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Long-term flow field monitoring at the Upper Rhine floodplains

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ABSTRACT: While the technical development of numerical and physical modelling of floodplain hydraulics has made great progress during the past decades, up to now very few field investigations have been conducted during flood events. In this context, the impact of different types of vegetation structures on the flow field has been systematically studied at a floodplain site of the Upper Rhine. The decisive impact of different types of vegetation on hydraulics and sedimentation was monitored online for several flood events with Acoustic Doppler Current Profilers. In the evaluation of the results of this experimental design, particular importance is attached to describing and comparing the temporal and spatial variations of flow velocity and its intensity at different water levels for an entire flood event and between different events.

Keywords: Upper Rhine, Floodplains, Flood events, Floodplain hydraulics, Flow velocities, Riparian vegetation, ADCP measurements

1 INTRODUCTION

1.1 *Background*

The correction and systematic development of the Upper Rhine between Basel and Karlsruhe during the last 190 years have led to a dramatic incision of the river bed by up to several metres and the loss of more than 700 km² of floodplain. This has caused the acceleration of flood waves and the increase of flood peaks. In particular, the construction of the hydraulic power stations in the last century played a decisive role for that development. Against this background, the rehabilitation of floodplain areas is essential to protect the Upper Rhine Valley against a 200 year flood event (Buck et al. 1993, Klaiber et al. 1997).

The success of plans and measures to restore floodplains and designate new flood retention areas for rivers depends on a fundamental understanding of the boundary conditions during flood events. Hydraulic conditions interact directly with vegetation and morphology and have a decisive impact on sedimentation and erosion (Baptist 2005, Corenblit et al. 2007, Horn and Richards 2007). While the technical development of numerical and physical modelling of floodplain hydraulics has made great progress during the past decades and several research groups have been highly involved in that issue (for instance Copeland 2000, Fischer-Antze et al. 2001, Righetti and Armanini 2002, Stoesser et al. 2003, Nicholas and McLelland 2004, Helmiö 2005, Baptist 2005, Järvelä 2005, Wilson et al. 2006), up to now very few field investigations have been conducted during flood events (Gerstgraser 2000, Meixner 2002, Bölscher and Ergenzinger 2003, Helmiö and Järvelä 2004, Rauch 2005, Rauch et al. 2005, Bölscher et al. 2005, Straatsma 2007).

Straatsma points out that only a few studies have been carried out to estimate in situ floodplain roughness during overbank flooding (Straatsma 2007). For the reasons he refers to Freeman et al. (1996). They note that it is difficult to locate field sites where water depths are sufficient to inundate the floodplain and where measurements can safely be performed. Moreover, field surveys are very labour-intensive and their timing depends on peak discharges (Straatsma 2007).

1.2 *Aims*

In this context, the impact of different types of vegetation structures on the flow field has been systematically studied over a period of several years at a floodplain site of the Upper Rhine. The aim of this investigation was to carry out in situ flow velocity measurements during entire flood events to obtain information about the evolution of hydraulics under different and natural conditions and to understand under which circumstances erosion and sedimentation take place at typical riparian vegetation sites.

The results of measurements for the year 2005 are given for this sample site. Particular importance is attached to describing and comparing the temporal and spatial variations of flow velocity and its intensity at different water levels for an entire flood event, across the entire water column and at a later date between different events. The analysis of the recorded data sets from 2005 primarily refers to the shape and values of measured curves and concentrates on two main aspects: (1) the changes of the flow field between the rising and falling stages of a flood event, (2) the differences between the open flow field of grassland compared with the densely vegetated riparian woodland.

1.3 *Study area*

The study area is located at a silted groin field of the Upper Rhine in south-western Germany between Basel and Breisach (Fig. 1). The site was chosen because its structure and proximity to the river allowed the interaction between flow field,

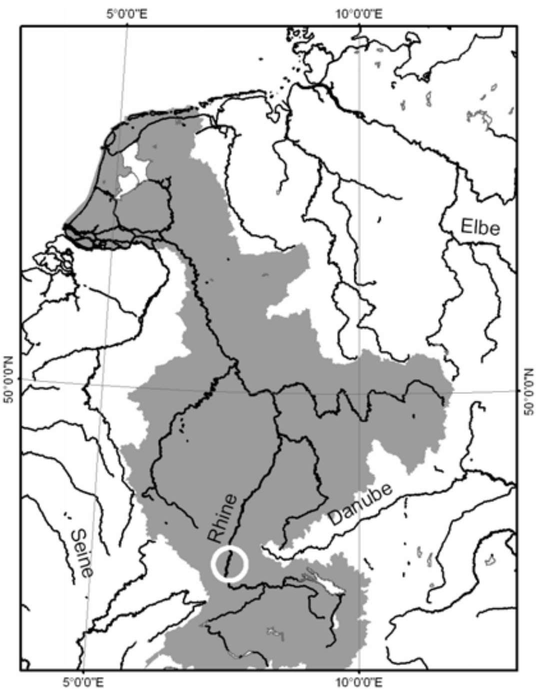

Figure 1. Location of the study area (white circle) at the Rhine catchment (data source: EEA Copenhagen 2010).

