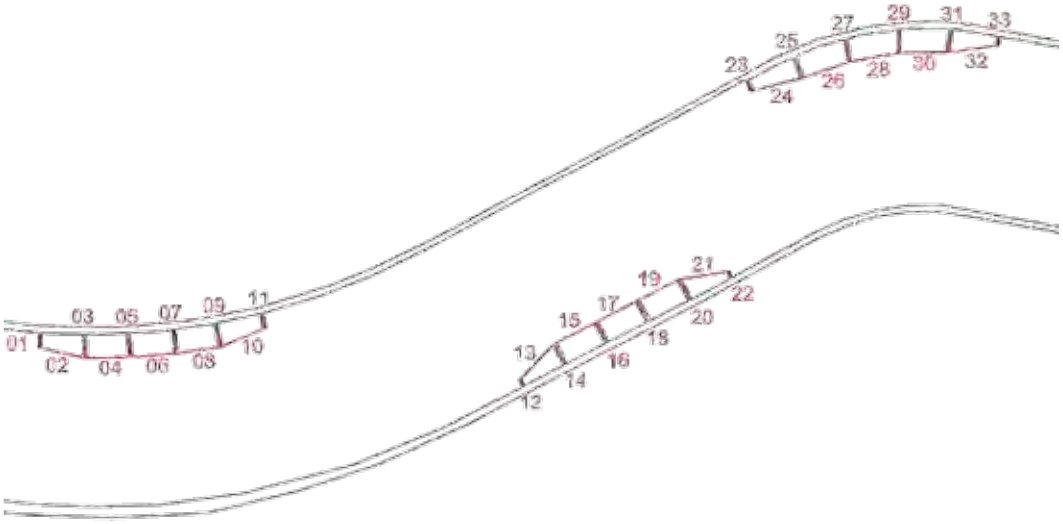


Figure 3 Arrangement of virtual nets in the 3D concept model

Numerical model runs with virtual nets were performed for several models and several discharges in order to derive general assumptions of particle behaviour in a standardized river sections containing engineering structures. Furthermore, particles were started at different locations. An overview is given in Figure 4.

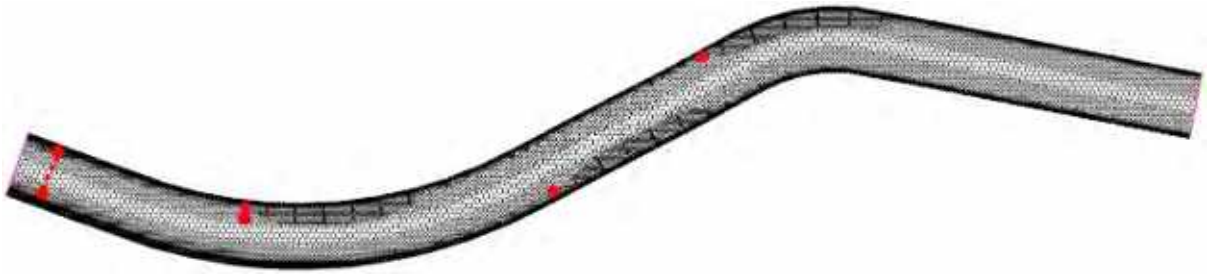


Figure 4 Starting points for particle tracing in the 3D concept model

3.2.1.4. Water age

Time steps of 0.5 s, with a time limit of 10800 s (3 hours) and a number of experiments of 10, were required for the calculation of the water age, with simultaneous activation of the "Random Walk" function. Water age was calculated individually for each groyne field. Within a previously defined structural polygon enclosing a groyne field, that time was calculated which a particle needs from the edge of the control volume to the present position.

3.2.2. 2D numerical model

3.2.2.1. 2D Particle tracing

In contrast to the 3D models, the calculation of the particle tracing was not carried out stationary, but quasi-stationary. Since in 2D models flow velocities and flow directions are depth-averaged, particle tracing can only be performed in this depth-averaged layer. The placement of the particles was determined on orographically right shallow banks of the Danube, since experiences from collection campaigns have confirmed accumulation zones of macroplastics in this area. The particle paths were calculated using time steps of 0.05 s (20 Hz), with a time limit of 3600 s (1 hour). The number of experiments has been limited to 10, with the "random walk" function activated simultaneously.

The data basis for the quasi-stationary particle tracing was a hydrograph of the gauging station Hainburg with a temporal resolution of 15 minutes. It is a flood hydrograph decreasing in about 12 days, starting from 24.10.2014 to 05.11.2014. The flow reaches its maximum at about 5724 m³/s and decreases to about 1621 m³/s.

As Figure 5 illustrates, an approximation to the actual measured discharges could be well achieved via a quasi-stationary calculation of the particle tracing. When calculating the particle tracing, RSim selects the discharge rate closest to the measured value.

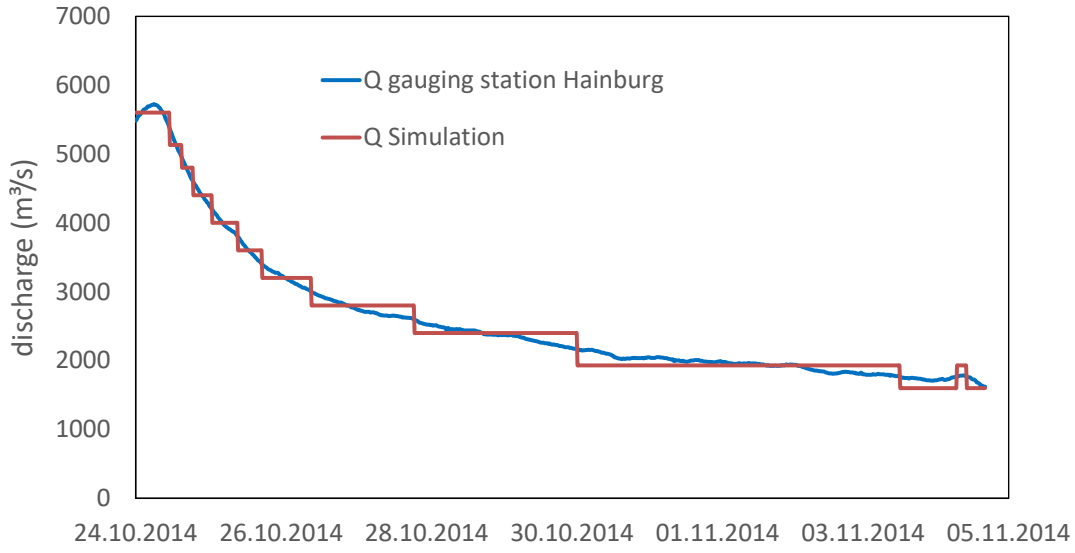


Figure 5 Hydrograph for quasi-stationary particle tracing

3.3. Field tests with GPS-tagged floating items

The aim of this survey was to evaluate the macro plastic transport in the Danube downstream of Vienna by means of GPS tracking. From the data transport distance and speed as well as evidence on stranding frequency were generated. The data collected is also used to establish correlations between items and stranding frequencies,

stranding causes/areas of stranding, discharge stage or wind conditions. In order to be able to derive such correlations, several measurements were carried out on different days with different discharges and water levels of the Danube.

In addition, the question should be clarified whether plastic articles are only stranded on the bank of the introduction, or whether they are also washed to the other bank, in order to subsequently be able to make more precise statements about the transport behaviour This question arises from the fact that three tributaries (Donaukanal, Schwechat, Fischa) flow into the Danube in this area, all of which flow through densely populated areas. At the same time macro plastic sampling campaigns show, that most accumulation zones are to be found on the right bank of the Danube River (Figure 6 up). Measurements therefore were started on the right bank as well as on the left bank using inflating paddle boats to follow the GPS-tracked items (Figure 6 lower left). Furthermore, the field survey is used to validate results of the numerical particle tracing as indicated in Figure 6 (lower right).

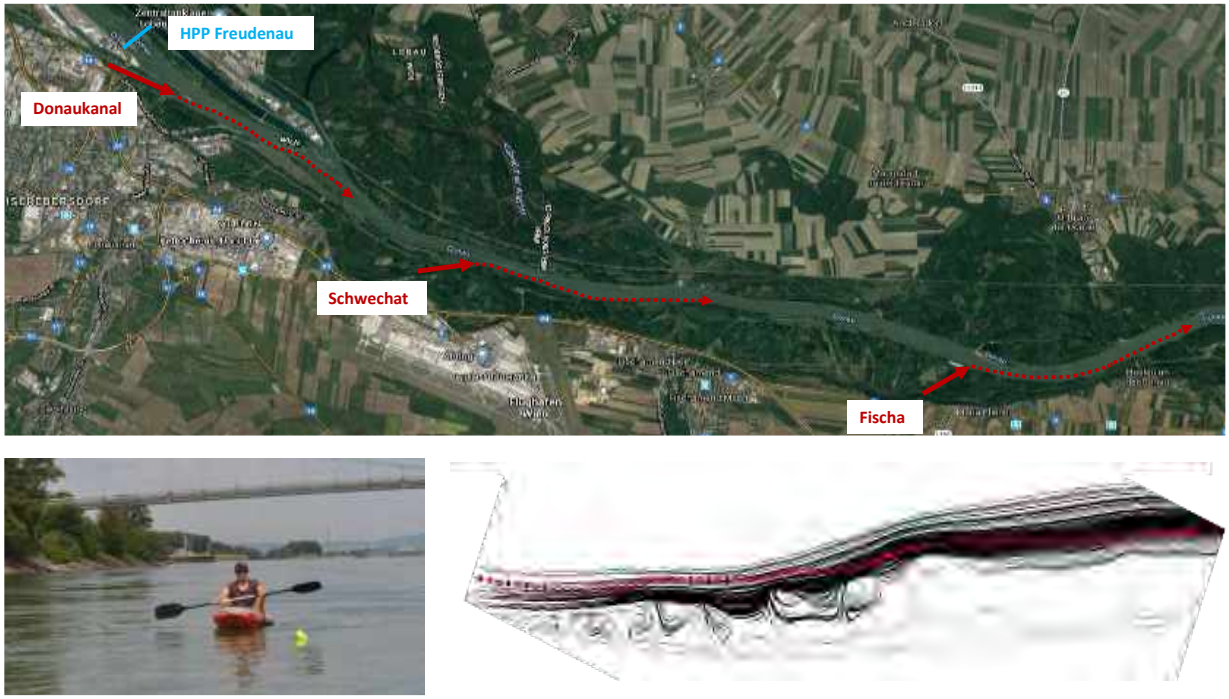


Figure 6 (up) filed survey approach showing a map of the investigation area with the tributaries Donaukanal, Fischa, Schwechat and the location of the HPP Freudenau, (lower left) following the GPS-tracked item with a paddle boat, (lower right) validation approach for the numerical model results using field data

Sampling activities show, that PET bottles, PU foam, XPS, EPS, shoes and tennis balls are frequently found in accumulation zones. Subsequently the items in the list below were fitted with GPS transmitters and accompanied by canoes in the test reach. Figure 7 displays the used items.

- plastic bottle empty
- plastic bottle filled
- XPS
- tennis ball
- shoe



Figure 7 Used items for the field survey

The used “INETIS” GPS mini-trackers from the french manufacturer Evolution Consulting were used in other macro plastic studies before (Tramoy et al., 2020). Technical information about the trackers is provided in Table 1.

Table 1 Technical data of the used INETIS GPS mini-trackers

GSM/GPRS	Dual-Band 900/1800 - Class 10
Measurement technologies	GPS, GSM, CellLocate GSM
Battery	Li-Po 3.7V, 500 mAh
Memory	21 000 locations
Functional range	-20°C to +55°C
Measurement functions	3D motion sensor, temperature sensor
Splashproof	IP67
Dimensions	41.5 x 42.5 x 18 mm
Weight	30 g
Charger communication	RFID 13.56 MHz
Power connection	230V/5V, USB/micro USB

The configuration and settings of the trackers can be manually adjusted in supplying software with an application file. Data logging intervals, intervals for sending positions and life messages can be set individually and appropriate towards the boundary conditions defined in a test run. An example for an application file is given in Figure 8.

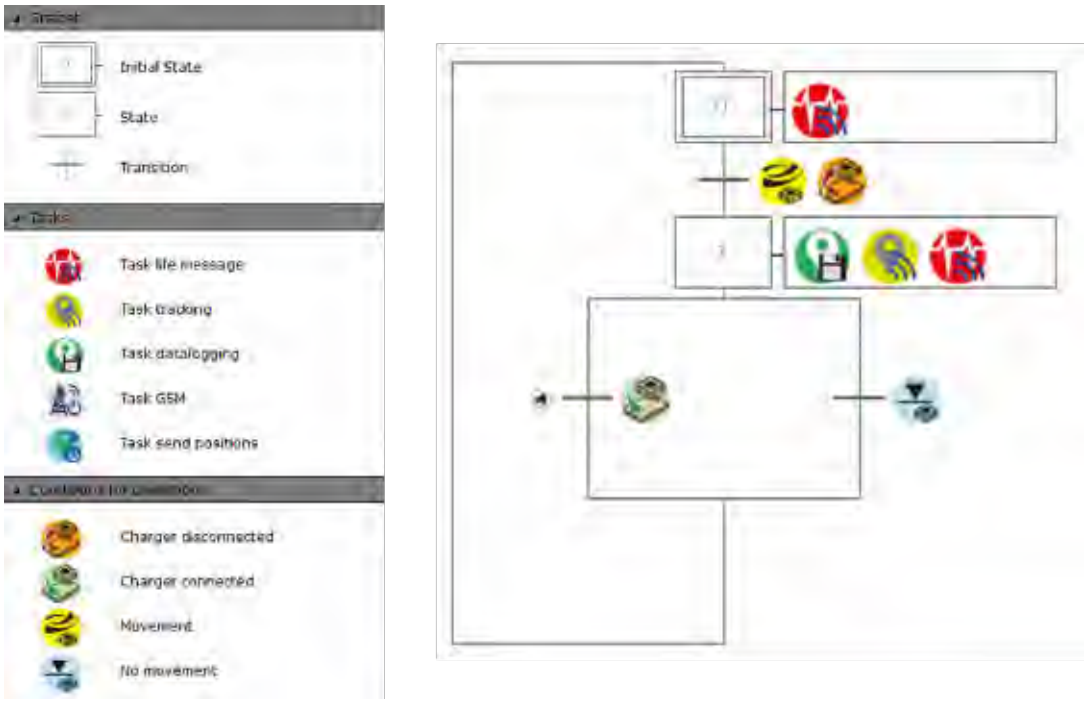


Figure 8 Visualisation of the used application file during the field tests in the Danube river

Table 2 contains an overview of GPS tracking performed at the Danube east of Vienna. A total of 13 tests took place at six dates between June and September 2020 covering a discharge range from 1250 m³/S and 2290 m³/s. Starting points were at the confluence of the Donaukanal into the Danube River for the right bank, and on the left bank of the Danube downstream of the HPP Freudenau. The ending points of the tests was chosen according to time and weather constrictions.

