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Constructed marginal shallow water zones along a navigable canal: possibilities and constraints for helophyte and aquatic vegetation

Andy Van Kerckvoorde*, Pieter Verschelde, Floris Vanderhaeghe, Maud Raman and Sophie Vermeersch

Research Institute for Nature and Forest (INBO), Kliniekstraat 25, B-1070 Brussels, Belgium

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Abstract – Banks of navigable canals are often stabilized with "hard" materials resulting in unsuitable conditions for marginal riparian vegetation. A constructed marginal shallow and sheltered water zone can favour riparian vegetation. In 1998, a new canal branch with shallow water zones was constructed along the canal Ghent-Bruges (Belgium). This study analysed plant vegetation development of these shallow zones, its spatial variation and its mid-way succession. For this purpose, riparian vegetation was investigated by plots in the middle of the shallow water zones, on the canal bank side and on the defence dam side in 2006 and 2009. The studied shallow water zones permitted the development of helophyte vegetation on the sides but hardly in the middle. Differences in number of taxa, diversity-index and Grime's competitiveness and ruderality were observed on the sides. The application of different construction materials is discussed as a possible cause. An increase of competitiveness and a decrease of ruderality indicated vegetation succession during the period 2006–2009. Rooted aquatic plant vegetation was poorly developed in the studied shallow water zones probably due to the deposition and accumulation of fine sediments. The results were interpreted in relation to possible design principles of shallow water zones and might be useful for waterway managers, policy-makers and technicians in future bank engineering projects along navigable canals. Moreover, the study contributes to the knowledge of mitigating negative ecological effects associated with navigation. Such bank rehabilitation measures may be necessary to achieve the ecological goals of the European Water Framework Directive.

Key words: bank stabilization / bank rehabilitation / riparian vegetation / Water Framework Directive / navigation

Introduction

Worldwide, freshwater biodiversity has declined faster than either terrestrial or marine biodiversity over the past 30 years (Jenkins, 2003). Threats to global freshwater biodiversity fall into five categories: overexploitation; water pollution; flow modification; destruction or degradation of habitat; and invasion by exotic species (Dudgeon *et al*., 2006). Freshwater habitat alterations are caused mainly by damming, flow regulation, channelization or bank stabilization (Malmqvist and Rundle, 2002). A consequence of these worrying tendencies has been the implementation of legislative measures such as the European Water Framework Directive (WFD; European Commission, 2000) which constitutes a landmark for integrated, sustainable water management across the European Union.

The overall goal of the WFD is to achieve good ecological status (GES) in all surface water bodies by 2015. GES requires that biology and water quality deviate only slightly from natural conditions. The WFD allows Member States to designate a water body as a heavily modified water body (HMWB) if the water body has substantially changed as a result of physical alterations by human activity. If a water body has been created by human activity then it may be designated as an artificial water body (AWB, for instance, a canal). Equally important, the WFD tries to get a better ecological status on HMWB and AWB, and takes account of environmental, economic and social considerations. The environmental WFD objective for HMWB and AWB is good ecological potential (GEP), which has to be achieved by

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*Corresponding author: `Andy.vankerckvoorde@inbo.be`

2015. GEP is a less stringent objective than GES and can be defined as the best example of biological conditions of a water body for which reasonable mitigation and best management measures have been taken without substantially affecting its use or environment (Acreman and Ferguson, 2010). The WFD prescribes that ecological status assessment of any water body is based on macrophytes, phytoplankton, benthic invertebrates and fish.

In navigable canals the physical forces of moving vessels generally affect banks with great magnitude because of limited available space and required depth-width ratio. Furthermore, canal banks sometimes protect adjacent areas from flooding especially in an urban environment or where adjacent land is lower than the canal water level. This results in the need for some kind of bank stabilization along canals. Until a few decades ago steep bank slopes with "hard"-armoured stabilization methods, such as concrete revetments or metal sheet-piles, were applied along waterways. As a result, riparian habitats along navigable canals are small with an artificially sharp transition between water and land. In this way, conditions for marginal riparian vegetation along navigable canals are unsuitable. In addition, hydraulic forces induced by moving vessels cause difficulties for vegetation establishment (Haslam, 1987) or hamper vegetation growth (Murphy *et al.*, 1995).