morphology and vegetation to be studied in situ. Because of the demands of shipping and energy production the Upper Rhine is divided into the Grand Canal d´Alsace (MQ 1400 m³/s) and the original course of the river (residual flow between 20 and 30 m³/s) 35 km upstream of the field site. A weir regulates the discharge distribution over the channel and old river course.

The elevation of the river bed is about 193 m a.s.l. (Fig. 2). The difference in height between the river bed and the top of the embankment is about 12 metres. The investigation area is 100 metres long and 100 metres wide. The water depth of the river at the mean discharge of 20-30m³/s varies between 2 and 3 metres. The groin field is dominated by longitudinal morphological structures at different levels (Figures 2-3). On the basis of the different inundation classes and the different types of vegetation, the site is subdivided into three zones. The highest east-west pulvinated parts have a mean height of three metres above the mean water level. This area is covered by herbs and grass and will only be inundated at a discharge >1000 m³/s and a water level in excess of 5 metres, which occurs once or twice per year. Single spots at the upstream and downstream borders of the site are dominated by bushes and older trees with rigid trunks. The lower areas are located between 0.5 and 1.5 m above the mean water level and are inundated by discharges > 100 m³/s, which have a high recurrence interval and can last for several days.

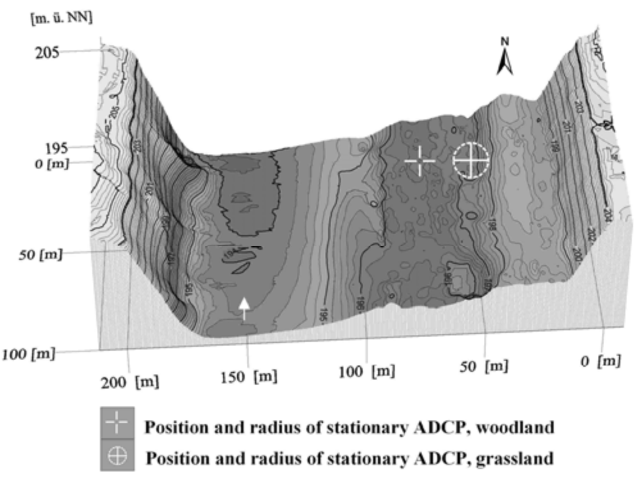

Figure 2. Topography and location of ADCPs (oriented map, vertical exaggeration: 1.5).

According to the distribution of vegetation types, the lower part of the floodplain can be subdivided into two areas. The first is located close to the main stream and is dominated by riparian woodland, namely 20-year-old non-rigid willows. The herb layer is a mixture of different types of grass and herbs. The morphology of this zone is dominated by small and steep ridges stretching from south to north. The second area between the willow belt and the upper inundation level is mainly covered by grass and herbs (Phalaris arundinacea, Urtica dioica). Occasional spots at the up- and downstream borders of the site are dominated by trees and bushes. After the convex transition from the upper grassland the morphology gently slopes towards the woodland. At the southern part a small water-bearing pool was formed. Both lower zones have been surveyed by velocity measurements.

2 METHODS

Two locations with relatively similar morphologies and topographies were chosen for flow field measurements (Fig. 2 and Fig. 3). In the following, the location at the riparian woodland zone will be referred to as field site 1 and the location of the lower grassland zone as field site 2.

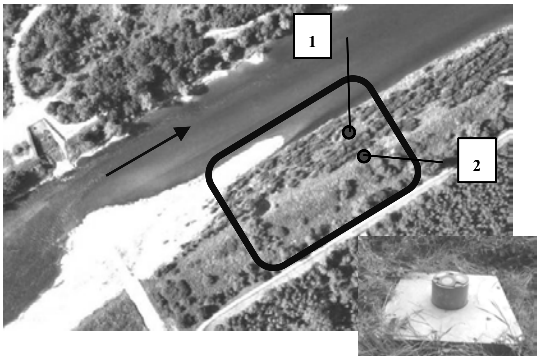

Figure 3. Study area (black framed) at mean discharge of 30 m³/s; (aerial photo is not oriented; black arrow labels the northward flowing stream; black circles tag both positions of stationary, bottom-mounted ADCPs (site 1, riparian woodland; site2, riparian grassland).