Table 2 Overview of GPS trackings performed at the Danube east of Vienna

Date	Items	Discharge (m³/s)	Start	End
04.06.2020	bottle filled, bottle empty, XPS	1250	right bank - Donaukanal	Orth an der Donau
09.07.2020	tennis ball, shoe	1830	right bank - Donaukanal	Bad Deutsch-Altenburg
15.07.2020	bottle filled, bottle empty	1645	right bank - Donaukanal	Bad Deutsch-Altenburg
14.08.2020	tennis ball, shoe	1810	right bank - Donaukanal	Bad Deutsch-Altenburg
19.08.2020	bottle filled, bottle empty	2290	left bank - HPP Freudenau	Wildungsmauer
13.09.2020	tennis ball, shoe	1504	left bank - HPP Freudenau	Bad Deutsch-Altenburg

Each measurement was observed uninfluenced until an irreversible stranding ended the single track as depicted in Figure 9. Time, cause and position of stranding was documented for further analysis. After documentation, the items were reintroduced in the system.



Figure 9 Stranded GPS-tagged item during the field survey

4. Results

The evaluation and discussion of the results towards numerical particle simulation is done in a concrete differentiation of the models and contains 2D and 3D particle tracing results for both 2D and 3D numerical models.

Subsequently, the results of the field experiments GPS-tagged floating macro plastic items are presented.

4.1. 3D model Haslau-Regelsbrunn

4.1.1. 2D particle tracing

4.1.1.1. Groyne fields

Looking at the 2D particle tracing in the near-surface layer during low flow conditions (Figure 10 up), a vortex formation with a vertical axis can be seen in each groyne field near the groyne head. The vortex centre is located close to the main flow. In some cases, there are also indications of secondary circular currents.

Comparing the calculated particle paths for mean water level with those at low water conditions, it can be seen that the number and size of the eddies is reduced due to the partial overflow of the guiding structure and the groyne heads (Figure 10 centre). In addition, a shift of the vortex centre behind the guiding wall toward the shore is evident. In the second groyne field downstream of the river section, the eddy assumes a compressed elliptical shape, while eddy formation in the third groyne field downstream is already very reduced compared to low water.

Figure 10 bottom shows clear differences to the particle paths at low water or mean water. Due to the almost completely submerged hydraulic structures, only isolated small eddies occur near the river bank. The eddy formation between the guiding structure and the groyne is completely absent.

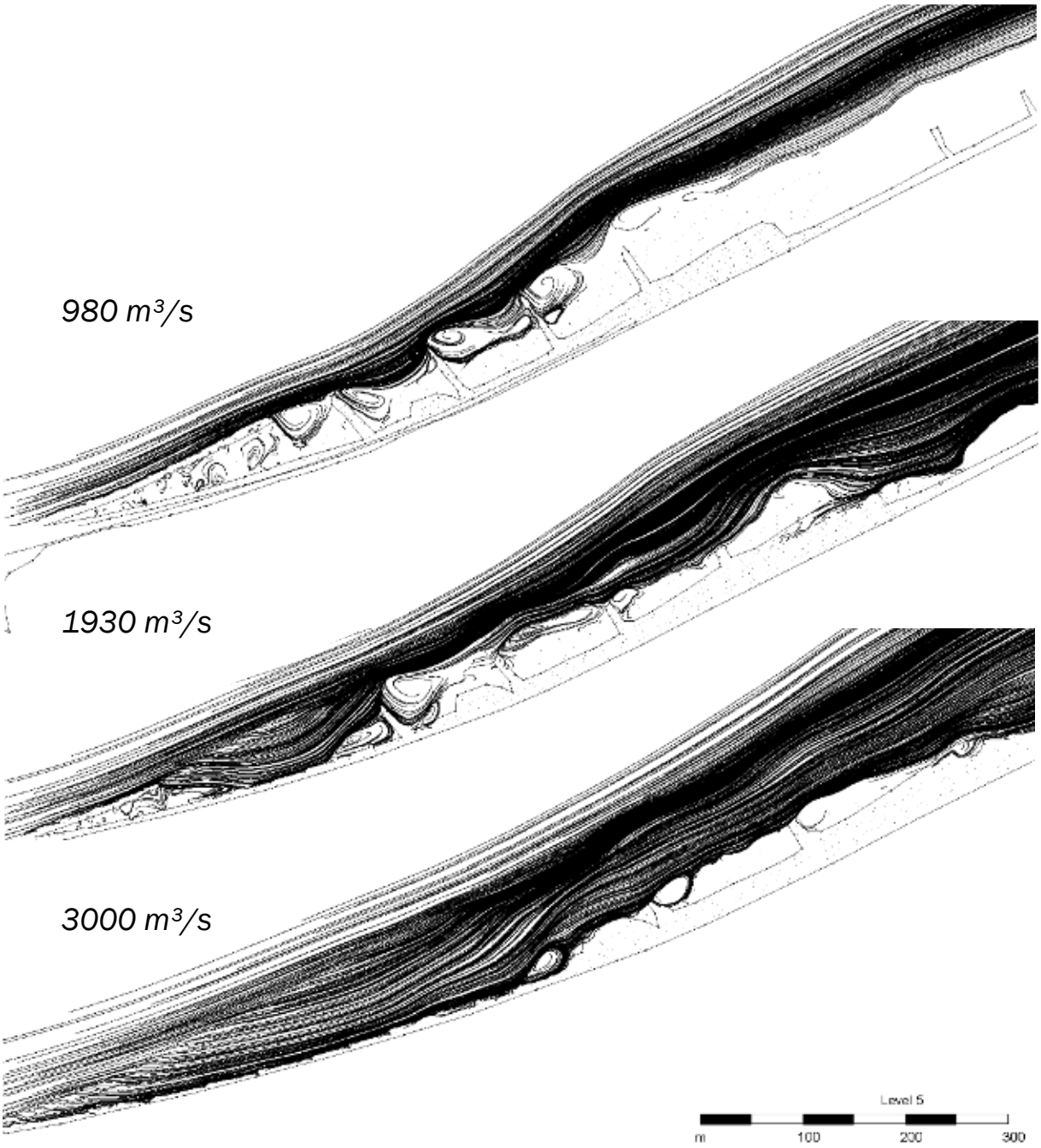


Figure 10 3D model Haslau-Regelsbrunn – Particle tracing (2D) – up: RNQ 980 m³/s, centre: MQ 1930 m³/s, bottom: Q 3000 m³/s – groyne fields

4.1.1.2. Main channel

If individual particles are placed in the main stream of the inlet area (Figure 11 up), it can be seen that no rail line leads into the still water zones during low water discharge. The main reason for this is the right bank guide vanes, which deflect the particles towards the main stream during low flow.

Figure 11 clearly shows, compared to low water conditions that due to the partial overflow of the tailrace some particles flow over the guiding structure during mean water level. If the particles subsequently pass the area, they move back towards the main stream due to the flow direction.

At a discharge of 3000 m³/s the trajectories near the right river bank lead into the still water zones behind the guiding wall and into the groyne fields. However, the majority of the particles pass the engineering structures due to the fact that they are submerged at this discharge stage.

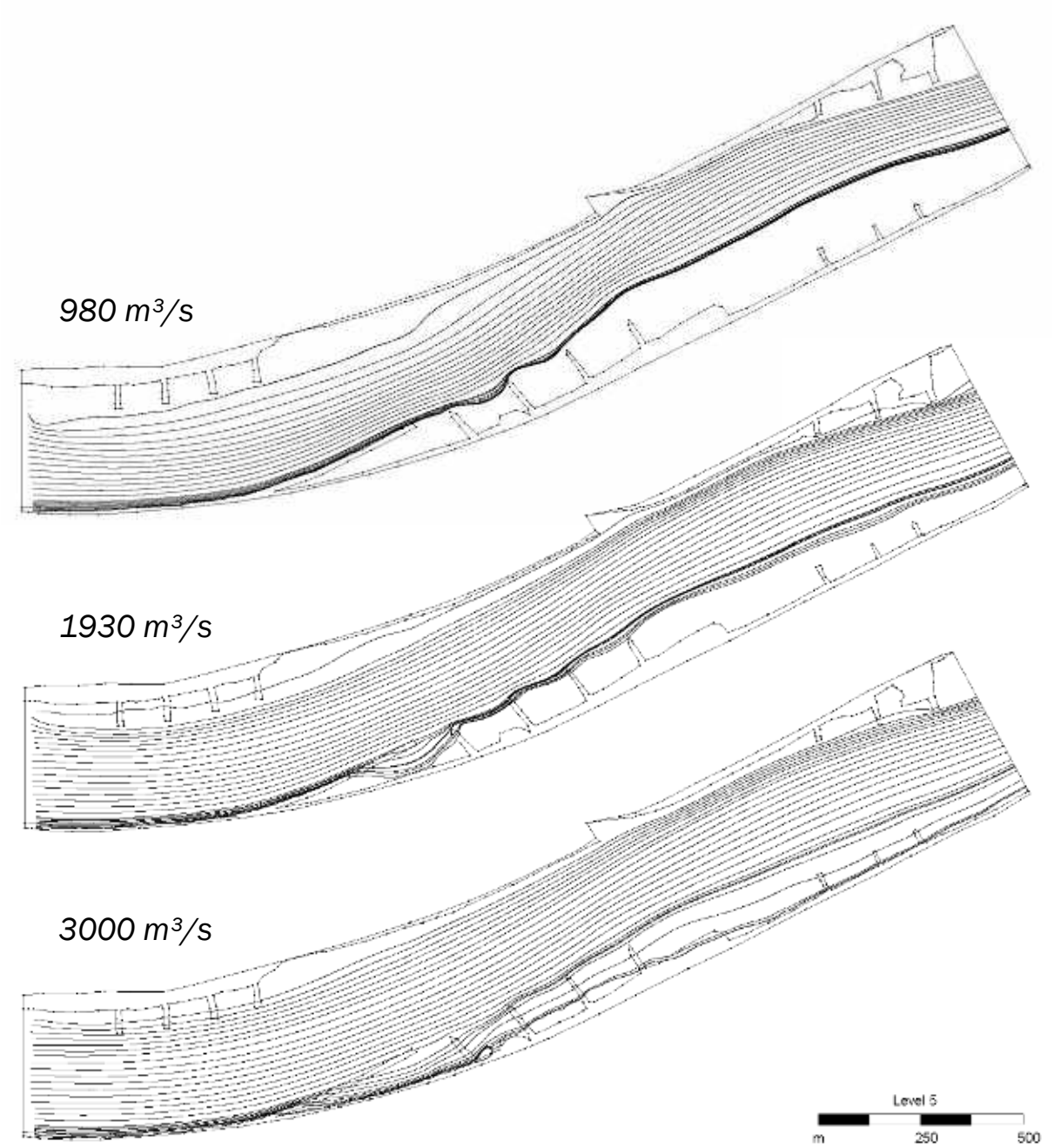


Figure 11 3D model Haslau-Regelsbrunn – Particle tracing (2D) – top: RNQ 980 m³/s, centre: MQ 1930 m³/s, bottom: Q 3000 m³/s – main channel

4.1.2. 3D particle tracing

The coloured representation of the trajectories in Figure 12 (upper-most part) shows the vertical layer of each particle for regulated low flow conditions (RNQ) with a temporal resolution of 0.05 s. Due to the high turbulence in the main channel and secondary currents, there is a frequent change in the vertical layers in which the particles move.

As a result of the curved planform of the modelled section, secondary currents occur that first push the particles toward the right bank, and then toward the left bank of the river. While left bank particles at the inlet area float on the surface, the particles near the right bank move along the river bed. This is due to the occurring secondary currents. At the turning point of the river bend, the direction of secondary current changes and vertical particle distribution inverses.

For mean water level Figure 12 (centre part) the particle distribution in the vertical levels follows similar characteristics as for low water conditions, whereas at the discharge of 3000 m^3/s (Figure 12 – lower most part) particle are more likely to stay in the same vertical level due to the fact that secondary currents are not that crucial as engineering structures are submerged at this discharge stage.