Marginal riparian vegetation occurring along canals, rivers or other waterways comprises only a small percentage of the landscape but nevertheless performs important functions. (1) Habitat provision. Riparian vegetation results in heterogeneous microhabitats and better conditions for fish populations (Wichert and Rapport, 1998; Mouton *et al.*, 2012). Aquatic vegetation provides substratum for invertebrates and zooplankton (Carpenter and Lodge, 1986). In correspondence with this, Armitage *et al.* (2001) observed a three times higher number of macroinvertebrate taxa and a five to six times higher total abundance of taxa in shallow vegetated riparian sites compared with the steeply sloped and artificial banks. Bats prefer bank side plants and avoid water bodies with no vegetation edge (Russ and Montgomery, 2002). (2) Bank stabilization. Vegetation strips can enhance bank stability by reducing both waves and current velocities (Coops *et al.*, 1996; CUR, 1999b) and by consolidating the soil with their roots and rhizomes (Caffrey and Beglin, 1996). (3) Water purification. Helophyte and aquatic vegetation can play a role in water purification (Dubois, 1994; Schulz *et al.*, 2003; Dhote and Dixit, 2009). (4) Pollination. In an urban environment or in intensively managed agricultural landscapes riparian vegetation strips can contribute to pollination (Herzon and Helenius, 2008). Pollination is an ecosystem service vital to the maintenance of wild plant communities and agricultural productivity (Potts *et al.*, 2011). As a consequence of the wide ranging benefits afforded by riparian plants, vegetation establishment and development has become a target in bank engineering projects within aquatic habitats.

Nowadays, there is increased emphasis on the need for ecological engineering (Mitsch and Jørgensen, 2003) and, as a consequence, ecologically friendly bank stabilizations are applied worldwide along waterways (as examples: Shields *et al.*, 1995; Caffrey and Beglin, 1996; Hoitsma, 1999; CUR, 1999a; Karle *et al.*, 2005; Evette *et al.*, 2009; Shi *et al.*, 2009; Hou *et al.*, 2010). Ecologically friendly bank stabilizations use vegetation for construction and promote the continuum between the terrestrial and aquatic environment. The present study focuses on an artificial marginal shallow water zone along a navigable canal as a type of ecologically friendly bank stabilization. The shallow water zone is constructed by building a dam parallel and in front of the actual bank. It is expected that the dam inhibits the hydraulic forces generated by moving vessels. As a result a sheltered zone between the actual bank and the dam with suitable condition for vegetation development is supposed (Söhngen *et al.*, 2008). However, the knowledge about short-term or long-term ecological responses in constructed shallow zone is very limited.

This study analysed the vegetation in a constructed shallow water zone along the navigable canal Ghent-Bruges. We addressed the following research questions:

1. Can helophyte and rooted aquatic vegetation establish and develop in the constructed shallow water zone?
2. Is there a spatial variation of the vegetation between the middle, the canal bank side and the defence dam side of the shallow water zone?
3. Did vegetation succession (a change of vegetation over time) happen? Vegetation sampling was undertaken eight years after bank construction. We refer to this stage of vegetation succession as mid-way succession.

The study contributes to the knowledge of mitigating negative ecological effects associated with navigation. Such mitigation measures may be needed in reaching the GEP required for artificial waterways according to the WFD.

Material and methods

Study area

The canal Ghent-Bruges is an artificially constructed waterway situated in the northern part of Belgium (Fig. 1). The canal partly lies in the valleys of two historical rivers ("Hoge Kale" and "Zuidleie"). The connection between these river catchments was dug out in the 13th century. To improve navigation, the canal was deepened, straightened, broadened and artificial canal branches were inserted, especially in the 20th century. Between 1995 and 1998 the sharp bend at Beernem was cut-off and a new canal branch with shallow water zones was constructed (coordinates: N 51°8'46.71" and E 3°17'29.90", Fig. 1). At the northern bank a shallow water zone with a length of 700 m was established; at the southern bank the constructed shallow water zone has a length of 300 m.