Field site 1 is located nearshore at an elevation between 196 and 197 metres and is dominated by non-rigid willow trees and a layer of herbaceous plants (Figures 3 and 5). The canopy height varies between 2-12 metres. Depending on the flood event, the grove is partly or completely submerged and, owing to the high elasticity of the tree crowns, changes its habitus depending on flow and water level (Oplatka 1998, Gerstgraser 2000, Rauch et al. 2005).

Field site 2 is similar in location and elevation to site 1, but it is 35 metres closer to the embankment and its vegetation mainly consists of Urtica dioica and Phalaris arundinacea with no woody plants (Figures 3-4). Whereas site 1 is located on the lee side of the willows, site 2 has an open channel structure permitting free flow.

This setup ensures that the impact of the main channel is low and that typical floodplain flow fields can be detected, and enables a comparative analysis and assessment of both sites (Fig.3). Both sites are equipped with bottom-mounted and remote-controlled Acoustic Doppler Current Profilers of the ADCP Workhorse Sentinel type (1228 KHz; RD Instruments).

This setup has been running since 2001 and values are permanently recorded over the year. Every 15 minutes around 1400 measurements are averaged, yielding high-quality data and eliminating noise and extreme values due to turbulence. The vertical profile is divided into 10 cm segments termed BIN. The initial blanking distance is 66 cm above ground level. Water velocity and various other parameters are measured at each segment.

Figure 4. Lower grassland, location No.2 with bottom-mounted ADCP (southward view).

Figure 5. Riparian woodland, location No.1 Study area at mean discharge (northward view in flow direction).

Figure 6. Study area at a discharge of > 1800 m³/s (northward view in flow direction).

3 RESULTS

3.1 *Flood frequency and profiling times during the study period*

The water depths from December 2004 to December 2005 were determined for the Hartheim study site (stream-km 210.5) on the basis of 15-minute gauge data from Neuenburg gauge (stream-km 199.5) and Hartheim (stream-km 214.2) provided by the Wasser- und Schifffahrtsamt Freiburg (Fig. 7). During the study period the water level gradients were between 0.86 and 1.05 ‰ and averaged 0.90 ‰. The study area was inundated by four smaller floods in mid-February, late April, early and late May, and the biggest flood from late August to early September. A common feature of all events is a steeply rising flood hydrograph. Only the analysed August flood – with a max. level over 200.5 m a.s.l. and a peak discharge of over 2100 m³/s – inundated the entire study site and its elevated ridges for a lengthy period and reached as far as the lower embankment. In 2005 the willow belt was flooded at levels between 196.6 and 197.2 m a.s.l. for 300-400 hours. Field sites 1 and 2 are also located within this area (Fig. 2 and 3).

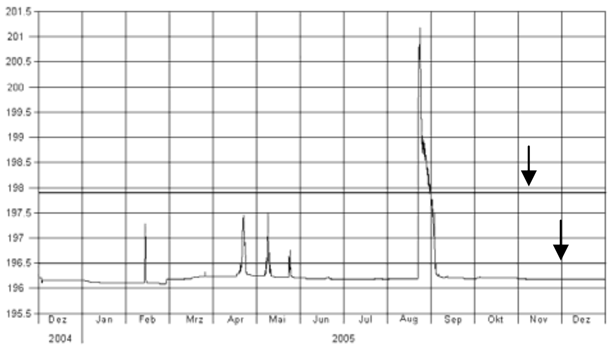

Figure 7. Calculated gauge data study site Hartheim, Dec. 2004- Dec. 2005 (left: water level [m a.s.l.], the lower continuous line shows the lower inundation level of the riparian woodland zone, the upper line marks the lower inundation level of the upper grassland zone; both lines marked by arrows; data base: gauge Neuenburg & Hartheim).

3.2 *Evolution of August 2005 flood event*

The flood wave approached at the field site at about 06:00 on 22 Aug. 2005 (the first signals were recorded at ensemble 3530) with a very steep water-level rise. A first maximum with a water level of 3.5 metres on the floodplain was reached at 23:06 on 22 Aug. 2005. The first minimum occurred at 6:51 on 23 Aug. 2005 with a water level of approximately 3 metres, i.e. 24 hours after the onset. A second maximum of almost 3.8 metres at the Hartheim floodplain and a peak discharge of more than 2100 m³/s at the Hartheim gauge (stream-km 214.2) occurred at 16:36 on 23 Aug. 2005. The subsequent sinking limb is about as steep as the rising limb of the flood. At about 11:00 on 24 Aug. 2005 the wave began to flatten and remained constant at just above one metre for a relatively long time before it finally ended at about 3 Sept. 2005.The entire flood lasted 13 days, of which 3 displayed a sharp rise with a double maximum and a rapid fall and the remaining 10 days a long and gently falling limb of the flood hydrograph. The August flood was the only notable event in 2005, but it already counts as one of the biggest events since the survey started in 2001.