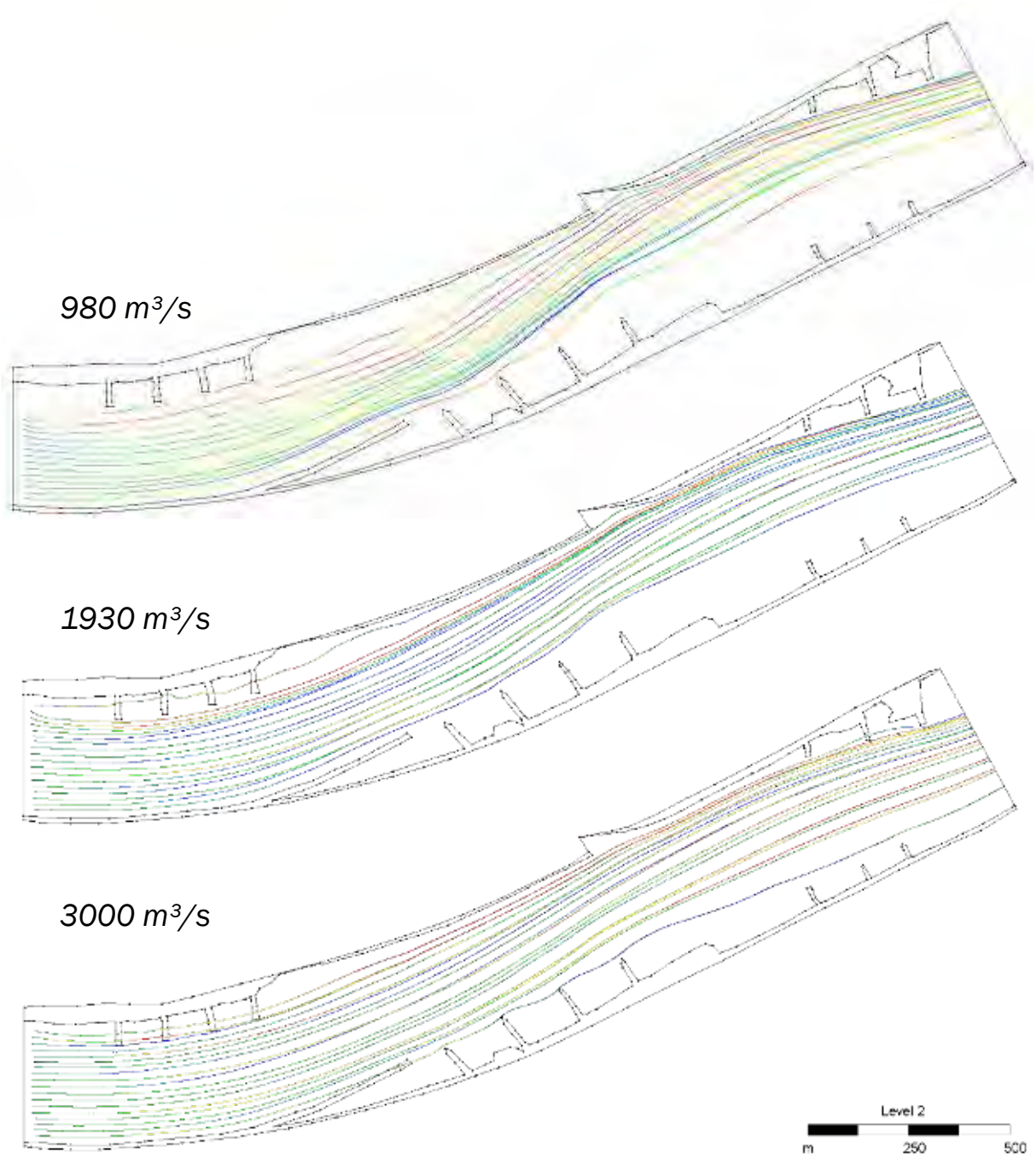


Figure 12 3D model Haslau-Regelsbrunn – Particle tracing (3D) – top: RNQ 980 m³/s, centre: MQ 1930 m³/s, bottom: Q 3000 m³/s – main channel

4.1.3. Water age

When looking at the calculated water age, it can be seen that for regulated low flow (Figure 13 - top) a water age of 3 hours occurs in all groyne fields. It has to be considered that the calculation of the water age is limited to 3 hours, which means that in reality the water age could be even higher. The high water age is caused by the poor water exchange with the main channel, since neither the guiding structure nor the groynes are submerged during low flow conditions. Furthermore, the low flow velocities of max. 0.9 m/s as well as the eddies in the groyne fields contribute to the high water age.

During mean flow conditions (Figure 13 centre) partial overflow and subsequent water exchange takes place in the area of the guiding wall, leading to a water age of up to 40 minutes. Furthermore, smaller vortex centres can be seen in the area between the groynes, which is reflected in a higher water age. In the section of the guiding structure that is not submerged, a water age of up to 3 hours can be observed. As the mean flow conditions (MQ) lead to an overflow of the groyne heads, small areas near the main channel show water ages of 30-70 minute. However, a majority of the groyne fields continue to have water ages of up to 3 hours. This is due to the persistently low flow velocities in the groyne fields, as well as the low water input into the groyne fields from the main channel.

Due to the complete overflow of the guiding wall at a discharge of 3000 m³/s, constant water inflow from the main channel takes place, which leads to a low water age (Figure 13 - bottom). Since the next groyne downstream is also overtopped, a maximum water age of about 40 minutes is calculated for this groyne field. The same applies to the groynes located downstream, whereas these show the maximum water age of 3 hours. Again, the main reason for the high water age is the continuous low water exchange with the main channel, as well as the low flow velocities within the groyne fields.

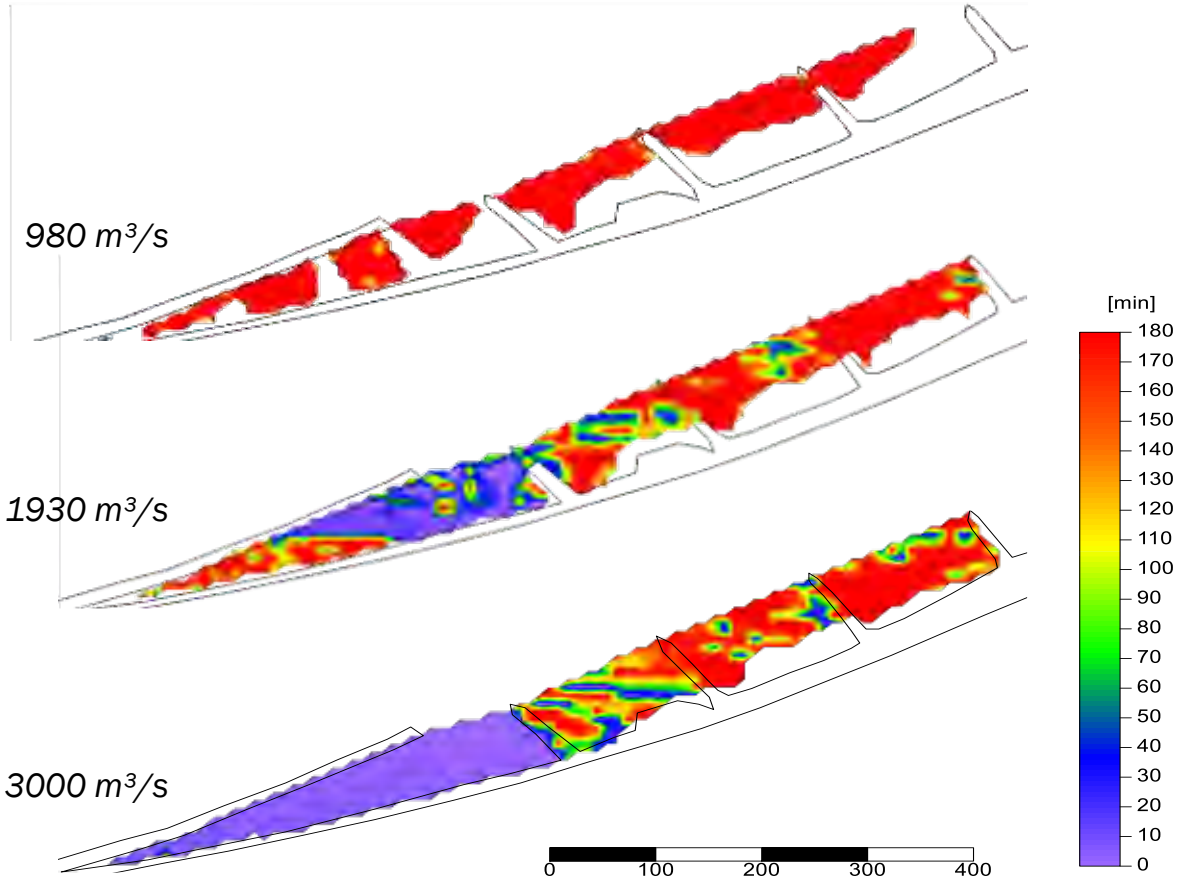


Figure 13 3D model Haslau-Regelsbrunn – water age – top: RNQ 980 m³/s, centre: MQ 1930 m³/s, bottom: Q 3000 m³/s – groyne field

4.2. 3D model Wildungsmauer-Witzelsdorf

4.2.1. 2D particle tracing

4.2.1.1. Groyne fields

If particle tracing is performed on the left bank near the model inlet area, which has numerous groyne structures, several primary and secondary vortexes are formed in the groyne fields at low water discharge (Figure 14 - top). Large eddies appear in the groyne fields even at mean water level (Figure 14 - centre). However, the centre of the eddy shifts towards the river bank. For the discharge of 3000 m^3/s there is hardly any significant eddy formation on the left bank due to the complete overflow of the groyne structures. Trajectories of the tracked particles follow a parallel direction over the submerged engineering structures (Figure 14 - bottom).

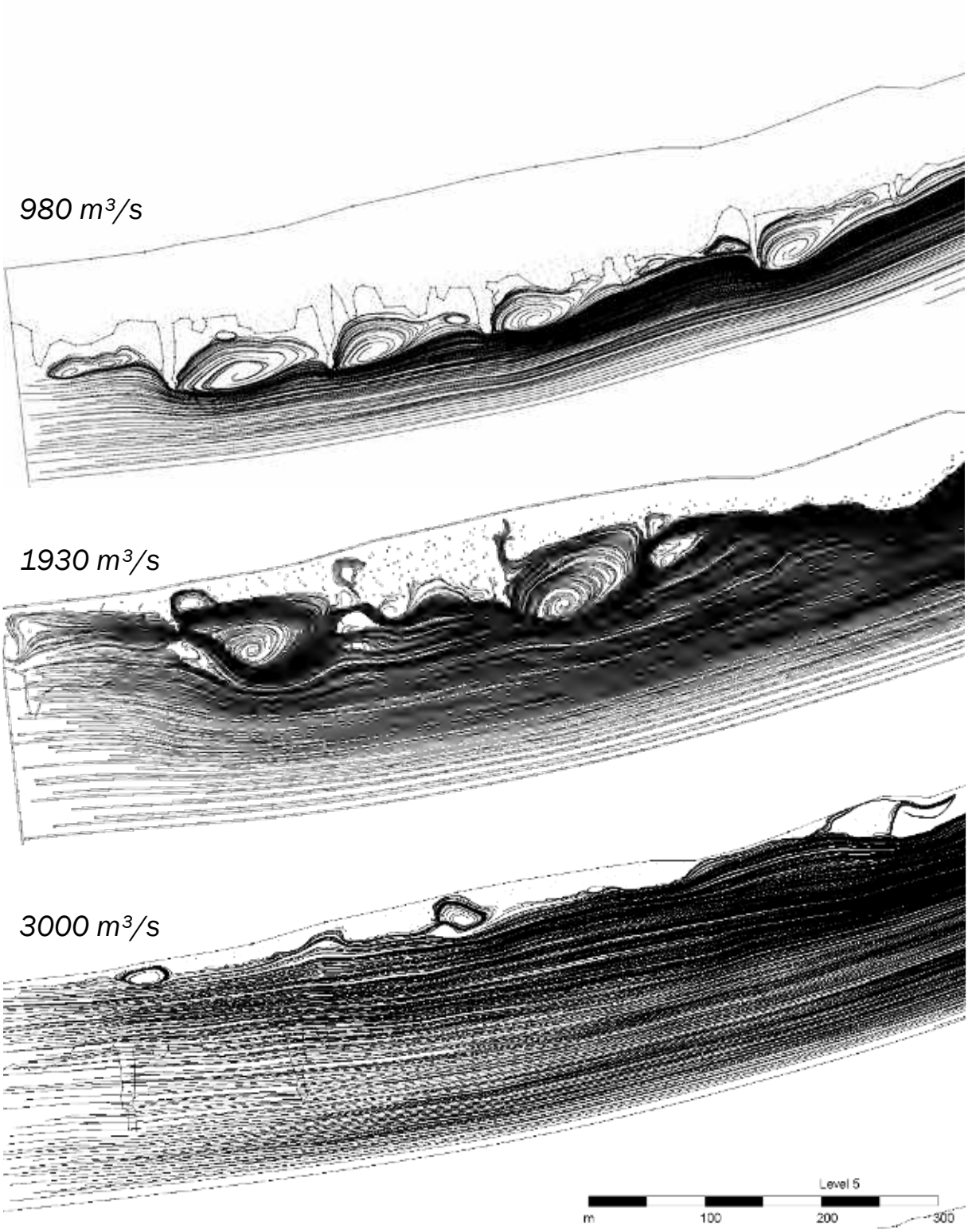


Figure 14 3D model Wildungsmauer-Witzelsdorf – Particle tracing (2D) – top: RNQ 980 m³/s, centre: MQ 1930 m³/s, bottom: Q 3000 m³/s – left bank groyne fields

Looking at the trajectories on the right bank downstream groyne field, where the spacing is shorter in the majority, a different flow pattern becomes visible in the groyne fields. Due to the different aspect ratio between groyne length

and groyne spacing, there is often only one large eddy in the groyne field during regulated low flow (Figure 15 up). Even at mean flow discharge (MQ), large eddies are still visible within the groyne fields. Only behind the fourth and fifth groyne - downstream - there are no more eddies due to the overflow of the structures. For the highest simulated discharge of 3000 m³/s a significant reduction in the number of eddy formations in the groyne fields is visible due to overflow of the structures (see Figure 15 - bottom).