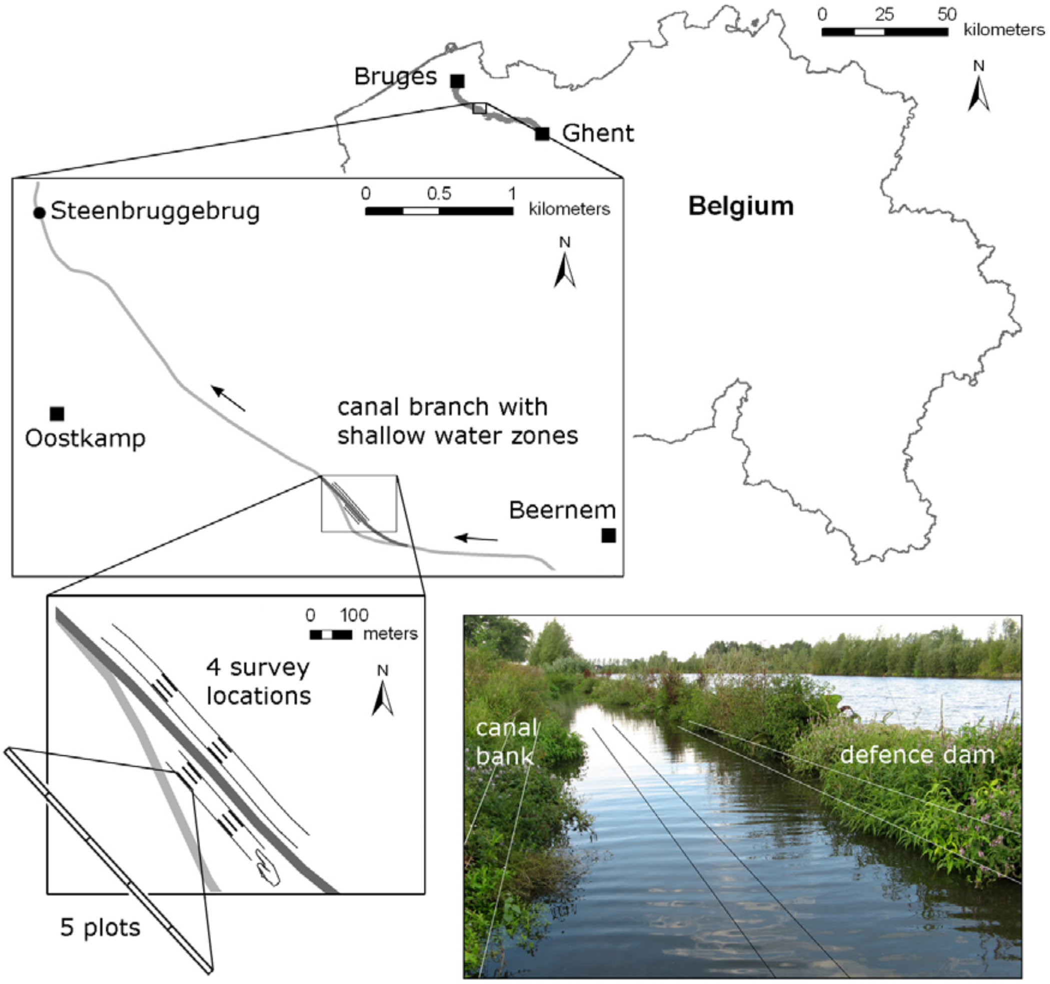

Fig. 1. Location of the canal Ghent-Bruges (light and dark grey line) in Belgium, the recently constructed canal branch (dark grey line) with marginal shallow water zones (double lines) and the 4 survey locations with plots examined. The place of water quality assessment at Steenbruggebrug is indicated by a circle. Arrows show normal water flow direction. The hand indicates the place and direction of the photograph. The lines on the photograph illustrate positions of vegetation sampling at canal bank side (two left lines), defence dam side (two right lines) and at the middle (two centre lines) of the shallow water zone.

A cross section of the constructed shallow water zone and some dimensions are shown in Fig. 2. The shallow water zone has a width of 4.1 m and a depth of maximum 50 cm, both at normal water level. The slope of the defence dam is 45° for the side to the shallow water zone and 37° for the side to main channel; the slope of the canal bank is 27°. The top of the defence dam lies 80 cm higher than normal water level. The defence dam is constructed by riprap covered with mastic asphalt; the canal bank by rock-filled gabion baskets (rock size: 0.3 m diameter). The shallow zones are connected to the main channel by means of 1 m wide openings in the defence dam (4 in the northern bank; 2 in the southern bank). No planting or seeding was performed.

The place of water quality assessment (sampling point of the Flemish government) on the canal Ghent-Bruges nearest to the study site is located at Steenbruggebrug (5500 m downstream of the study site, Fig. 1). In this place, water from the main channel was sampled. Some water quality characteristics are listed in Table 1. The water of the canal can be considered as heavily enriched (Mainstone and Parr, 2002). Constant water level is pursued in the canal Ghent-Bruges. In 2010, about 3900 commercial vessels passed at the study site and about 1600 pleasure boat passages were registered at Moerbruggebrug (2500 m downstream of the study site). The canal Ghent-Bruges is classified as an artificial water body according to the WFD.