The flow velocities at both sites show the characteristic pattern of highest values occurring with rising water level and towards the water surface. The complete data sets are not displayed, but selected profiles are given in the following section in table 1 and in figures 8-13. At site 2 the highest velocities of 1.3-1.5 m/s occur in the upper third of the water body. As expected, velocities decrease to values of 1 m/s and fall to about 0.7 m/s in the lower third. Below 1 m depth velocities fall even further and reach levels of less than 0.5 m/s. After 60 hours velocities are less than 0.5 m/s and falling steadily. The trend is similar at site 1, but velocities never reach the levels of site 2. The highest levels of almost under 1 m/s were reached with the second maximum close to 4 metres in the upper third of the water column. The velocities at sites 1 and 2 converge only after 60 hours, the values within the willow grove (site 1) always remaining lower and strongly tending towards 0 m/s.

3.3 *Scheme of results for selected profiling times*

This section addresses the vertical profiles of flow velocity during the rising and falling limb of the flood hydrograph. The following diagrams (Figures 8-13; abscissa, velocity [mm/s]; ordinate, water level [m]) show selected vertical velocity profiles from field site 1 (riparian woodland zone) and field site 2 (lower grassland zone). The water depth is related to the surface of the floodplain location of the ADCP sites; the heights of surfaces are similar.

The selection begins at time 1 with the rising water level before the first peak of inundation (Fig. 8 and Fig. 11; t1-t3). Figs 9 and 12 display the later stage beyond the first maximum towards the first minimum (t4-t7). The data set is completed with the section between the second maximum and the falling limb of the hydrograph till a water level of 1.4 metres (Fig. 10 and Fig. 13; t8-t12). Table 1 gives the corresponding ensemble number, dates, times and statistical values for selected flood times for site 1 and 2. The distribution for the curves of Fig. 8 to Fig. 13 varies significantly. In general it can be described by different linear or more complex log functions.

3.4 *Results for selected profiling times – riparian woodland site*

Woodland (site 1, Figures 8-10): The single means of the selected profiles vary between 65 and 781 mm/s (average of sum t1-t12: 300 mm/s). The minimum and maximum are reached at t12 (10 mm/s, falling water level after the second peak of inundation) and at t8 (979 mm/s, second flood peak), respectively. On average the lowest values are always close to the floodplain surface (73 mm/s) and the highest values are situated close to the water surface (468 mm/s). Thus the lower segment of the flow field (Tab. 1, bottom values) shows significant low and constant values between 30 and 108 mm/s. The uppermost values (Tab. 1, top values) are reached close to the water surface (101 – 882 mm/s). With some exceptions the sampled top data are almost congruent with the max. values, whereas the bottom flow data are almost always higher than the min. flow values.

Between time 1 and time 3 (rising stage) the distribution is almost stable on a low level for the measured velocity data of the woodland zone (site 1). The extreme values fluctuate between 27 and 199 mm/s, the average values range between 65 and 107 mm/s. From t1 up to t3 with a water level of 2 metres, the flow field is attenuated by the vegetation at a very low but constant level; hence – and compared with later situations - a steep curve and only a narrow margin are formed between the lower and upper values of the water column, which vary between 38 and 199 mm/s (Fig. 8).

With continuing inundation (Fig. 9, t4-t7) the curve alters towards a more linear form, characterised by a greater velocity range between the lowest and highest parts of the water column. At the lowermost depth cells (0.75 m) all profiles show the same pattern but with a stant low flow beneath 110 mm/s. The range of the stages t4 and t5 is quite similar, whereas the range of t6 (3.50 metres) differs from t5 but is almost similar to t7 at the falling stage. Although t5 and t7 are measured at the same water level of 3 metres, both profiles vary in type. After the first flood peak the increase of flow velocity up to the water surface reaches 700 mm/s; at t5 only 400 mm/s were approached. In addition, comparison of the lower and upper profile sections of t6 and t7 (0.7 to 2.7 metres and upwards of 2.7 metres) shows for the upper section a situation that seems to be on a constant level of 700 mm/s, the increase is almost zero. However the flow field of the lower section is characterised by a linear increase of the velocity. With rising stage up to the second maximum, the slope of the curve decreases weakly, thus the range between bottom and top expands. In contrast to the lower section with values still remaining at a very low level (>110 mm/s), close to the water surface the velocity increases from 681 to 812 mm/s. The average shows also its topmost value with 781 mm/s. As already mentioned above, the curves stay almost linear until the minimum after the first flood peak (see t6-t7). In contrast to that, the shape of the flow field describes a more typical logarithmic form from the second peak on. The water body of the lower segments up to 2 metres is accelerated, a non-uniform flow field has been formed, whereas

