

EXPERIMENTAL OBSERVATIONS ON FLOW RESISTANCE THROUGH EMERGENT VEGETATION

Anna Chiara Bixio⁽¹⁾

⁽¹⁾Department of Hydraulic, Maritime, Environmental and Geotechnical Engineering, University of Padua, 20 Street Loredan, 35131 Padua, Italy, phone: +39 04 8275424x; fax: +39 049 8275446; e-mail: acbixio@idra.unipd.it

ABSTRACT

Due to its efficacy in phytoremediation processes, reed-type vegetation has been widely used in constructed wetlands for water quality improvement and in river restoration projects. However, its application has been based on experience rather than hydraulic principle, and limited knowledge exists concerning the hydraulic resistance properties of reed beds. Experimental studies are needed to quantify vegetative flow resistance, in order to improve the mathematical representation of the physical processes that influence flow resistance and also to assess the values of associated parameters in numerical models of surface-water flow which are widely used for wetland design and management.

This paper presents the first results of the experimental measurements performed during summer 2006 in a reed-vegetated flume located inside the Monselice wetland, in northern Italy. The flume was appositely built up for experiments preserving undisturbed the natural local vegetation, mainly consisting in *Phragmites australis* plants.

A differential piezometer system was used to evaluate energy losses along the flume. Experiments were conducted for four different flow depths varying between about 0.30 and 0.60 m and three flow rates between 20 and 30 l/s.

The Manning's n coefficient, commonly used to express flow resistance in open channels, was computed from measured flow rate, water depth and water surface slope data.

Keywords: flow resistance, emergent vegetation, experimental measurements

1 INTRODUCTION

Reeds are a vegetation type widely diffused in natural conditions in Italian rivers and wetlands. Further, reeds are often planted in constructed and re-constructed wetlands for water quality improvement, because of their extensively recognized efficacy in phytoremediation processes (ANPA, 2000) and their low cost.

Quantification of reeds hydraulic resistance is essential for design and management of wetland systems (Jordanova et al., 2006).

Literature works evidence that hydraulic resistance induced by emergent vegetation depends both on individual plant characteristics, such as stem diameter and number, dimensions and distribution of leaves, flexibility, and features of the whole reed bed, particularly stem density and arrangement (Jarvela, 2004). There's clear evidence also of the variation of vegetation resistance with water depth, due to vertical variation of biomass distribution (Kadlec and Knight, 1996; Nepf and Vivoni, 2000; Defina and Bixio, 2005) and with water velocity (Hall and Freeman, 1994; Musleh and Cruise, 2006). Resistance determination is complex because of the seasonal variation of all these characteristics (Shih and Rahi, 1982; Hall and Freeman, 1994; Kadlec and Knight, 1996).

The most common friction coefficient employed in open channel flow models is the Manning's one. There's a fundamental problem with the utilization of Manning's equation to wetland surface water flow: Manning's equation is a correlation for turbulent flows, while surface flow in wetlands generally develop in laminar or transitional flow regimes based on open channel flow criteria. Under these conditions, Manning's n is strongly velocity

dependent. There is also a difficulty with the extension of open channel flow concepts to densely vegetated wetlands, since the resistance to flow in wetlands is dominated by drag exerted by stems and litter, with bottom drag playing a very minor role, while the frictional effects that retard flow in open channel are associated mainly with surface drag of channel bed and walls. As a consequence, Manning's formula is in principle not applicable to surface flow in wetlands.

Anyway, use of Manning's n is still widespread for its simplicity, and the majority of existing information on wetland surface flow has been interpreted and reported via Manning's equation (Kadlec and Knight, 1996). For these reasons, many recent literature works suggest to employ Manning's equation, considering and evidencing the dependence of the friction coefficient n upon velocity and depth as well as vegetation characteristics (Kadlec and Knight, 1996; Tsihrintzis and Madiedo, 2000;).

The majority of research on resistance to flow due to emergent vegetation is based on theory and experiments with artificial vegetative elements such as cylinders and plants prototypes (Jarvela, 2004).

Experimental published data on flow resistance with real reeds are very limited. Meijer and van Velzen (1999) carried out some tests with natural reeds placed in a concrete-wall laboratory flume. James et al. (2004) investigated the hydraulic resistance of flow through reed vegetated channels using harvested reeds, foliated and defoliated, set vertically in a regular rhomboidal pattern inside a test flume. The lack of field experimental data regarding undisturbed reed vegetation is evident.