Vegetation sampling

In this study, we consider aquatic vegetation as strictly aquatic, submerged or free floating plant taxa; helophytes as semi-aquatic, emergent plant taxa.

Helophyte and aquatic vegetation were surveyed in the shallow water zone at 4 randomly selected locations (2 in the northern bank; 2 in the southern bank; Fig. 1). In each location, the vegetation of the shallow water zone was investigated at three positions: the defence dam side, the

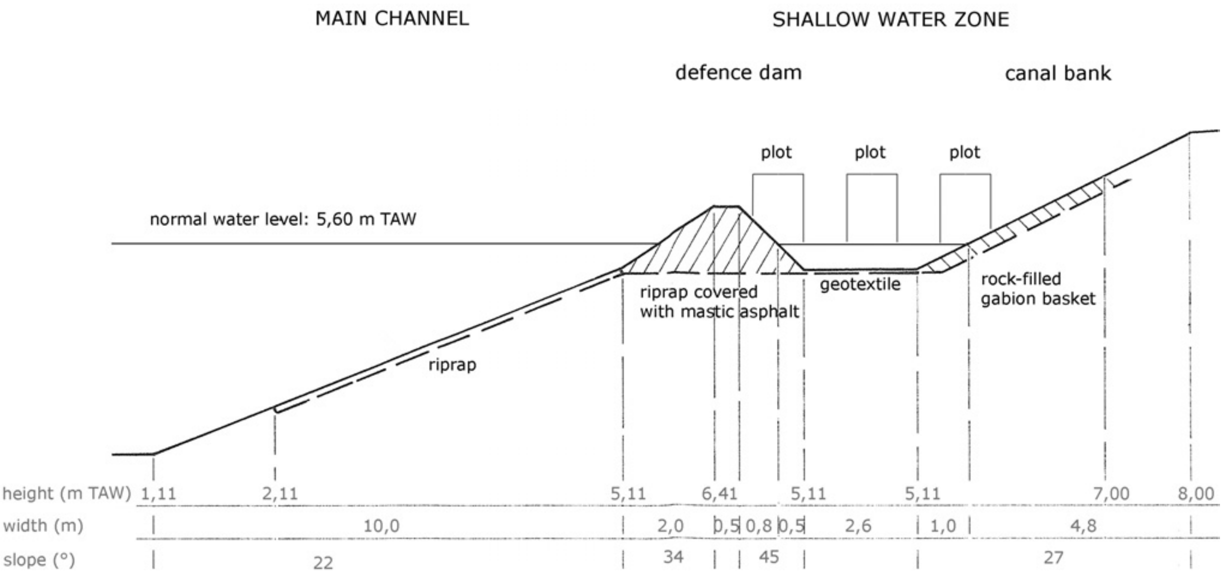

Fig. 2. A cross profile of the constructed shallow water zones showing width, height, slopes, materials used and positions of plots. TAW is a Belgian ordinance level corresponding to height of mean sea level at low tide. Zero m TAW is about 2.3 m below local mean sea level.

Table 1. Mean, minimum and maximum values of chemical and physical water characteristics ($n = 12$) of the canal Ghent-Bruges in 2009 at Steenbruggebrug (5500 m downstream of the study site), measured by the Flemish government (www.vmm.be).

Parameter	Unit	Mean	Min.	Max.
pH		7.77	7.49	8.05
Dissolved oxygen	mg $O_2.L^{-1}$	6.80	3.58	9.54
Biochemical oxygen demand (5 days)	mg $O_2.L^{-1}$	1.80	0.89	2.70
Chemical oxygen demand	mg $O_2.L^{-1}$	26.6	19.9	38.7
Nitrate (NO_3^-)	mg $N.L^{-1}$	4.84	2.90	8.20
Nitrite (NO_2^-)	mg $N.L^{-1}$	0.17	0.02	0.55
Ammonium (NH_4^+)	mg $N.L^{-1}$	1.32	0.08	3.30
Total Kjeldahl nitrogen (KjN)	mg $N.L^{-1}$	2.44	1.10	4.50
Orthophosphate (oPO_4^{3-})	mg $P.L^{-1}$	0.34	0.18	0.46
Total phosphorus	mg $P.L^{-1}$	0.60	0.37	0.93
Conductivity (at 20 °C)	$\mu S.cm^{-1}$	838	492	1105
Total suspended solids	$mg.L^{-1}$	20.45	11.80	40.80

Table 2. Cover-abundance scale used to describe the vegetation in the plots and the cover values used in further analyses.