Table 1. Selected data of site 1 and 2 for time series t1-t12 (resulting velocities of x,y,z)

Statistics of velocity data sets 08 2005				Riparian woodland zone RWZ - site 1 Flow velocities [mm/s]						Riparian grassland zone RGZ - site 2 Flow velocities [mm/s]					
Profile Nr		RWZ	RGZ	Mean	Min	Max	Std	Bottom	Top	Mean	Min	Max	Std	Bottom	Top
t1	Profile Data Ensemble Number = First Ensemble Date = 05/08/22 First Ensemble Time = 07:06:31.80	3532	3532	107	38	190	63	38	146	118	18	239	95	239	31
t2	Profile Data Ensemble Number = First Ensemble Date = 05/08/22 First Ensemble Time = 07:51:31.80	3535	3535	65	27	104	26	46	101	38	11	115	31	115	24
t3	Profile Data Ensemble Number = First Ensemble Date = 05/08/22 First Ensemble Time = 09:36:31.80	3542	3542	94	28	199	44	94	199	122	24	280	79	74	280
t4	Profile Data Ensemble Number = First Ensemble Date = 05/08/22 First Ensemble Time = 13:36:31.80	3558	3558	150	13	296	92	108	296	458	103	792	229	103	792
t5	Profile Data Ensemble Number = First Ensemble Date = 05/08/22 First Ensemble Time = 16:51:31.80	3571	3571	207	31	424	133	83	424	854	264	1168	299	264	1155
t6	Profile Data Ensemble Number = First Ensemble Date = 05/08/22 First Ensemble Time = 22:36:31.80	3594	3594	462	47	758	257	63	725	969	274	1289	290	274	1283
t7	Profile Data Ensemble Number = First Ensemble Date = 05/08/23 First Ensemble Time = 06:51:31.80	3627	3627	396	30	701	244	30	681	966	304	1236	264	304	1236
t8	Profile Data Ensemble Number = First Ensemble Date = 05/08/23 First Ensemble Time = 16:36:31.80	3666	3666	781	107	979	230	107	882	1125	378	1413	269	378	1407
t9	Profile Data Ensemble Number = First Ensemble Date = 05/08/23 First Ensemble Time = 20:41:17.44	3692	3680	593	80	824	254	80	812	975	324	1262	264	324	1262
t10	Profile Data Ensemble Number = First Ensemble Date = 05/08/24 First Ensemble Time = 02:56:17.44	3705	3705	449	61	713	229	72	685	743	204	979	232	204	974
t11	Profile Data Ensemble Number = First Ensemble Date = 05/08/24 First Ensemble Time = 10:26:17.44	3735	3735	205	39	412	137	79	412	458	110	684	182	110	684
t12	Profile Data Ensemble Number = First Ensemble Date = 05/08/24 First Ensemble Time = 21:41:17.44	3780	3780	94	10	258	85	72	258	90	19	165	47	19	165
t1-t12	Magnitude [mm/s]; mean values			300	43	488	150	73	468	576	169	802	190	201	774

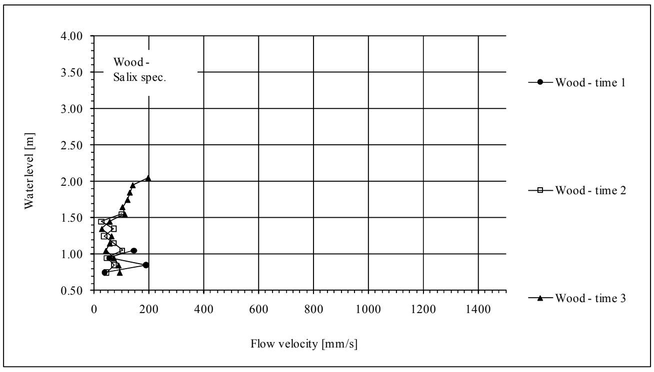

Figure 8. Flow velocity at riparian woodland, progression before the first flood peak.

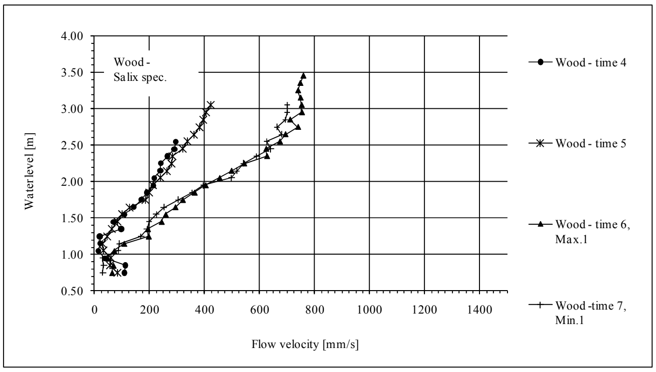

Figure 9. Flow velocity at riparian woodland, progression during rising and falling stages of the first flood peak.