For these reasons, in the context of a wide experimental and modelling study of the hydraulic behaviour of wetlands, finalized to the assessment of the effects of wetlands on nutrient release into the Venice lagoon (Bixio et al., 2005; Bixio and Cerni, 2006), it was decided to build up an experimental flume inside a reed-vegetated area of the Monselice wetland, in the province of Padua.

The aim of the work is investigation of hydraulic resistance of undisturbed reed beds and evaluation of resistance variation due to seasonal plants growth and decay, with different experimental measurements to be taken in various moments of the vegetative cycle of plants.

This paper reports the first results of the tests realized in the flume during summer 2006.

2 STUDY AREA

The Monselice surface flow wetland (Figure 1) is located in the southern part of Monselice town, in the province of Padua, in the territory of the Land Reclamation Consortium Adige Bacchiglione. The wetland, not yet full operating because of administrative problems, was recently constructed to treat effluents of the local municipal wastewater primary treatment plant. It was designed to treat a medium discharge of 60 l/s.

The wetland is about 6 hectares wide, has a mean water depth of 0.8 m and a medium storage volume of 28000 m³. It is formed by 2 independent basins, connected by control gates. Both the basins consist in a main channel of variable width and depth with lateral wide flood plains.

After flowing through the wetland, with a mean residence time of about 5.5 days, water is discharged into the Desturo channel, which borders the system to the east.

At the end of construction works, in the year 2003 the area was planted with *Phragmites australis*, which rapidly covered the whole flood plain areas. When flume construction works started, at the end of may 2006, the local reed vegetation was very dense, about 150 stems/m².

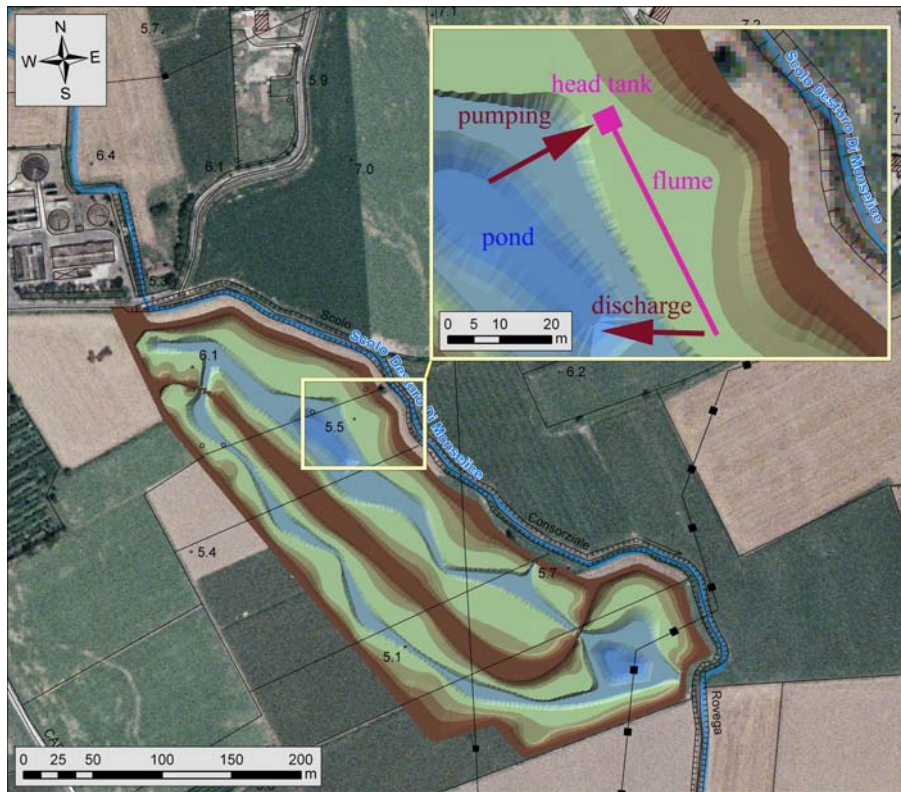


Figure 1: The Monselice wetland, with the location and the functioning scheme of the experimental apparatus.

3 EXPERIMENTS

Experiments were conducted in a 60 m-long by 1.60 m-wide flume with vertical sidewalls located in a flat flood plain area of the wetland, generally unsubmerged in ordinary functioning conditions of the wetland, close to a little pond which can be easily inundated by opening a gate (Figure 1).