	Plot-cover	Number of individuals	Cover values
Dominant	$> 75\%$	Irrelevant	87.5
Half covering	50–75%	Irrelevant	62.5
Quarter covering	25–50%	Irrelevant	37.5
Covering	5–25%	Irrelevant	15
Frequent	$< 5\%$	101–1000	4
Occasional	$< 5\%$	11–100	3
Rare	$< 5\%$	4–10	1
Very rare	$< 5\%$	1–3	0.5

canal bank side and in the middle (Fig. 1). Vegetation was sampled by means of 5 adjacent plots (10 × 1 m) lying parallel to the banks (Fig. 1). Plots on the sides of the shallow water zone were placed in such a way that the centre line (parallel to the banks) corresponds with the edge of water (at normal water level; Fig. 2). In total, 60 plots were studied: 20 plots from the defence dam side, 20 plots on the canal bank side and 20 plots in the middle of the shallow water zone. In each plot, the number and cover of different plant species were described by a slightly modified cover-abundance scale of Braun-Blanquet (1964) which is listed in Table 2. Field work was carried out in

August 2006 and the same 60 plots were re-examined in August 2009. Before further analyses, the cover-abundance scale was transformed into cover values (Table 2).

Vegetation characteristics

To consider vegetation establishment and vegetation development, Shannon-Wiener index for diversity (Shannon, 1948) and total cover by herbs and total cover by shrubs were used.

To detect patterns of mid-way vegetation succession and spatial variation, Grime's competitiveness and ruderality were calculated. Grime (2001) distinguishes two categories of external factors that affect vegetation: stress and disturbance. Stress comprises the phenomena that restrict photosynthetic production; disturbance is associated with the partial or total destruction of plant biomass. Three primary plant functional types are recognized: ruderal (low intensity of stress and high disturbance), stress tolerant (high intensity of stress and low disturbance) and competitor (low intensity of stress and low disturbance). We followed the CSR-classification of different species according to Hodgson *et al.* (1995). The competitiveness and ruderality for a vegetation sample was calculated with the method described by Hunt *et al.* (2004). This method uses weighted averages (with weight determined by the cover of each taxon in a plot) to calculate competitiveness and ruderality of the vegetation.

To detect other possible patterns of mid-way vegetation succession and spatial variation, cover by phreatophytes was used. We used the classification of Londo (1988). He divided plant taxa that are largely groundwater or surface water dependent into hydrophytes obligate phreatophytes and non-obligate phreatophytes. Hydrophytes (H) are taxa requiring permanent water for their development and have vegetative parts located under or floating on the water surface. Obligate phreatophytes are taxa which only grow within the area of influence of the groundwater. Obligate phreatophytes include taxa characteristic of water tables below (F) or at (W) the soil surface. Non-obligate phreatophytes are taxa which will grow beyond the area of influence of the groundwater if other factors, such as soil texture, soil pH and climate, permit. Non-obligate phreatophytes include taxa growing usually within the sphere of influence of the water table (V) or taxa usually growing beyond the influence of groundwater on calcareous soil but within its influence on other soils (K). We used taxa belonging to the classes H, W, F, V and K as phreatophytes.

To judge conservation value of species, classification according to the Red List of vascular plants in Flanders and the Brussels Capital region was used (Van Landuyt *et al.*, 2006). Red Lists indicate the conservation status of species and show which species may become extinct in the near future (Mace *et al.*, 2008). The standard methodology to calculate species conservation status is proposed by the IUCN and is based on rarity and rate of decline (IUCN, 2003).

Ordination

To detect patterns of mid-way vegetation succession or spatial variation a community analysis was undertaken. The species composition of the plots located on the sides of the shallow water zone was examined by applying correspondence analysis (CA; Leps and Smilauer, 2003). As the gradient length in a preliminary detrended correspondence analysis (DCA) exceeded 3 standard deviation units, non-linear ordination methods were chosen (Jongman *et al.*, 1995). Ordinations were performed on most abundant taxa (cover values of at least 4% in at least one plot) with logarithmic transformation of the cover values. The matrix consisted of 80 records and 36 taxa. We used 2 nominal explanatory variables (with classes between brackets) which were coded as a series of dummy variables (Jongman *et al.*, 1995): year (2006, 2009) and plot site (canal bank or defence dam; Fig. 1). These variables were plotted onto the CA ordination diagram as supplementary data. CA and DCA were carried out with the CANOCO-package version 4.5 (ter Braak and Smilauer, 2002) with default options (CA: scaling on inter-species distances and biplot scaling; DCA: detrending by segments).