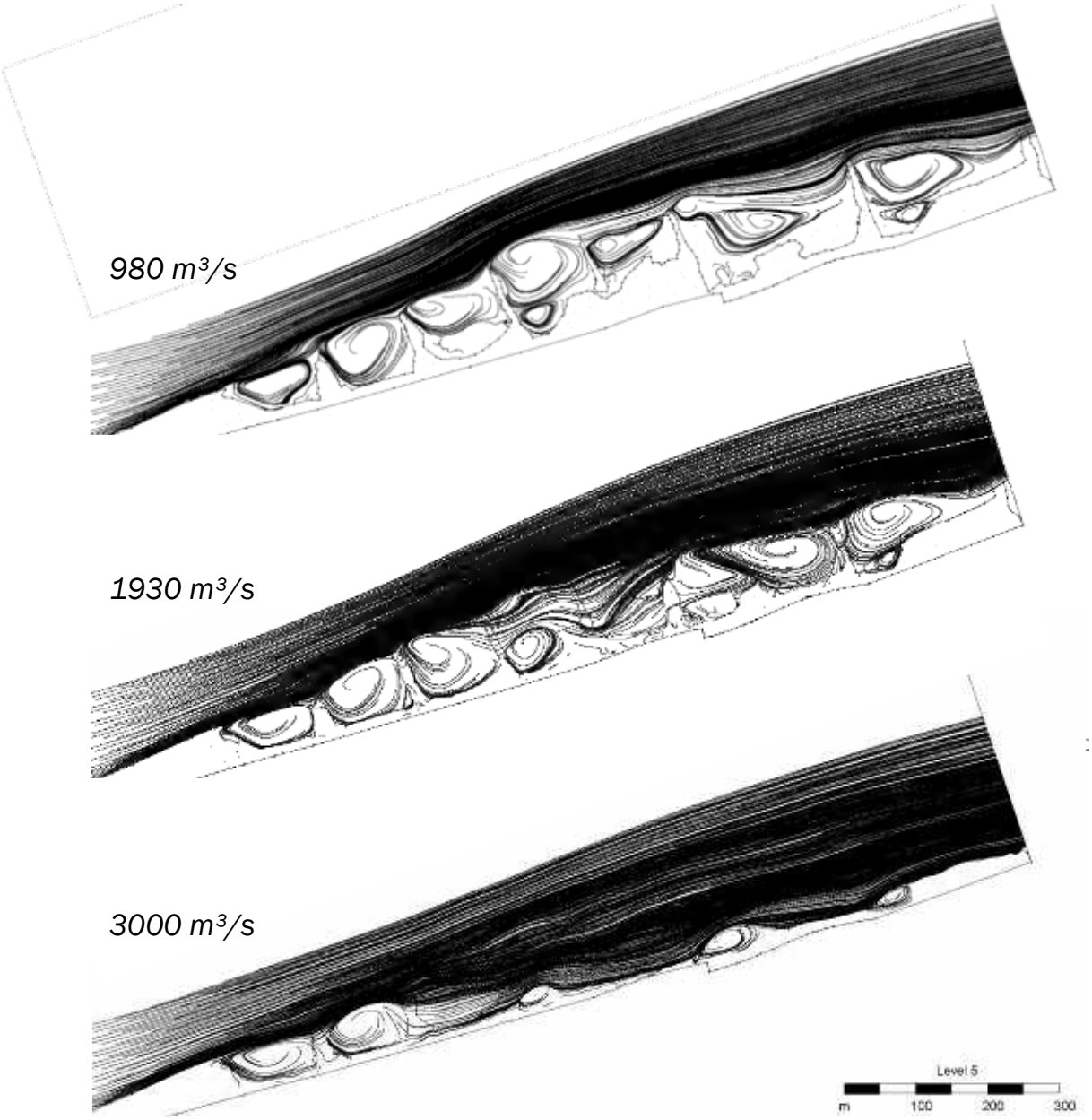


Figure 15 3D model Wildungsmauer-Witzelsdorf – Particle tracing (2D) – top: RNQ 980 m³/s, centre: MQ 1930 m³/s, bottom: Q 3000 m³/s – right bank groyne fields

4.3. 3D concept model

The evaluation of the individual data of the particle path lines in combination with the results of the virtual nets is carried out in this chapter for the concept models 2 and 3 referring to inner and outer bend morphology with

groyne fields (model 2) and a single groyne structure (model 3). A comparison of the layout of hydraulic structures implemented in the 2 models is provided in Figure 16.

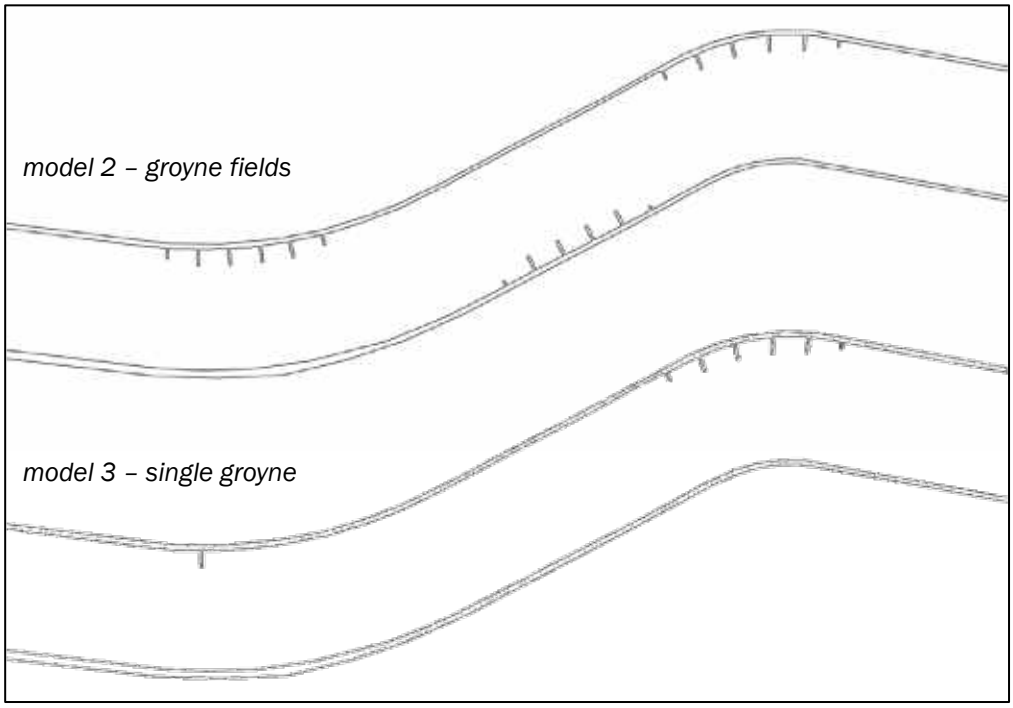


Figure 16 Layout of hydraulic structures - top: model 2 - groyne fields, bottom: model 3 - single groyne

The aim of this simulation with additionally installed meshes was a more precise statistical evaluation. An overview of used starting positions containing evenly distributed (black dotted line), left bank (green cross) and right bank (blue cross) particles as well as particles distributed in front of the groyne fields (red cross) is provided in Figure 17.

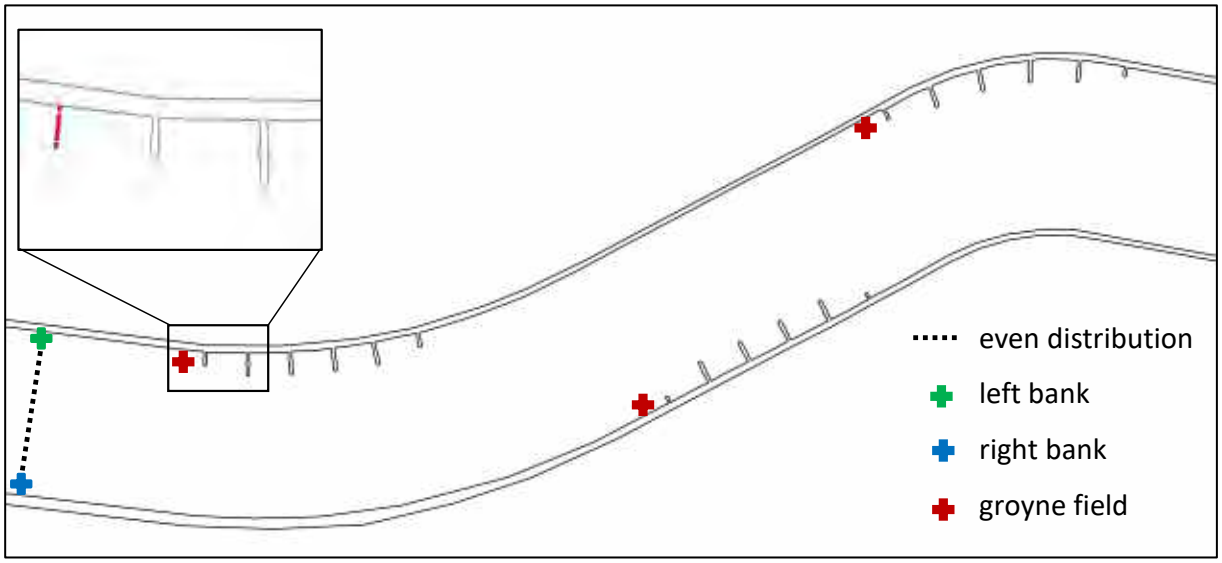


Figure 17 Starting positions of particles in the concept model

4.3.1. Model 2

4.3.1.1. Evenly distibuted particles

For the particles started uniformly over the entire profile, the majority of those pass through the river section without stranding in a groyne field. Figure 18 displays an averaged result over different depth layers from the discharge 980 m³/s, 1800 m³/s and 1930 m³/s. The highest modelled discharge was excluded, because the statistical analysis here is influenced by particles flowing over the submerged groynes and lead to detection in the nets at this water level. Generally, the centre of the groyne fields tends to have the highest stranding possibility in all three groyne fields. According to the statistical evaluation, the largest deposition occurs after the third groyne in the upstream left bank groyne field. Furthermore, particles launched in the depth-averaged layer of the river show a somewhat greater probability of deposition than those started in the surface near layer.

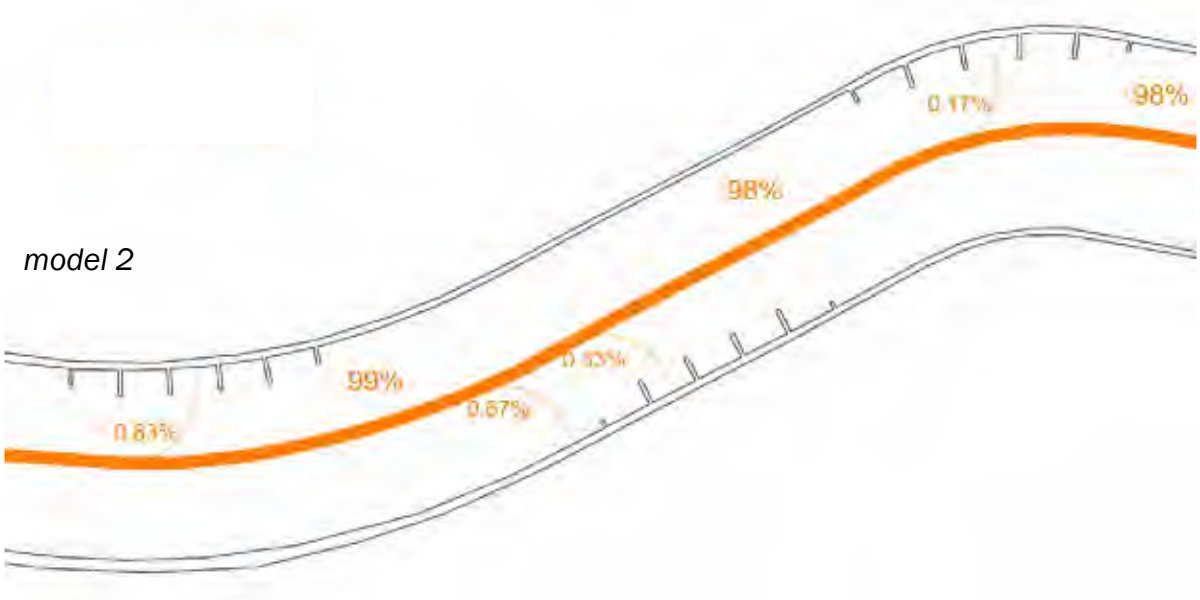


Figure 18 Particle tracking - mass flow diagram - model 2 – average values over the discharges 980 m³/s, 1800 m³/s and 1930 m³/s and layers – evenly distributed particles

4.3.1.2. Left bank particles

For the particles launched on the left bank at the beginning section, the difference between 1800 m³/s and mean flow conditions (MQ) is clearly visible (see Figure 19). While at the lower discharge approx. 60% leave the area without diverting into the groyne fields, at MQ only approx. 41% do. Most particles are found in the centre of the groyne fields behind the third groyne. While at 1800 m³/s the third field located in the upstream left bank groyne field has the most particles with approx. 12%, at mean water the third field in the downstream groyne field is the most affected with approx. 30%. Furthermore, the subsequent fourth field is to be mentioned, which also shows somewhat more particles compared to the other fields at both discharges.