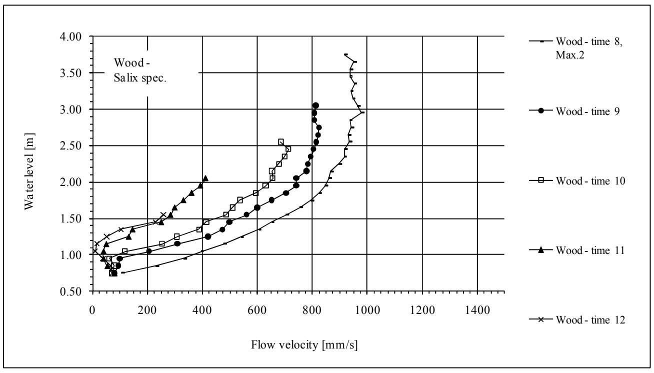

Figure 10. Flow velocity at riparian woodland, progression during falling stage of the second flood peak (v max. = 979 mm/s).

the flow field at the upper section still remains at a very constant, uniform level and oscillates around 900 mm/s. The weak rise is almost linear up to the water surface and shows marked similarities to time t6 and t7. From that second maximum on, the mean values decrease from 781 to 94 mm/s (t8-t12). Until t10 these flow characteristics do not change. Again, the flow above the level of 2 metres stays almost constant, and beneath that level the non-uniform flow field remains unaffected. The curve of t11 and t12 becomes more linear again but remains at a higher level compared with the situation at t3 (Fig.10). As regards vertical velocity distribution after t7, the vertical profile therefore divides into an upper and a lower section

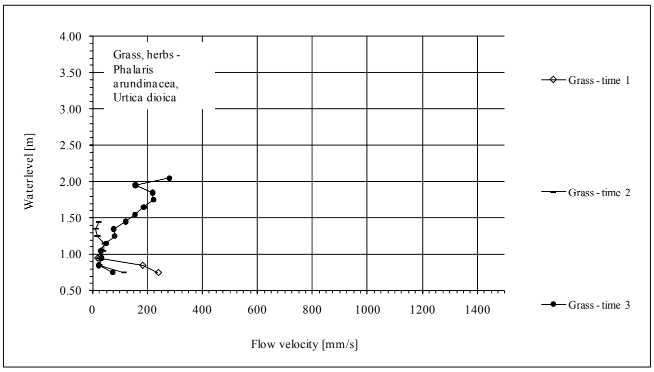

Figure 11. Flow velocity at riparian grassland, progression before the first flood peak.

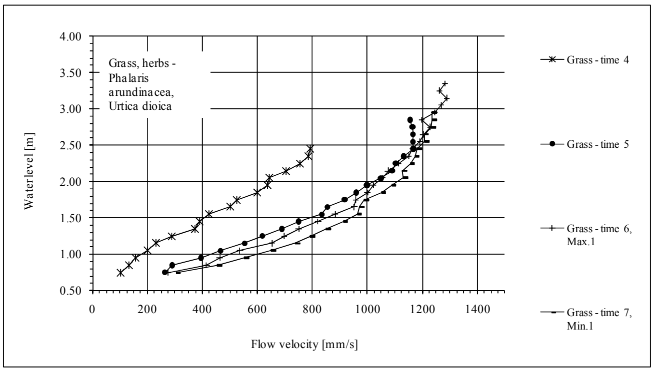

Figure 12. Flow velocity at riparian grassland, progression during rising and falling stages of the first flood peak.

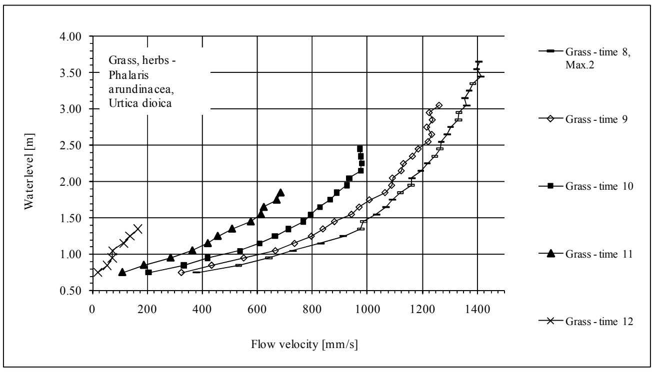

Figure 13. Flow velocity at riparian grassland, progression during falling stage of the second flood peak (v max. = 1413 mm/s).

at a level of 2 metres and with regard to the time series up to and after t7 the flow field changes from a linear to a more logarithmic form with an almost constant low velocity close to the floodplain level and expanding values beneath the water surface.