Linear mixed-effect models

To detect patterns of mid-way vegetation, succession and spatial variation models were worked out to analyse the effect of plot site (canal bank or defence dam), year of investigation and their interaction on different response variables. The response variables were number of taxa, Shannon-Wiener diversity, cover by herbs, cover by shrubs, cover of phreatophytes, competitiveness and ruderality. The response variable cover by shrubs did not have an underlying normal distribution so this variable was logit transformed.

Since the same plots were investigated in different years (2006 and 2009) and plots close to each other (at the same location) were not independent of each other, simple linear regression cannot be used. Models that can cope with this dependency are mixed-effect models by modelling a fixed component as in simple linear regression and, in addition, model a part of the variance (Pinheiro and Bates, 2000). This was accomplished in our model by designating location as a random factor, while year of investigation and plot site (canal bank or defence dam) were fixed factors. Consequently, we could estimate the overall effect of the factors of interest (*i.e.*, the fixed factors), while taking into account the correlation between plots from each location.

We started with the most complex model and tried to simplify the model using log-likelihood-ratio tests, which check if the simpler model explains significantly less variation than the more complex model (Cox and Hinkley, 1974).

These statistical analyses were conducted within R (R Development Core Team, 2011) using the nlme package (Pinheiro *et al.*, 2011).

Table 3. Observed native helophyte taxa, non-native helophyte taxa, rooted aquatic taxa and free floating aquatic taxa in plots (2006 and 2009) of the shallow water zone. For each taxa, the mean cover ± standard error of mean together with the number of plots where a taxon was present (value within brackets) are shown per plot site (in the middle of the shallow water zone, on the canal bank side and on the defence dam side). Concerning the native helophyte taxa only those with cover values of at least 4% in at least one plot are noted.