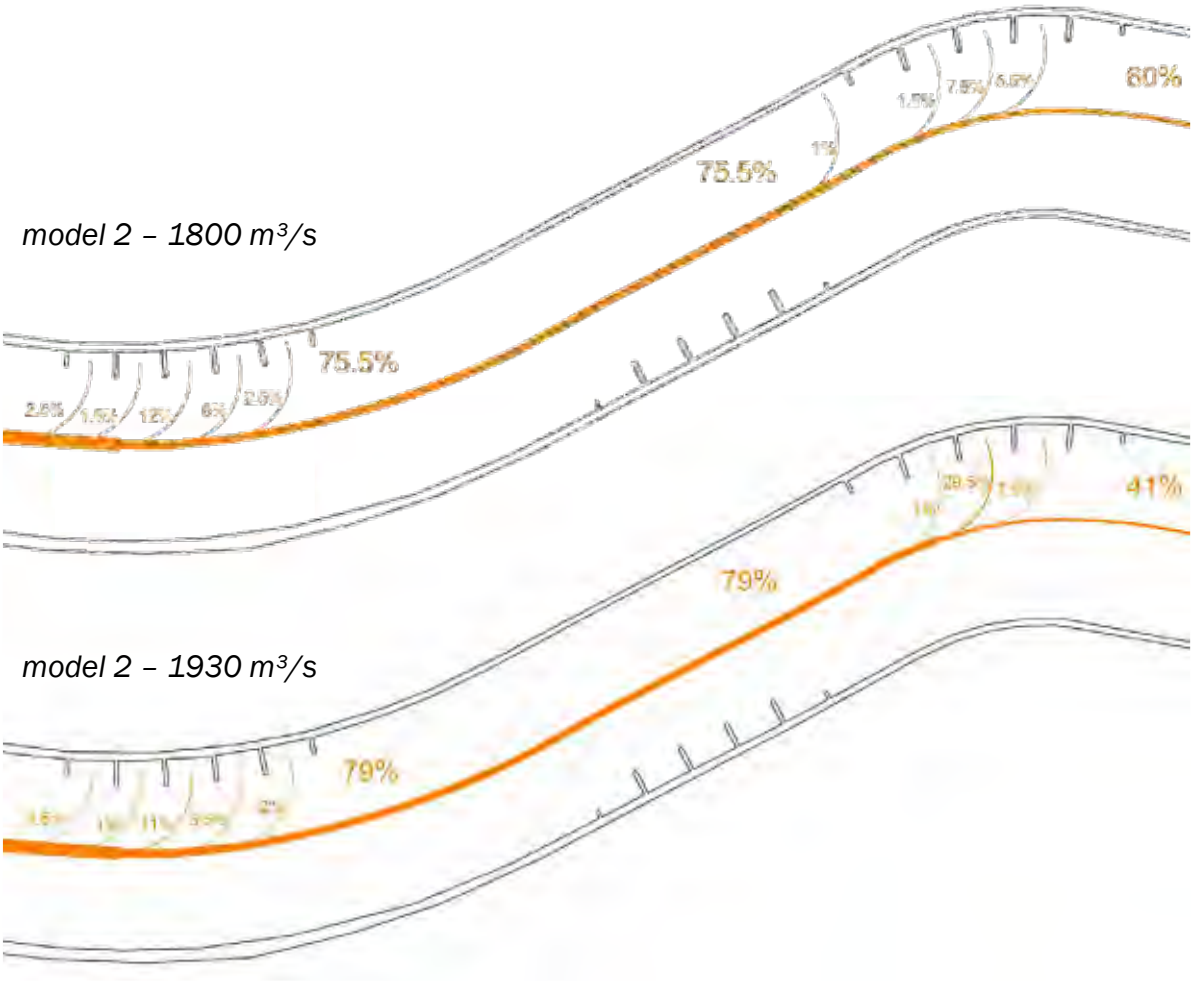


Figure 19 Particle tracking - mass flow diagram - model 2 – top: 1800 m³/s, bottom: 1930 m³/s – average values for depth average and surface layer – left bank particles

4.3.1.3. Right bank particles

The particles launched on the right bank are also evaluated with respect to the flow conditions. At a discharge of 1800 m³/s, with approx. 37%, a large part of the plastic particles already gets stuck before the first groyne of the groyne field. An explanation for this would be the lower water level, where the particles can more easily get stuck

at the first obstacle encountered. In comparison, during mean flow discharge only about 10% of the plastic particles are diverted into the river engineering structures and the remaining 90% are transported through the section.

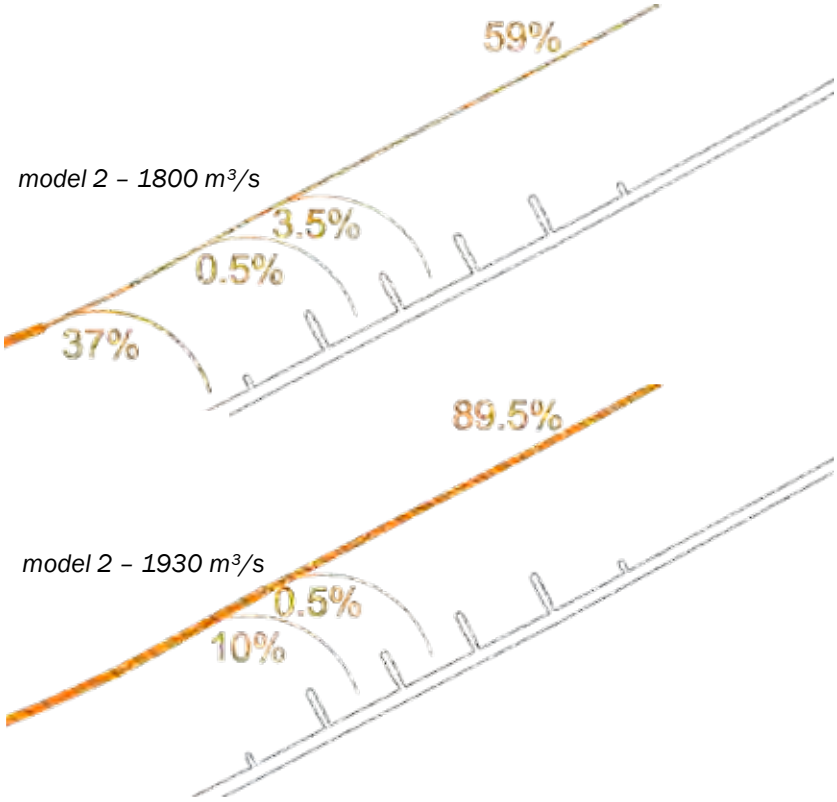


Figure 20 Particle tracking - mass flow diagram - model 2 – top: 1800 m³/s, bottom: 1930 m³/s - average values for depth average and surface layer – right bank particles

4.3.1.4. Goyne field particles

Left bank upstream groyne field

Upstream of the left bank upstream groyne field, 8 different locations with a specific distance from the shore were chosen as starting positions. The points were arranged along a previously defined line at equal distances in order to evaluate possible influences of the distance to the bank. Figure 21 gives a visual impression of the particle tracks derived from a simulation during mean water conditions. It is clearly visible, that those particles started near the shore line (Figure 21up) are more likely to flow into the vortex formation upstream of the first groyne compared to the centre and groyne head near starting position.

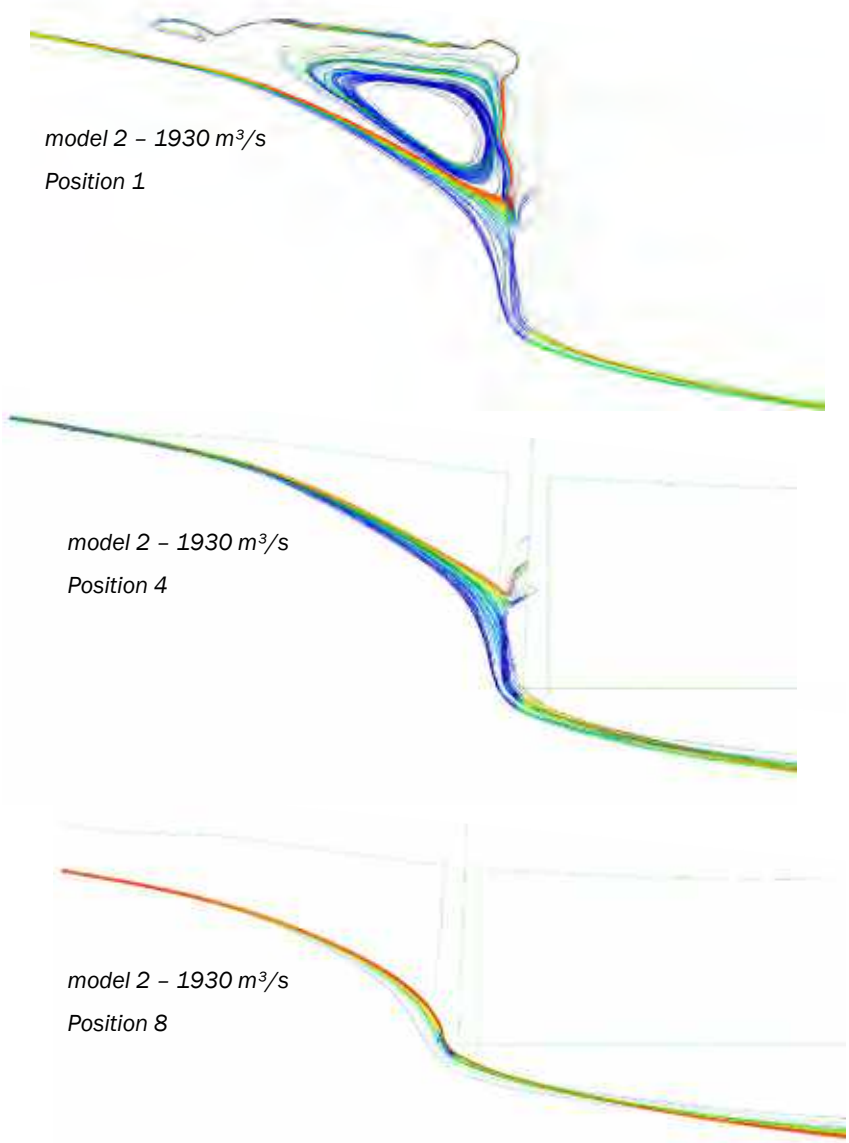


Figure 21 Particle tracks - model 2 – 1930 m²/s - top: bank near starting position, centre: centre starting position, bottom: groyne head near staring position – left bank upstream groyne field

As a further result a mass flow diagram containing averaged information from all groyne field starting positions during a discharge of 1930 m³/s were gathered in Figure 22 comparing those particles started in the depth average layer (Figure 22 - top) with those started in the surface layer (Figure 22 - bottom). Generally both simulations result in a quite similar overall accumulation with 59 respectively 54 % of particles transported through the model reach. The highest number of stranded particles is found and detected in front of the first groyne close to the starting position.

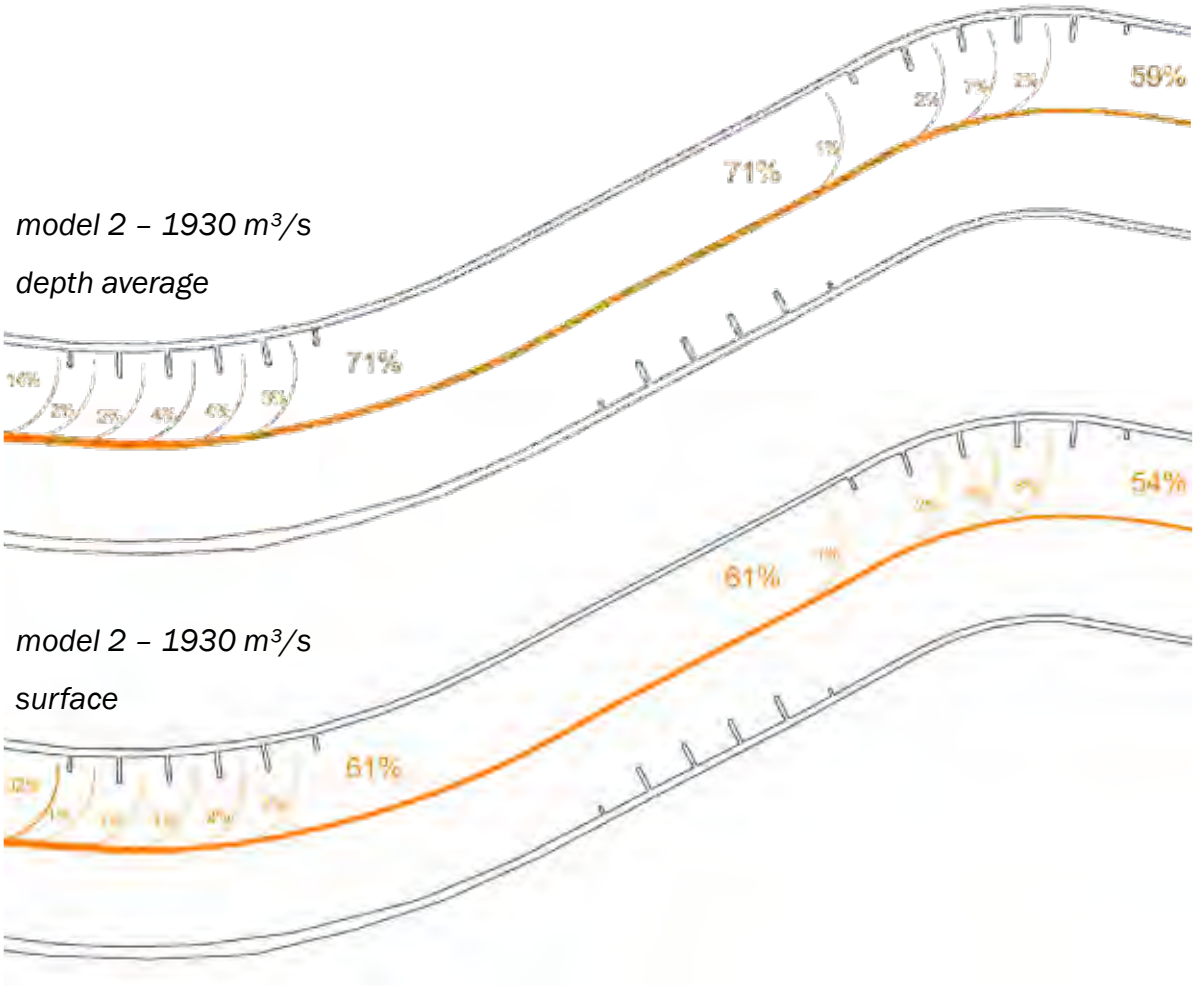


Figure 22 Particle tracking - mass flow diagram - model 2 – 1930 m²/s - top: depth average particles, bottom: surface particles – left bank groyne field – averaged starting positions

Simulations carried out at a discharge of 1800 m³/s generally show similar characteristics. However, with a range 33 to 52 % of passing through particles depending on the starting position and the starting depth, the interaction with the groyne field seems to be more intensive. Also, the effect of maximum accumulation in the centre of the groyne field – as also described in Figure 19 is clearly established.