3.5 *Results for selected profiling times – riparian grassland site*

Grassland (Figures 11-13; site 2): The single means of the selected profiles vary between 38 and 1125 mm/s (average of sum t1-t12 576 mm/s). The minimum and maximum are reached at t2 (11 mm/s, rising water level before the first peak of inundation) and at t8 (1413 mm/s, second flood peak), respectively. On average the lowest values are always situated close to the floodplain surface (201 mm/s), whereas the highest values can be located close to the water surface (774 mm/s). The lower segment of the flow field (Tab. 1, bottom values) shows values oscillating between 19 and 378 mm/s. Also the uppermost values of the single profiles (Tab. 1, top values), which are mostly reached close to the water surface, vary between 24 and 1407 mm/s. With some exceptions they are congruent with the min. and max. values. In comparison to site 1 all values of site 2 (mean, min., max., bottom and top) are significantly higher at all flooding stages.

The flow field of t1–t3 shows mean values between 38 and 122 mm/s, with a min. of 11 and a max. value of 280 mm/s. Until t2 it is characterised by higher velocities close to the ground and inside the grass layer (between 115-239 mm/s) compared with the upper profile sections. The slope of the curves is steep and negative and the range is low. From t3 onwards, the curve is modified towards a more linear shape. It seems to be analogous to the situation at the woodland site 1.

With rising water level (Fig. 12) up till t4 (2.5 metres), the flow field becomes almost uniform with a linear vertical flow distribution and reaches a mean of 458 mm/s (150 mm/s at site 1). Whereas the bottom values turn out to be very similar at both locations (103 versus 108 mm/s), the top values vary significantly between site 1 and 2 (296 / 792 mm/s). The vertical distribution of the flow velocity has altered at t5 towards a more typical log profile. And at all segments of the profile the flow has increased. Compared to site 1 the slope of curve is less steep and the range between bottom and top of the grassland zone is more than twice as high. Also the min. and max. values of site 2 (min. 264 m/s, max. 1168 mm/s) are eight and two times higher, respectively. The lowest values are reached close to the bottom, the highest values of 1155 mm/s close to the water surface. It results in a four times higher mean of 854 mm/s at site 2. As already mentioned the curves of t5 and t7 vary significantly at site 1. This cannot be observed at site 2, where the values increase slightly, but in general the vertical distribution remains almost equal. At site 1 almost all profiles are characterised by a more or less linear curve progression. On the contrary, at site 2 this kind of progression changes after t4 towards a logarithmic one (t5-t7).

With the second peak (t8) the absolute maximum of 1413 mm/s is gained close to the top. It is more than 60% higher compared with the absolute maximum of site 1, the min. value is three times higher. Bottom and top values are almost congruent to the min. and max. values, this applies also to site 1. Thus the relationship of bottom and top values of site 1 is analogous to site 2. It results for site 2 in an increase of average velocity of 44% with regard to site 1 (1125 mm/s versus 781 mm/s), and 16% in relation to t7 (1125 mm/s versus 916 mm/s). At the falling limb of the hydrograph (Fig. 13), the log profiles are almost consistent till t10; only the absolute values decrease at all segments of the water column. From t10 to t12 the curve of function becomes more linear. The mean values drop from 975 mm/s at t9 to 458 mm/s at t11. They are almost identical for site 1 and 2 at around 90 mm/s at t12. The top values shift from 1262 mm/s over 684 to 165 mm/s (bottom: 324 over 110 to 19 mm/s). With the exception of t12 and in contrast to site 1, the flow velocities at all segments of site 2 are remarkably higher. As already specified for site 1 the velocity distribution between the onset and end of the flood (t2 versus t12) is completely different (Fig. 11 and 13).

The mean values at the non-wooded site 2 vary between 38 and 1125 mm/s; in general they alternate at the riparian woodland (site 1) between 65 and 593 mm/s (Table 1). Thus the flow rate at site 1 is between 9% and 76% lower, and the biggest difference of mean flow velocity is reached shortly before the first flood peak at t5 (207 mm/s at site 1 versus 854 mm/s at site 2). Comparing site 1 with site 2 this leads to an average of 50% lower flow rate at the riparian woodland site for the entire flood event 2005 (t1-t12). If only the flood peaks are considered (t6, t8), the difference between site 1 and the grass-grown site 2 ranges between 52 and 31%. It can also be demonstrated for both sites that the mean flow rate at comparable water levels has always increased after the second flood peak. In addition, the mean flow rate at site 2 always exceeds that at site 1.