	Abbreviation	Middle	Canal bank side	Defence dam side
Native helophyte taxa				
Alisma plantago-aquatica L.	ALISMPLA	0.0 ± 0.0 (0)	0.5 ± 0.4 (10)	0.0 ± 0.0 (2)
Alnus glutinosa (L.) Gaertn.	ALNUSGLU	0.0 ± 0.0 (0)	0.5 ± 0.4 (4)	0.8 ± 0.5 (2)
Arrhenatherum elatius (L.) Beauv. ex J. et C. Presl	ARRHEELA	0.0 ± 0.0 (0)	1.3 ± 0.5 (10)	0.0 ± 0.0 (0)
Bidens cernua L.	BIDENCER	0.0 ± 0.0 (0)	2.2 ± 1.6 (12)	5.9 ± 2.3 (18)
Bidens tripartita L.	BIDENTRI	0.0 ± 0.0 (0)	0.1 ± 0.0 (6)	3.8 ± 1.2 (19)
Calystegia sepium (L.) R. Brown	CALYSSEP	0.0 ± 0.0 (0)	2.4 ± 0.7 (28)	0.6 ± 0.4 (14)
Cirsium arvense (L.) Scop.	CIRSIARV	0.0 ± 0.0 (0)	1.0 ± 0.4 (20)	0.0 ± 0.0 (0)
Epilobium hirsutum L.	EPILOHIR	0.0 ± 0.0 (0)	6.0 ± 1.9 (20)	3.3 ± 0.9 (20)
Eupatorium cannabinum L.	EUPATCAN	0.0 ± 0.0 (0)	5.1 ± 1.1 (20)	0.9 ± 0.5 (11)
Filipendula ulmaria (L.) Maxim.	FILIPULM	0.0 ± 0.0 (0)	4.2 ± 1.0 (20)	0.8 ± 0.5 (4)
Heracleum sphondylium L.	HERACSPH	0.0 ± 0.0 (0)	1.9 ± 1.3 (4)	0.0 ± 0.0 (0)
Holcus lanatus L.	HOLCULAN	0.0 ± 0.0 (0)	0.8 ± 0.4 (8)	0.0 ± 0.0 (2)
Juncus effusus L.	JUNCUEFF	0.0 ± 0.0 (0)	0.5 ± 0.4 (9)	0.0 ± 0.0 (0)
Juncus inflexus L.	JUNCUINF	0.0 ± 0.0 (0)	0.8 ± 0.5 (3)	0.0 ± 0.0 (0)
Lycopus europaeus L.	LYCOPEUR	0.0 ± 0.0 (0)	8.4 ± 1.5 (32)	3.4 ± 0.7 (33)
Mentha aquatica L.	MENTHAQU	0.0 ± 0.0 (0)	1.4 ± 0.6 (10)	5.7 ± 2.4 (13)
Myosotis scorpioides L.	MYOSOSCO	0.0 ± 0.0 (0)	12.1 ± 2.2 (34)	19.6 ± 3.6 (35)
Phragmites australis (Cav.) Steud.	PHRAGAUS	5.3 ± 3.0 (3)	18.5 ± 4.8 (15)	2.9 ± 2.2 (3)
Polygonum hydropiper L.	POLYNHYD	0.0 ± 0.0 (0)	1.3 ± 0.6 (9)	2.4 ± 1.1 (11)
Pulicaria dysenterica (L.) Bernh.	PULICDYS	0.0 ± 0.0 (0)	0.9 ± 0.5 (4)	0.0 ± 0.0 (0)
Rorippa amphibia (L.) Besser	RORIPAMP	0.0 ± 0.0 (0)	0.7 ± 0.4 (12)	1.8 ± 0.7 (15)
Rubus spp.	RUBUS-SP	0.0 ± 0.0 (0)	2.0 ± 1.6 (4)	0.4 ± 0.4 (5)
Rumex hydrolapathum Huds.	RUMEXHYD	0.0 ± 0.0 (0)	3.2 ± 0.9 (23)	1.1 ± 0.5 (21)
Salix spp.	SALIX.SP	0.0 ± 0.0 (0)	9.6 ± 2.8 (17)	28.7 ± 5.7 (23)
Scutellaria galericulata L.	SCUTEGAL	0.0 ± 0.0 (0)	2.4 ± 0.7 (26)	0.1 ± 0.0 (7)
Solanum dulcamara L.	SOLANDUL	0.0 ± 0.0 (0)	2.4 ± 0.7 (24)	0.1 ± 0.0 (7)
Sparganium erectum L.	SPARGERE	1.6 ± 1.6 (1)	8.5 ± 3.7 (10)	1.2 ± 0.6 (4)
Stachys palustris L.	STACHPAL	0.0 ± 0.0 (0)	3.3 ± 0.8 (27)	7.3 ± 2.1 (23)
Tanacetum vulgare L.	TANACVUL	0.0 ± 0.0 (0)	1.7 ± 1.0 (13)	0.0 ± 0.0 (1)
Urtica dioica L.	URTICDIO	0.0 ± 0.0 (0)	3.0 ± 0.8 (26)	0.2 ± 0.1 (9)
Valeriana repens Host	VALERREP	0.0 ± 0.0 (0)	0.7 ± 0.2 (21)	0.6 ± 0.4 (9)
Non-native helophyte taxa				
Angelica archangelica L.	ANGELARC	0.0 ± 0.0 (0)	3.3 ± 1.7 (18)	3.7 ± 1.0 (22)
Bidens frondosa L.	BIDENFRO	0.0 ± 0.0 (0)	2.5 ± 0.8 (16)	1.6 ± 0.6 (30)
Buddleja davidii Franch.	BUDDLDAV	0.0 ± 0.0 (0)	0.0 ± 0.0 (0)	1.2 ± 0.6 (9)
Rooted aquatic taxa				
Callitriche spp.	CALLI-SP	0.8 ± 0.5 (2)	1.5 ± 0.5 (15)	0.7 ± 0.2 (11)
Free floating aquatic taxa				
Hydrocharis morsus-ranae L.	HYDRMORS	0.0 ± 0.0 (0)	0.0 ± 0.0 (1)	0.0 ± 0.0 (1)
Lemna minor L.	LEMNAMIN	0.0 ± 0.0 (0)	0.2 ± 0.1 (2)	0.2 ± 0.1 (2)

Results

In total, 76 different taxa were surveyed. Table 3 lists the native (only the most abundant taxa) and non-native helophyte taxa, rooted aquatic taxa and free floating aquatic taxa. *Callitriche* spp. were found as rooted aquatic taxa with a low main cover (0.7–1.5%). Free floating aquatic species consisted of *Hydrocharis morsus-ranae* L. and *Lemna minor* L. and reached low main cover values (< 0.5%). Three non-native species occurred, *Angelica archangelica* L., *Bidens frondosa* L. and *Buddleja davidii* Franch. with cover values between 0 and 4%. In the middle of the shallow water zone only 3 taxa were noted: *Phragmites australis* (Cav.) Steud. (with main cover value of 5%), *Sparganium erectum* L. (main cover of 2%) and *Callitriche* spp. (main cover of 1%).