Water can be pumped from the pond into the head tank placed at the upstream end of the flume thanks to two centrifugal variable-discharge pumps (Figure 2). After flowing into the flume, water is discharged again into the pond (Figure 3). Once the pumps are turned on, several minutes are required to reach a steady, recirculating current in the flume.

The flume construction works were conducted in such a way that undisturbed reed-type vegetation inside the flume itself was preserved.

The walls of the flume were realized employing wooden boards 2.00 m long by 0.50 m wide. Each wall was formed by two rows of 30 boards each laid one on top of the other. The lower boards were horizontally fixed into the ground for a depth of 10-20 cm in such a manner that their upper edges were all at the same absolute level. Some wooden piles were deeply driven into the ground to support boards. Then, the upper rows of boards were placed and fixed to the piles too (Figure 4).

All the joints between boards were realized by using silicon rubber, so that the impermeability of the walls was guaranteed.

A levee was built along the lateral walls by tamping silty-clayey soil with an excavator (Figure 5). The upper part of the levee was shaped horizontal to allow easy flume inspection.

Similar works were executed to build up the trapezoidal head tank, about 3.50 m wide and 3.5 m long. The walls and bottom of the tank were waterproofed by fixing a double nylon tarpaulin; concrete hollow bricks were employed to build up an internal wall, to damp inlet turbulence and eliminate swirl.



Figure 2: Water pumping into the head tank.



Figure 3: Water discharge into the pond.

A rectangular sharp-crested weir was placed at the upstream end of the channel to allow measurement of incoming flow rate (Figure 6); free flow conditions at the weir were verified for all test conditions.

An adjustable rectangular weir was positioned at the downstream end of the flume, to allow control of tail water depth and to provide outgoing discharge measurements. This weir was realized by superimposing a variable number of 0.10 m by 0.10 m wooden stoplogs on a 20 cm high sill; the upper stoplog was provided of a steel thin-plate weir (Figure 7).

For each test, when the number of stoplogs was established, silicon rubber joints were carefully realized between the different logs, to avoid local water losses.

We took particular care in these operations since the correct estimate flow rates at the upstream and downstream weirs is of fundamental importance to evaluate the entity of possible water losses along the flume, due to infiltration under the lateral walls.

A differential piezometer system was used to measure water depths at 14 sections of the channel and at 1 point inside the tank. The distance between test sections was 4.5 m.

The system was realized by boring the lateral walls of the apparatus, with all the bores aligned at the same absolute level, about 10 cm above the bottom of the channel, and connecting each bore to a pressure gauge with water column by a plastic pipe (Figure 8).

Water depths can be measured in this way with a precision of 1 mm.

The first observation point was placed close to the downstream weir, to provide a measurement of water depth useful also for outgoing discharge evaluation. The last observation point, located inside the tank near the upstream weir, allows incoming discharge evaluation.



Figure 4: The experimental flume.



Figure 5: Construction of the lateral levees.



Figure 6: The upstream weir at the head tank.



Figure 7: The downstream adjustable weir.

Four different downstream level conditions were considered, corresponding to 1, 2, 3 and 4 wooden logs positioned at the downstream weir. For the previously described need of realizing rubber joints between logs, we started from the lowest level and moved towards the higher ones.

The water surface profile was measured for each downstream boundary condition for three different flow rates. The desired values of flow rates were equal to 20, 25 and 30 l/s. Due to difficulties in accurate pump regulation the real values were slightly different (Table 1).

Each test was repeated to verify data consistency.



Figure 8: The differential piezometer system for water depth measurement.

For which concern vegetation characteristics, at the beginning of the flume construction works, in may 2006, reeds were prevalently dry because of the low precipitation and high temperature values which characterized spring 2006. The density of reeds was high, about 100-200 stems/m²; plants were very thin, with stem diameter varying between 4 and 10 mm, and about 2 m high.

When the flume was built up and water started to flow, there was a rapid growth of new *Phragmites* plants, together with *Typha latifolia* and some other herbaceous vegetation inside the flume.

During experiments, which took place during the months of june and july, vegetation characteristics along the flume were analyzed (Figure 9), leading to the identification of three main different vegetative types, characterized by diverse reed density and stage of growth,

and by presence or absence of other herbs (Table 2). Dry reeds height was about 2 m, green reeds were generally 0.6-1.0 m tall so that they were not submerged by water during experiments. On the contrary, the major part of the other herbaceous vegetation was shorter than 0.5, and was submerged during some tests.