Right bank groyne field

During 1800 m³/s the majority of the launched particles in front of the right bank groyne field is transported past the groynes leading to an amount of 90 % of particles leaving the modelled reach without stranding. The visualisation comprises a tendency of depositions after the second groyne (Figure 23) as also recognized with the virtual nets.

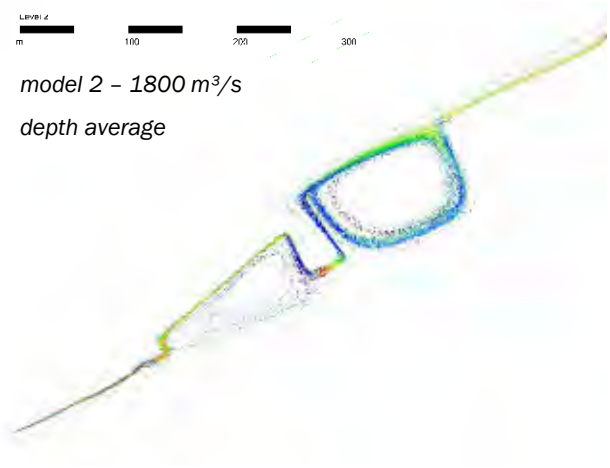


Figure 23 Particle tracks - model 2 – 1800 m²/s – right bank groyne field

4.3.2. Model 3

As for model 2 also for model 3 (with the single groyne structure on the right bank upstream) simulations were undertaken. They provide particle paths as well as detections of particles with virtual nets in order to quantify potential accumulations. Hence differences in the efficiency of single groynes compared to groyne fields were investigated.

Again, particles were started evenly distributed, left bank, right bank and in front of the groyne fields for mean flow conditions and for a discharge of 1800 m³/s. Generally, the interaction of particles with the accumulation zone of the single groyne was relatively low. Over both discharges and starting depths, for the evenly distributed particles, more than 99 % of which left the reach without stranding tendencies. Also, for left bank and right bank particles as well as for the particles started upstream of the groyne fields, a very low amount was detected within the nets. Figure 24 depicts an example for the particle paths (top) and the mass flow (bottom) of particles started upstream of the left bank groyne field in the depth average layer indicating that only 3 % of the started particles enter the accumulation zone near the groyne field. Compared to the same scenario in model 2 with the groyne field layout, where, depending on the layer and discharge around 30 % of the particles entered the accumulation zones in the upstream groyne field, this number is much lower.

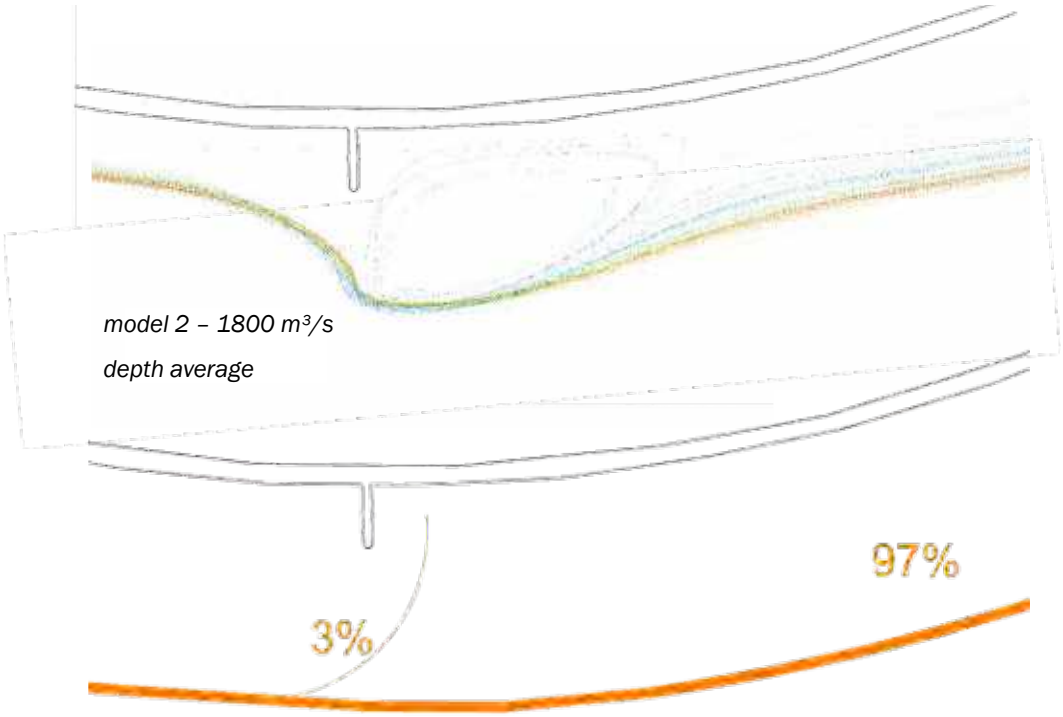


Figure 24 Particle tracking - model 3 – 1800 m²/s - top: particle paths, bottom: mass flow diagram – left bank groyne field – depth averaged starting positions

4.4. 2D model Vienna-Bratislava

In Figure 25 the results for the unsteady particle tracking for a flood event as described in 3.2.1.1 are plotted for several discharge stages near Fischamend. The particle paths as well as the occurring water levels for the selected discharge values are are depicted in a sequence.

The water level at a flow of 5600 m³/s large-scale flooding of the inundation area is evident. Placing particles at the orographic right flat bank near Fischamend reveals, that the particles take different courses. While some pathways end at the right shallow bank, the other particles flow in the direction of the Fischa River into a side channel system of the Danube. At a flow of 4400 m³/s in the northern part only the side arms are connected, but the inundation area is no longer flooded. Also, south of the main channel differences are visible compared to the water level at a flow of 5600 m³/s. Both side arms south of the Danube are still connected to the main river and the Fischa River. However, those areas where the particles are stranded are already dried out at this water stage. In addition, a backwater of the Fischa River and a correspondingly large-scale flooding of the foreland before the confluence into the side arms of the Danube are visible. The same is valid for a discharge of 3200 m³/s, where side channels, both north and south of the Danube, are still connected. Differences are visible in a flatter water level gradient as well as less submerged areas. At mean water level (1930 m³/s) northeast of the Danube only a downstream connection for the tributaries without any flow is given. Furthermore, south of the Danube, the Fischa flows directly into the main stem of the Danube River, since the other branches have also dried up.

5600 m³/s



4400 m³/s



3200 m³/s



1930 m³/s

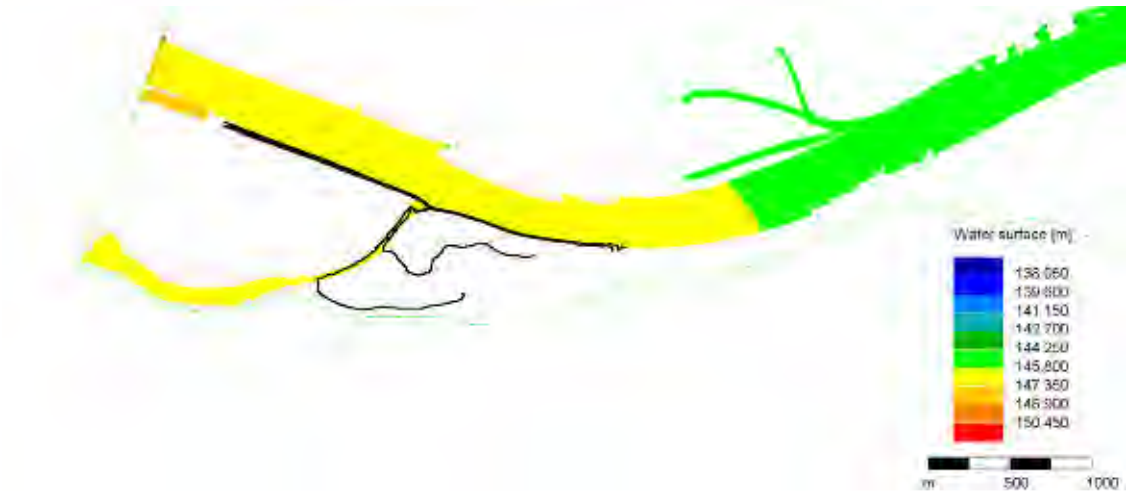


Figure 25: 2D model Vienna - Bratislava - water level and particle tracing near Fischamend - 5600 m³/s, 4400 m³/s, 3200 m³/s, 1930 m³/s

Figure 26 illustrates the course of the particle paths on the basis of the terrain model. During scaling, attention was paid to the best possible representation of the height difference, especially in the floodplain. The graph shows that those tracks which are stranded in the floodplain also end in sinks in the terrain.

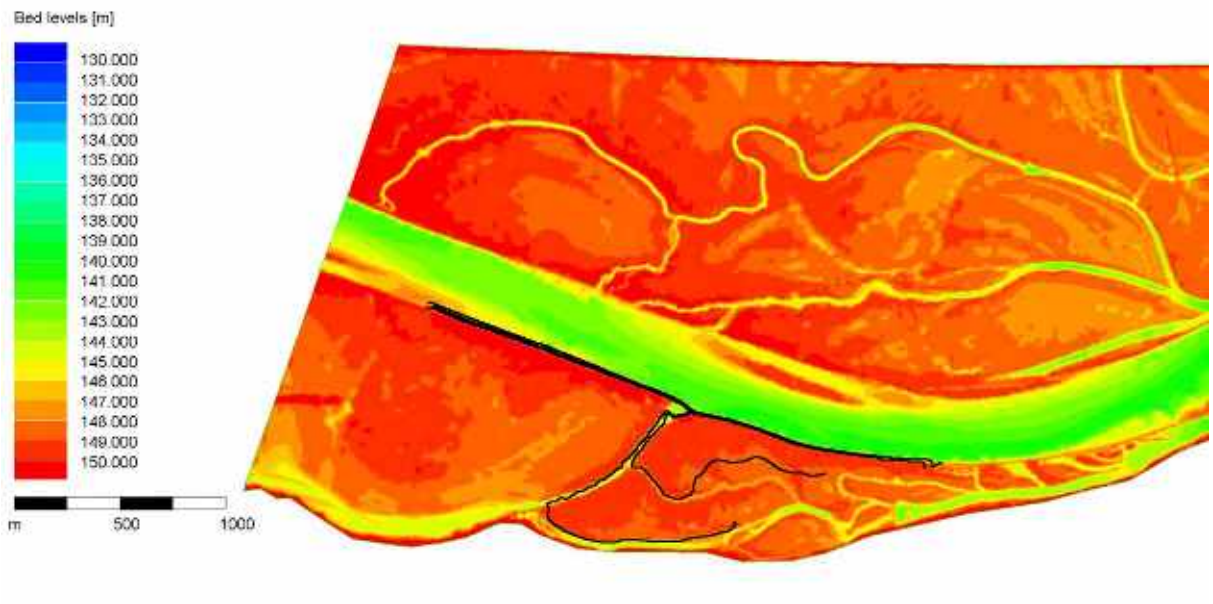


Figure 26: 2D model Vienna - Bratislava – digital terrain model and particle tracing near Fischamend

In Figure 27 the results for the unsteady particle tracking for a flood event as described in 3.2.1.1 are plotted for several discharge stages near Haslau. The particle paths as well as the occurring water levels for the selected discharge values are depicted in a sequence.

At a discharge of 5600 m³/s, most of the inundation area of the Danube is flooded and the side arms are connected to the main stem on both sides. Looking at the particle tracks, some particle strand again on the right bank of the Danube downstream of the point of origin. Some particles, however, flow into the right bank side channel system. While one particle path from the tributary finds its way back into the main river, other particles strand in the foreland of the Danube. As for the previous analysis, also at the location near Haslau, the floodplain subsequently dries out with the reduction of discharge and water level and subsequently at a discharge of 1930 m³/s even the whole side arm is disconnected from the main channel. The particle tracking clearly shows that during flood events bank near particles find their way into the forelands mainly via the side branch system and tend to accumulate in sinks of the floodplain.