4 DISCUSSION AND CONCLUSION

This study describes the flow characteristics of a densely wooded and a grass-covered floodplain at the Upper Rhine by field data of a long-term monitoring. The analysed data sets were recorded during a summer flood in August 2005. The profiles t1-t12 (Figures 8-13) represent a selection of different inundation levels at vertical steps of 0.5 metres at the rising and falling limbs of the flood hydrograph. Each profile is assembled by measuring cells ordered along the water column above the bottom-mounted ADCPs. Every single cell is 10 cm in height.

The analysis of the data sets indicates distinct differences of the vertical velocity distribution between both sites and at several points in time. In principle, at almost all stages of the flood event of

August 2005, the distribution of the curves vary (1) between the sites, (2) at each individual site at the same water level before and after the flood peaks, and (3) at different stages of the flood event for each site. Since the flow field at site 2 is only affected by the grass layer, the different flow characteristics of site 1 must be caused simply by the flow resistance of the willows.

In general, the relationship of flow velocity as a function of water depth can be characterised by a linear increase up to a water level of 2.5 metres. With continuing flooding and further ascending and descending water level, the distribution of the curves can be better described by different kind of log functions for both sites. Whereas at site 2 the typical log profiles increase smoothly, at site 1 the values reach an almost constant value at 2 metres height. Thus it can be demonstrated that the upper profile sections at site 1 are obviously affected by the canopy layer of the riparian woodland zone.

One more decisive point is that the range between bottom and top and the distribution of the curves at the same water level differ significantly from each other before and after the peak of flooding. In general the velocity range is higher and the slope of curve is less steep after the second flood peak. As the gradient of the water table is lower at the falling stage of the hydrograph (~0.95 ‰ before the first peak –with a maximum of 1.05 ‰- versus ~0.90 ‰ after the second peak) this behaviour is due to the changed resistance of the canopy layer. The resistance of the vegetation alters remarkably the velocity distribution at least twice at site 1. This can be clearly demonstrated by a comparison of the situation t5, t7 and t9 (Fig. 9 and 10; water level 3 metres). These changes do not follow one single distribution, but can rather be described by different linear and log functions; the distribution of the curves depends on the point in time and the maximum water level. Site 2 does not show these characteristics.

As a result of our observations during and after single flood events and in reference to the obtained results, it can be argued that the different vertical flow field characteristics are determined by: (1) the amplitude and number of peaks of the flood event, (2) the declining flow resistance of the grass layer, (3) the increasing compression of the canopy layer, (4) and an irreversible deformation of the canopy layer, in the kind of bending or breaking of more rigid branches (and also the blade of grass) from a certain water level on (> 2.5 metres for the woodland site). Some of these issues have already been discussed, for instance by Fathi-Maghadam and Kouwen (1997), Oplatka (1998), Copeland (2000), Gerstgraser (2000), Järvelä (2002), Järvelä (2003) and Rauch (2005).

It is well established that the longitudinal water level gradient respectively the slope and the run of the discharge curve of a flood are the driving forces, which determine the hydraulic boundary conditions for the initial flow field characteristics at a certain point of the river and the floodplain during floods. These initial flow field characteristics are modified by the kind of vegetation structure and the resistance properties of the vegetation itself. This could be demonstrated by the comparison of the riparian woodland and grassland field site. Furthermore the interaction between vegetation, flow depth and flow field cannot be described by one single function as the characteristics change depending on the period, amplitude and season of the flood event and the properties of the vegetation.

Our field data showed that the riparian woodland has a remarkable effect on the flow field during all stages of flooding. It has the strongest impact on the flow field at the beginning of the measured flood. With ongoing inundation, especially at the subsequent limb of the hydrograph, this effect diminishes. Although the flow resistance of the woodland site seems to decrease with ongoing flooding, the flow velocity at the floodplain is significantly affected if both data sets of site 1 and 2 are compared directly. The hydraulic response of a floodplain differs distinctly depending on the maximum level of inundation, how many peaks occurred and how long a flooding will last at a certain water level. The crucial point is that it results in a distinct variation of vegetation resistances and thus in overall different velocity profiles.

The recorded data sets may give a deeper insight into hydraulic processes of vegetated floodplains under natural boundary conditions. They serve as a contribution to adjust, verify and enhance the hitherto well-elaborated numerical and physical models (Wilson et al. 2007). In addition, already existing models of the investigation area can be compared with the results of that field survey (e.g. Yoshida and Dittrich 2002, Helmiö 2005). Both the ongoing development of models and further field surveys are necessary to promote plans and measures to restore floodplains and to designate new flood retention areas.

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