Green reeds had a stem diameter of 5-20 mm. It was not possible to describe geometric characteristics of other herbaceous vegetation, which varied randomly in type and dimensions along the flume.

Test	Downstream level [m]	Flow rate [l/s]
P1	0.3	20.0
P2	0.3	25.0
P3	0.3	29.0
P7	0.4	18.0
P8	0.4	25.0
P9	0.4	29.0
P10	0.5	17.0
P11	0.5	25.0
P12	0.5	27.0
P13	0.6	19.0
P14	0.6	25.0
P15	0.6	30.0

Table 1: Tests characteristics.

The major experimental difficulties were due to initial considerable water losses along the flume, due to localized infiltration under the boards. To remedy this problem, some clayey soil was inserted manually inside the flume just along the base of the walls, and the lateral levees were further compacted. The results of these operations were satisfactory, since lateral losses were limited to less than 5 % of incoming discharge. Anyway, to avoid additional troubles of this kind, we preferred to use just the less powerful pump for experiments, renouncing to consider the higher flow rates (up to 100 l/s) which could be obtained employing the other pump.



Figure 9: Analysis of vegetation characteristics.

Vegetative type n.	Description
1	dry reed: 165 stems/m ² ; green reed: 80 stems/m ² ; other herbs: many
2	dry reed: 105 stems/m ² ; green reed: 15 stems/m ² ; other herbs: many
3	dry reed: 90 stems/m ² ; green reed: 20 stems/m ² , well growth; other herbs: irrelevant

Table 2: Vegetative types description.

4 RESULTS

The water surface elevations at each measuring section for each run were determined by the differential piezometer system.

The energy line was then calculated at each section as:

$$H = z + y + \frac{v^2}{2g}$$

where H [m] is energy level, z [m] is bottom elevation, y [m] is flow depth, v [m/s] is mean velocity and g [m²/s] represents gravitational acceleration. Velocity v was calculated starting from measured discharge and water level values.

The energy line slope j was determined by differentiating the energy line H at each section with respect to change in distance x along the flume :

$$j = \frac{dH}{dx}$$

Manning's n [sm^{-1/3}] for each tract of the flume was then calculated as:

$$n = \frac{1}{v} j^{0.5} R_H^{2/3}$$

where R_H is the hydraulic radius of the flow.

The Manning's roughness coefficient calculated in this way in principle comprises both wall and vegetation resistance; since wall friction can be considered negligible if compared with vegetative one, we can assume n as exclusively due to reed vegetation.

Figure 10 reports water surface profiles as measured by the differential piezometer system for the various tests.

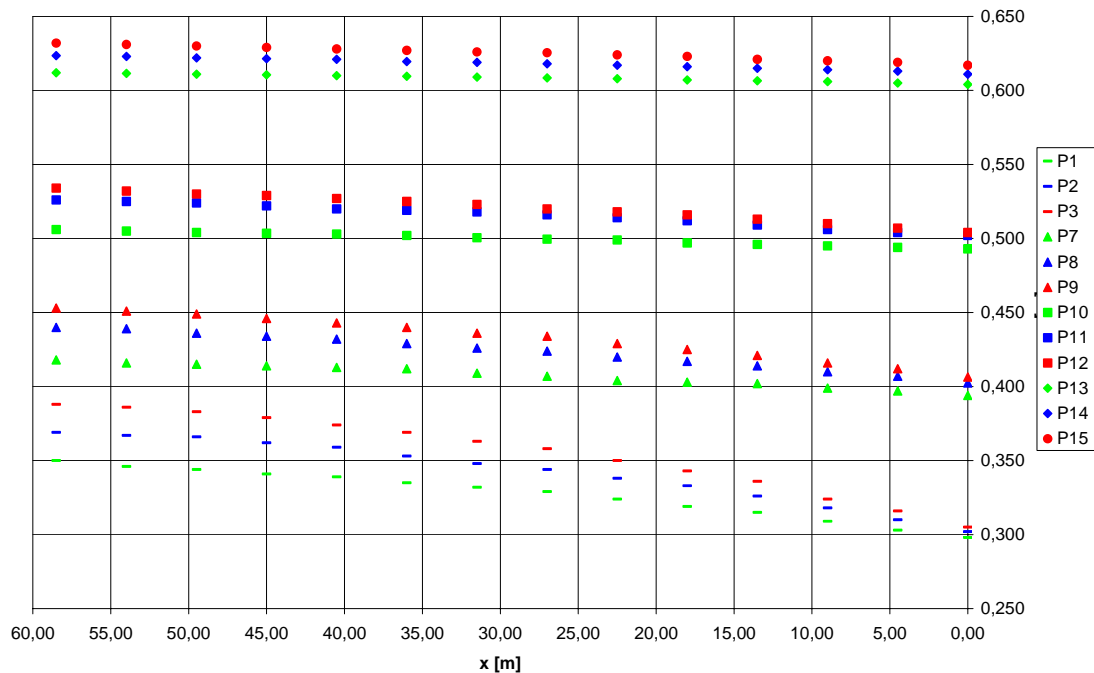


Figure 10: Water surface elevations measured at the 14 sections along the flume for the various tests (x=0 corresponds to the downstream section).