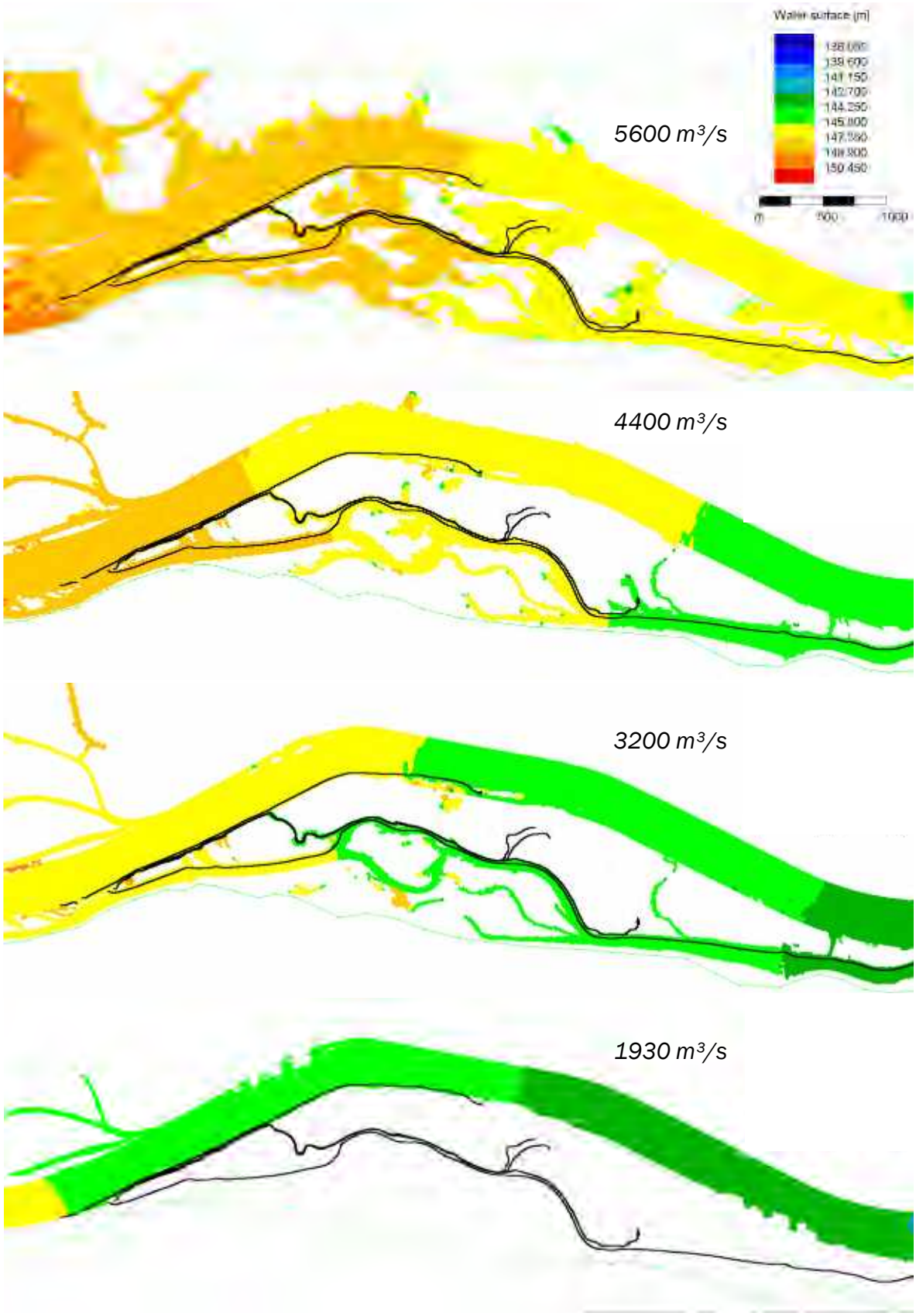


Figure 27: 2D model Vienna - Bratislava - water level and particle tracing near Haslau - 5600 m³/s, 4400 m³/s, 3200 m³/s, 1930 m³/s

When considering the representation of the trajectories in the terrain model (Figure 28a) frequent deposition in depressions becomes visible, especially for those pathways that end in the floodplain. In addition, the individual side arms that carry water in the foreland under certain runoff conditions can be clearly seen. This helps to explain the concrete setting of the respective particle paths.

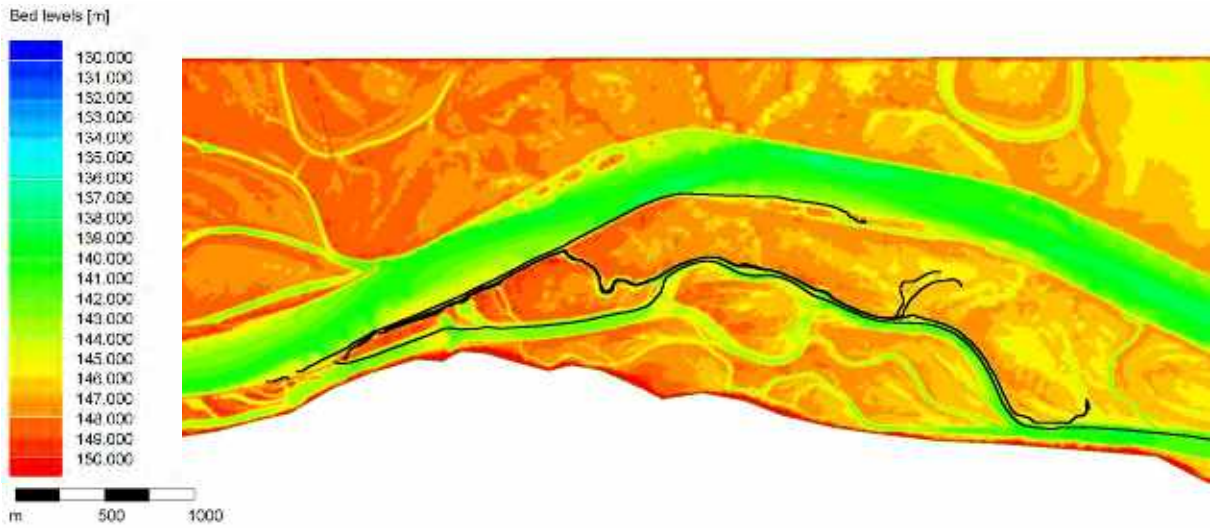


Figure 28: 2D model Vienna - Bratislava – digital terrain model and particle tracing near Haslau

4.5. Field tests with GPS-tagged floating items

During the field survey to evaluate the macro plastic transport in the Danube downstream of Vienna by means of GPS tracking, 35 stranding events were detected for a total of 13 single tracks of floating items. From the data generated, transport distances, stranding frequencies and stranding causes/ areas were analysed.

A visual analysis of the particle tracks taken with a temporal resolution of 1 minute gives a first impression of the flow paths. Figure 29 contains examples for different characteristic of the particle tracks along the project reach. In the starting area (Figure 29a) all items – right bank as well as left bank – follow a bank near parallel flow path. Figure 29b refers to a more downstream section at stream-km 1910. Here the Danube is characterised by a river bend with a groyne field in the inner bank and gravel bank in the outer bank. Due to the flow constrictions on both sides, the most items are obviously diverted more to the river centre, whereas some of them ended up deposited in the right bank groyne field. Another area where deposition occurred related to groyne structures on the right bank of the Danube River is provided in Figure 29c. This section near Haslau-Regelsbrunn is also known as an accumulation zone from former samplings, the accumulation trend here could be observed within the field tests.

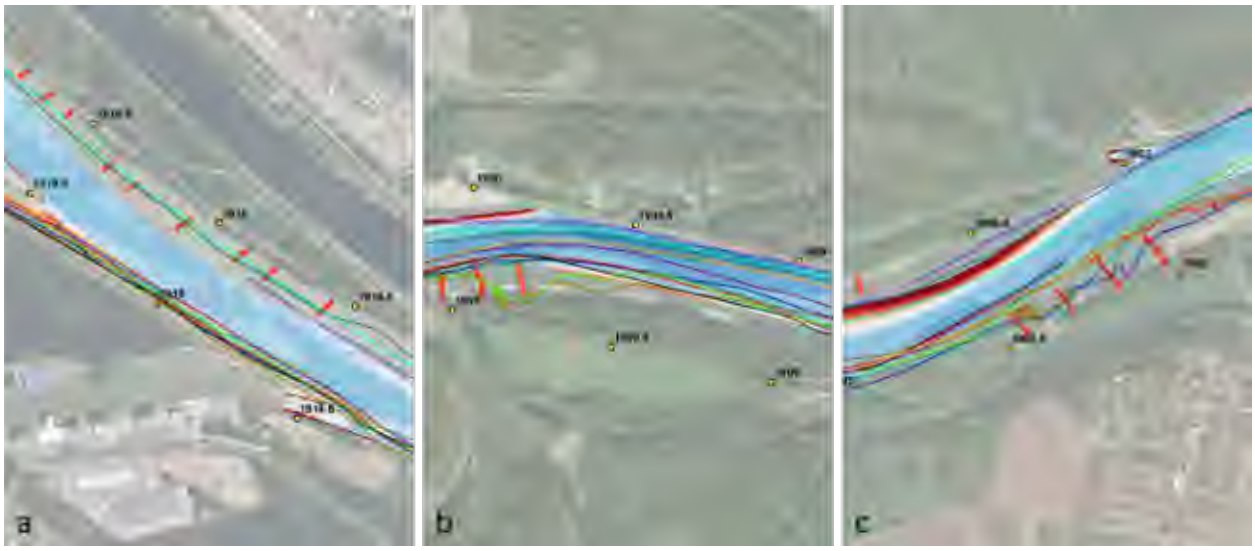


Figure 29 Particle tracks of GPS-tagged floating items - (a) starting area with tracks in main stream direction (b) area of flow diversion induced by hydraulic structures (c) groyne field accumulation zone

The field measurements conducted were also used to validate results of the numerical particle tracing. Figure 30 provides a comparison of particle tracks derived from the field survey (up) and numerical simulations (bottom) for comparable discharges around mean water levels, showing good correlation of the flow paths.

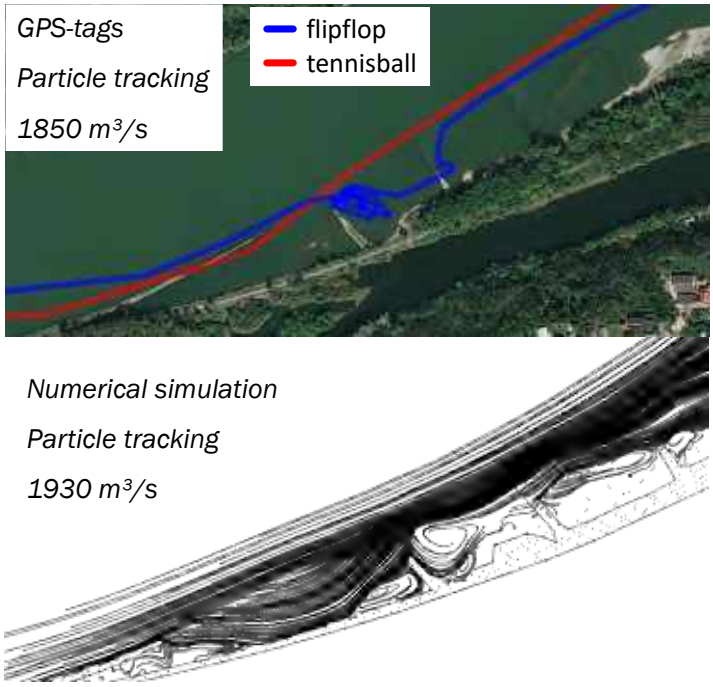


Figure 30 Comparison of particle tracks derived from the field survey (up) and numerical simulations (bottom)

Figure 31 left contains particle paths observed during the field test at the confluence of the Schwechat River. Numerous particles were drifting and stranding in the upstream groyne field. One particle also stranded in the area downstream of the confluence, where accumulations could be well observed in the field as shown in Figure 31 right.

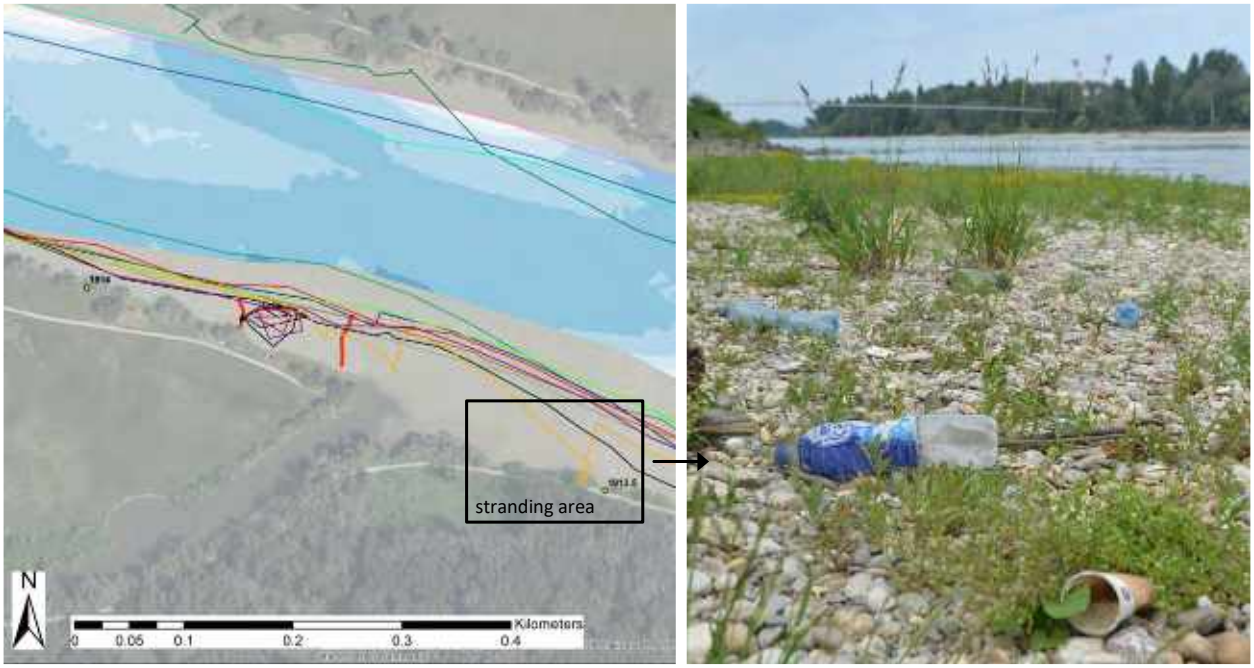


Figure 31: Particle paths observed during the field test (left) and macro plastic accumulations found in the stranding area

A statistical analysis based on the data from the field tests revealed, that most of the strandings take place at fixed banks (41 %) and groyne fields (29 %) as shown in Figure 32. Minor depositions were detected at gravel banks (18 %), in side channels (6 %) and in areas with backwater situation due to confluences of side channels (6 %). The high percentage of accumulation at fixed banks can be explained by the fact, that between Vienna and Bratislava around 70 % of the river banks are characterized by fixed embankments with riprap stones. Also, groyne fields are frequently found at both banks of the Danube leading to flow path diversions towards the shore line and subsequent strandings.

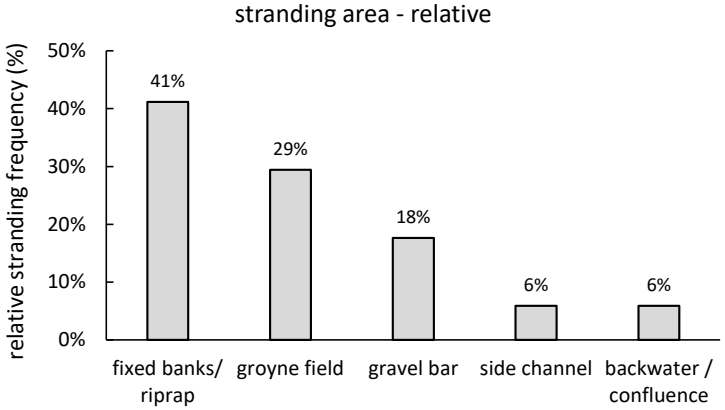


Figure 32: Relative stranding frequency related to area of stranding

Furthermore, the analysis of the gathered data towards average travel distances was calculated for the different items (tennisball, flipflop, bottle filled, bottle empty). The XPS was excluded in this analysis, as there was only 1 field test using this item. Figure 33 depicts the results, showing the calculated distances and the number of single tracks used for each item, ranging from 7.1 km to 15.7 km based on 6 to 11 single tracks. The average travel distance until a macro plastic item deposits was found at 10.4 km.

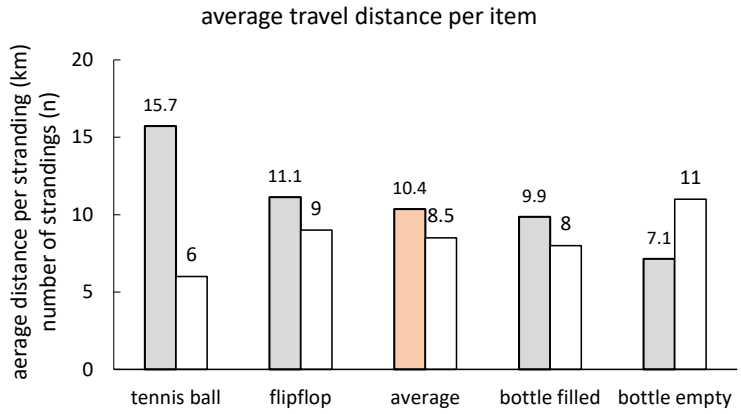


Figure 33: average travel distance per items and stranding

To evaluate the influence of discharge, the average number of strandings during each survey day was plotted against the average daily discharge in the Danube river as depicted in Figure 34. Due to the low amount of data there is no strong correlation, however, a higher stranding possibility can be observed at higher discharges due to more interaction between main channel and groyne fields.

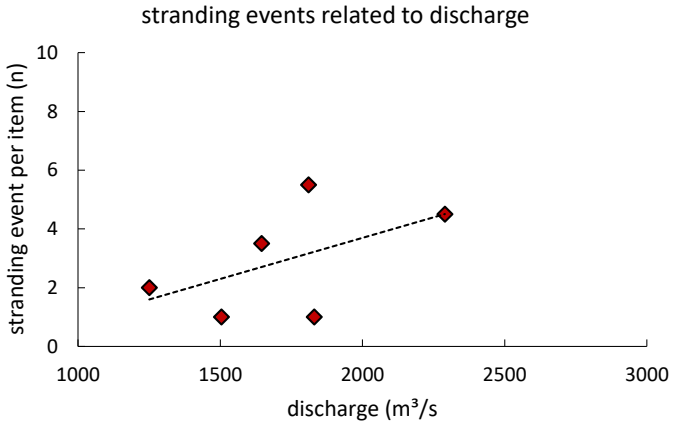


Figure 34 stranding events in relation to the average daily discharge in the Danube River

Towards the question, whether plastic particles are only stranded on the bank of the introduction, or whether they are also washed to the other bank, the distances from the centre of the fairway were plotted for all tracks in Figure 35. For the interpretation of the graph it has to be stated, that there is a natural oscillation of the paths when referring them to the centre line of the fairway due to morphological reasons. However, it can be stated on this graph, that all particles stayed on the side they were introduced, both left bank and right bank items. Only two items significantly crossed the centre line of the fairway temporarily before traveling back to the side they were launched. This analysis clearly underlines, that particles stay on the side they are entering the system. Therefore, it is likely, that the three right bank tributaries (Donaukanal, Schwechat, Fischa) flowing into the Danube in this area, all of which flow through densely populated areas, can be a reason for the higher amount of macro plastic found at the right bank of the Danube river compared with the left bank.

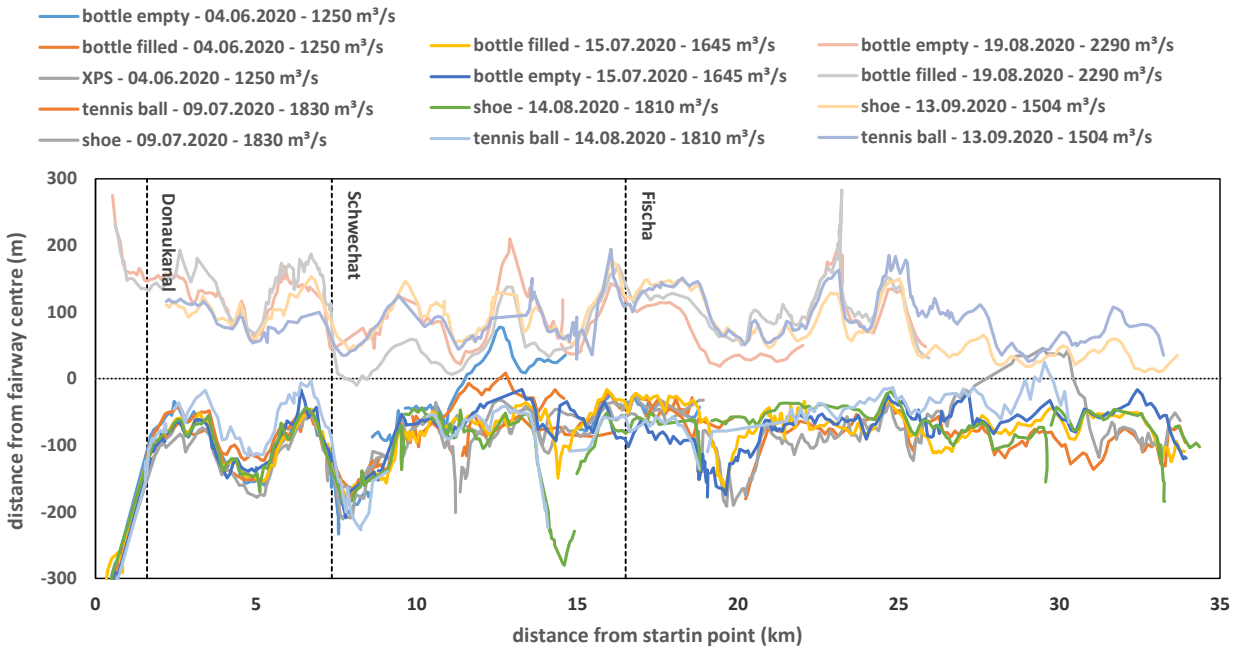


Figure 35 particle paths in longitudinal direction and with distance from the centre line of the fairway

Besides, the influence of wind on strandings could be classified to a very low level for almost all objects except the XPS during the performed tests. One influence that was difficult to detect in this work was navigation, as the swell caused by ships, often very sudden, frequently removed the trackers from the main current. This resulted in transport close to shore, which encouraged stranding that would not have occurred in this form within the natural stream.

5. Summary and conclusion

Within activity 3.7 "Parameters and indicators for plastic accumulation processes" it was aimed to describe fluvial processes related to plastic waste in river systems by the means of numerical simulations and particle tracing in particular. Therefore, the following models built up within activity 3.6 "3D hydrodynamic modelling of selected plastic accumulation zones" in order to improve process understanding of macro plastic transport in the Danube River east of Vienna:

- 3D model Haslau-Regelsbrunn: river-kilometer 1901 - 1903,5
- 3D model Haslau-Wildungsmauer-Witzelsdorf: river-kilometer 1903,5 1891,7 - 1895,2
- 2D model Vienna-Bratislava: river-kilometer 1907 - 1881,3
- 3D concept model

The resulting 2D and 3D parameters of flow velocities and flow directions, bed shear stresses, partial flows and water level positions for different discharge conditions are a prerequisite for the application of virtual particle tracing, as performed within this activity. By visualization of the particle tracks, as well as calculation of the water age, assumptions towards accumulation potential have been concluded. Additionally, the implementation of virtual nets, able to detect single particles in arranged groyne fields of the concept model, enabled a quantification of particle mass flows related to hydraulic engineering structures. Furthermore a field survey was conducted to increase knowledge of plastics transported in river systems, which was also used to validate the numerical model results as well as to create a broader understanding of particle flows. Following findings can be concluded from the investigations:

<u>Flow chart of accumulation behaviour related to hydraulic structures and discharge levels:</u>

- A flow chart regarding water age and vortex formation describing accumulation effects related to engineering structures depended on discharge levels was developed based on virtual particle flow simulations (see Figure 36)
- Significant vortex formations and high water age within the groyne fields was observed at low water level (980 m^3/s) leading to marginal macro plastic accumulation in the bank-near area
- Partial overflow of groynes and guiding walls occurs at mean water level (1930 m^3/s) leading to moderate vortex formations with more exchange between main stream and groyne fields marking initial accumulation in the bank-near area
- Entire overflow of groynes and guiding walls was observed at 3.000m^3/s leading to a remobilisation of accumulated macro plastic
- Water level lowering was identified to have a high probability for macro plastic to accumulate within the groyne fields

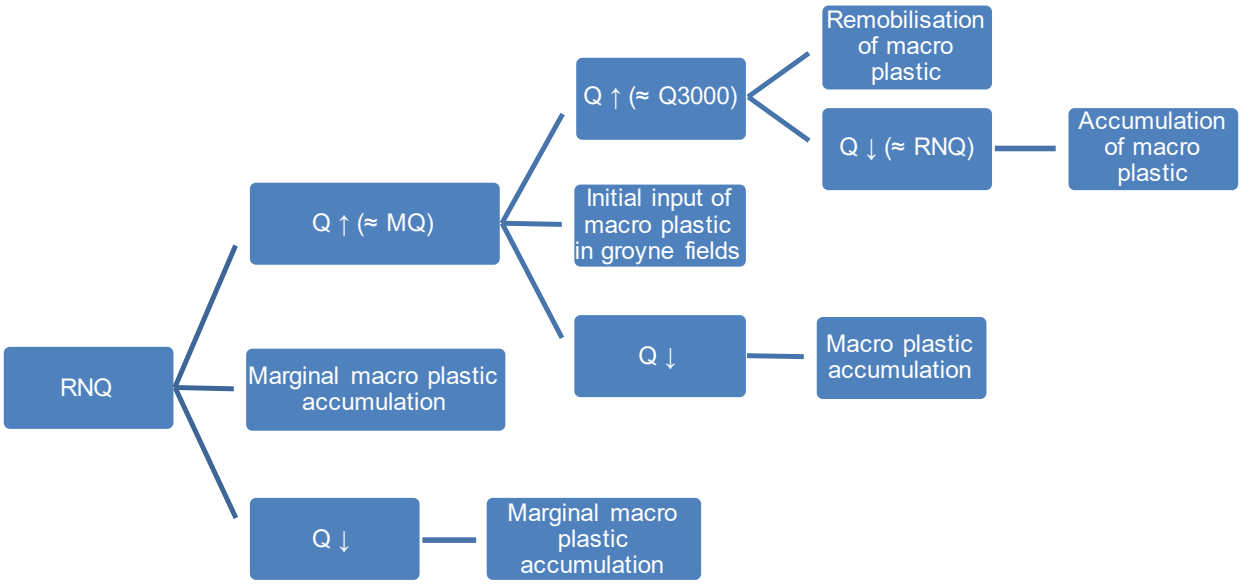


Figure 36 Flow chart of macro plastic accumulations related to engineering structures depending on discharge levels

Mass flow of simulated particles:

- A quantification of mass flows of virtual particles was derived from the 7 km artificial concept model using the particle tracking tool and additionally implemented virtual nets.
- It was found, that most particles in the main channel pass through the section without interaction with hydraulic structures between low water and mean water discharge. 98 % of the particles started evenly distributed over the cross section left the 7 km reach without accumulation in one of the groyne fields.
- Particles launched near the bank or upstream from groyne fields, however, showed a high probability to accumulate again. On the left bank characterized by 2 groyne fields (each having 6 single groynes) between 40 % and 60 % left the section without accumulation. The other part was detected by one of the virtual nets and therefore are associated to groyne field accumulation
- Furthermore, a clear tendency towards the highest accumulation potential in the centre of the groyne field was observed within the scope of the simulations

Floodplain particle flows:

- Floodplain particle flow paths were investigated by quasi-steady simulations of a flood wave using a large scale 2D numerical model. Simulations show, that particles are likely to drift into side arms as well as into natural sinks of the floodplain area where accumulation was observed both in the model as well as in nature.

Field survey using GPS-tagged floating items:

- A series of field tests using GPS-tagged floating items revealed, that macro plastic tends to stay on the river bank it is introduced into the system. Both, particles started on the right river bank as well as on the left river bank, were found to run mostly bank-parallel without switching to the opposite riverbank. As the tributaries Donaukanal, Schwechat and Fsicha are all entering the Danube River at its right side after flowing

through highly populated areas, macro plastic coming from these sources is very likely to end up on the right river bank of the Danube.

- Most of the strandings were detected at fixed banks (40 %) and groyne fields (37 %), based on the fact, that between Vienna and Bratislava around 70 % of the river banks are characterized by fixed embankments with riprap stones. Furthermore, the frequently found groyne fields at both banks of the Danube lead to flow path diversions towards the shore line and subsequent strandings.
- Travel distances with respect to the used item (tennis ball, flipflop, bottle filled, bottle empty) ranged between 7.1 km to 15.7 km with an average value of 10.4 km per stranding.
- Higher stranding possibility was observed at higher discharges due to more interaction between main channel and groyne fields
- Good correlation between simulated particle tracks and detected flow paths during the field survey was observed
- Macro plastic accumulations were documented within the field test in stranding areas of the GPS-tagged items

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