The range of stem Reynolds number ($Re_D = vD/\nu$), where D [m] is stem diameter and ν [sm⁻²] is kinematic viscosity of water, is about 100-800, indicating that all the test runs were in transitional flow regime.

Water depths vary between 0.3 and 0.63 m, averaged flow velocity between 0,019 and

0.058 m/s.

The energy line slope j ranges between 10^{-4} and 10^{-3} , increasing with decreasing downstream water depths and decreasing discharge values.

The calculated Manning's n values result to vary in the range $0.14 - 0.45 \text{ s m}^{-1/3}$, not very dissimilar to other published data regarding different types of wetland vegetation (Tsihrintzis and Madiedo, 2000).

To evaluate the dependence of Manning's n on depth, the values of the coefficient n calculated for each tract of the flume for each test are plotted against the corresponding measured values of water depth in Figure 11.

These data referring to the different tracts of the flume can be averaged for each test to evaluate the mean variation of n with depth, as reported in Table 3.

Calculations show a general trend of increase of n values with increasing water depth up to $y \approx 0.5 \text{ m}$, followed by a decrease of n values. This can be explained considering the variation of biomass distribution with depth: vegetative frontal area increases between $y=0$ and $y=0.5 \text{ m}$ thanks to increased leaf density, determining an augment of vegetative resistance to flow, then diminishes because of the limited height of herbaceous vegetation which is submerged by flows deeper than 0.5 m .

The relationship of the resistance coefficient to the velocity is shown in Figure 12; test-averaged data are reported in Table 3.

We can observe a general trend of reduction of n with increasing velocity, in agreement with other published experimental data regarding emergent vegetation (Hall and Freeman, 1994; Musleh and Cruise, 2006).

Hall and Freeman (1994) suggest that the reduction in n values with increasing velocity could be due to advection of turbulence from upstream stems on flow around the downstream stems; advection of turbulence may reduce flow resistance by causing early transition to a turbulent boundary layer at the downstream stems, reducing their local drag characteristics.

Anyway, in our experiment these results must be considered also in light of the fact that a limited bending of herbaceous vegetation was observed.

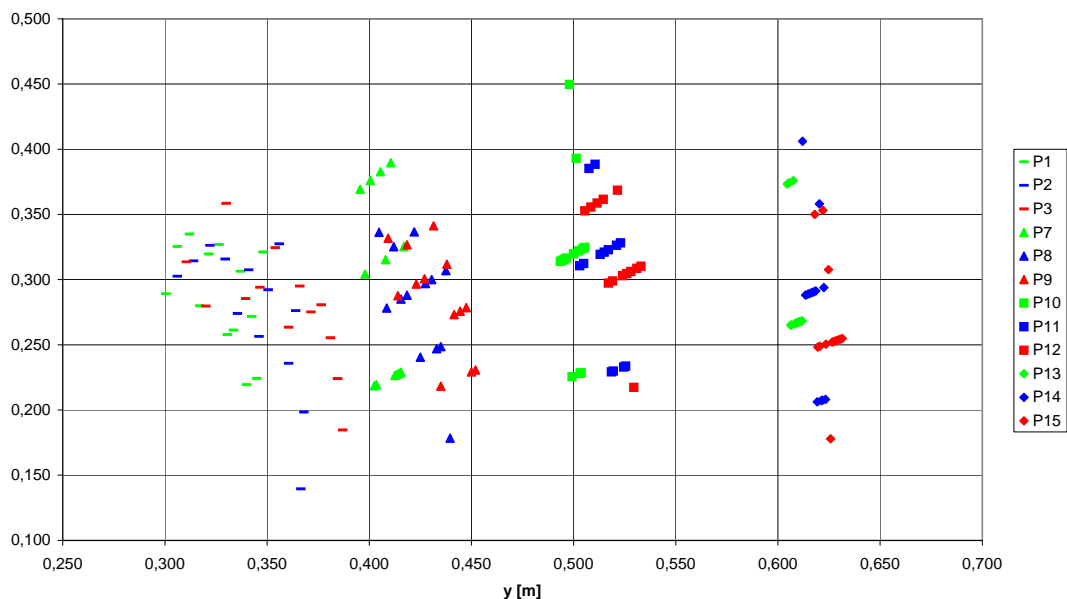


Figure 11: Experimental results: Manning's n versus depth.

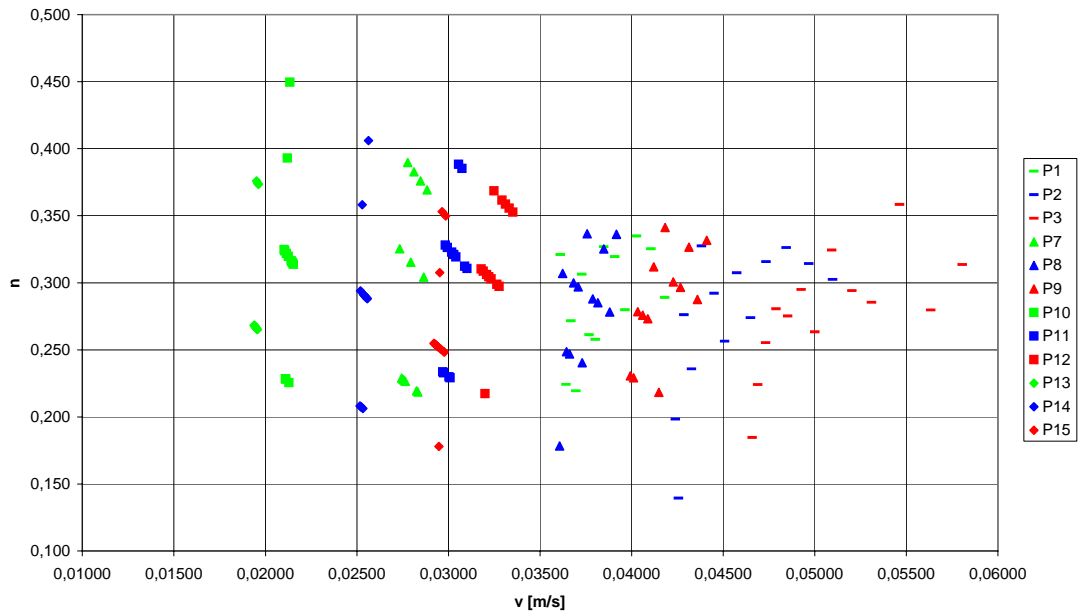


Figure 12: Experimental results: Manning's n against medium velocity.

Test	y [m]	v [m/s]	n [sm ^{-1/3}]
P1	0,33	0,04	0,287
P2	0,34	0,05	0,274
P3	0,36	0,05	0,280
P7	0,41	0,03	0,293
P8	0,42	0,04	0,282
P9	0,43	0,04	0,285
P10	0,50	0,02	0,314
P11	0,52	0,03	0,303
P12	0,52	0,03	0,319
P13	0,61	0,02	0,292
P14	0,62	0,03	0,279
P15	0,63	0,03	0,266

Table 3: Averaged results in terms of water depth, velocity and Manning's n for the different tests.

5 CONCLUSIONS AND FUTURE WORK

This paper reports the results of the first set of experiments performed during summer 2006 in a test flume built up inside the Monselice wetland, characterized by typical undisturbed reed-type vegetation consisting mainly in *Phragmites australis* plants.

Starting from measured flow rate, water depth and energy line slope data, vegetation resistance to flow in terms of Manning's n was evaluated, and relevant relationships with flow parameters were analyzed.

For the investigated range of water depths varying between about 0.3 and 0.6 m and flow rates of 20, 25 and 30 l/s, the calculated Manning's n values result to vary between 0.14 sm^{-1/3} and 0.45 sm^{-1/3}, comparable to other published data regarding different types of wetland

vegetation.

The dependence of Manning's n on water depth is evident and reflects the variation of plants biomass distribution along the vertical direction, also taking into account the presence of some herbaceous vegetation of limited height within reeds.

The roughness coefficient n shows a decreasing trend with increasing flow velocity.

Other experiments will be performed in the future in different seasons, with the aim of assessing the seasonal variation of flow resistance due to plants growth and decay.

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