H. morsus-ranae has a conservation value since this species belongs to the category "vulnerable" in the regional Red List of vascular plants. All other species belong to the categories "least concern" or "not applicable (non-native species)".

Taxa with highest cover on the sides of the shallow water zone were *Salix* spp., *Myosotis scorpioides* L., *P. australis*, *Lycopus europaeus* L. and *S. erectum*. Taxa with higher cover values in plots from the canal bank side compared with plots of the defence dam side were *S. erectum*, *L. europaeus* L., *P. australis*, *Epilobium hirsutum* L., *Eupatorium cannabinum* L., *Filipendula ulmaria* (L.) Maxim. and *Heracleum sphondylium* L. Taxa associated with the defence dam side were *Bidens tripartita* L., *Stachys palustris* L., *Salix* spp., *M. scorpioides* and *Mentha aquatica* L.

Boxplots of different vegetation characteristics per plot site and per year of investigation are illustrated in Fig. 3. The median values of number of taxa, Shannon-Wiener diversity and cover by herbs and competitiveness were higher in plots on the canal bank side compared with plots from the defence dam side. Cover by shrubs and ruderality had higher median values in plots from the defence dam side.

In plots on the canal bank side, median values for number of taxa were lower while median values for Shannon-Wiener diversity and for cover by shrubs were higher in 2009 compared with 2006. In plots on the defence dam side, median values of number of taxa, Shannon-Wiener diversity and cover by herbs were higher in 2009 compared with 2006. In plots from the canal bank side, cover by herbs was 100%, with the exception of one plot in 2009 and one plot in 2006. In plots from the defence dam side, median value of cover by herbs was 75% for 2006 and 85% for 2009. At both sides of the shallow water zone, the median values for ruderality were lower and median values for competitiveness were higher in 2009 compared with 2006.

The linear mixed-effect model analysis revealed significant effects of plot site, year of investigation and the interaction between them for different response variables (Table 4). Negative coefficients for plot site in the final models indicate higher values in plots on the canal bank side compared with plots from the defence dam side. Negative coefficients for year of investigation mean higher values in plots of 2006 compared with plots of 2009. For Shannon-Wiener diversity and cover by shrubs final models show significant effects of plot site only. In the final models, the coefficient of plot site is negative for Shannon–Wiener diversity and positive for cover by shrubs. For cover by phreatophytes, ruderality and competitiveness the effect of plot site and year of investigation was significant in the final models. Negative coefficients of plot site were calculated for cover by phreatophytes and competitiveness; a positive coefficient for ruderality. Positive coefficients for year of investigation occurred in cover by phreatophytes and competitiveness; a negative coefficient for ruderality. The final model for number of taxa has plot site (negative coefficient), year of investigation (negative coefficient) and the interaction of plot site and year of investigation as significant effects. Since the response variable cover by herbs reached 100% in nearly half of the plots, it was not appropriate to define a model for this variable.

The CA-diagram of plots on the sides of the shallow water zone with passively added nominal variables is shown in Fig. 4. A cluster with mainly plots of 2006, both from canal bank or defence dam, is situated in the right and middle part of the diagram. Species associated with this cluster are *Bidens cernua* L., *B. tripartita*, *Polygonum hydropiper* L., *S. palustris* and *Tanacetum vulgare* L. Another cluster of plots, mainly with plots of 2009 and from the defence dam side, is situated on the upper left part of the diagram with *Salix* spp., *Alnus glutinosa* (L.) Gaertn., *A. archangelica* and *E. hirsutum* as characteristic taxa. In the lower left part of the diagram, plots from the canal bank side (both from 2009 or 2006) are clustered with *P. australis*, *F. ulmaria*, *H. sphondylium*, *Juncus effusus* L., *Calystegia sepium* (L.) R. Brown and *Urtica dioica* L. as associated taxa.

Discussion

Helophyte vegetation

The constructed marginal shallow water zones along the canal Ghent-Bruges clearly provide appropriate conditions for establishment of native helophyte vegetation. The development of helophyte vegetation in constructed shallow water zones was also observed along navigable canals (Boeters *et al.*, 1997; Boedeltje *et al.*, 2001) and along navigable rivers (Weber *et al.*, 2012).

A helophyte vegetation is often sparsely developed in banks of navigable canals without shallow water zones (Willby and Eaton, 1996; Weber *et al.*, 2012). In general, riparian habitats along navigable canals are small and conditions for vegetation are not suitable due to steep slopes and high water depths. Furthermore, moving vessels generate hydraulic forces (waves and currents) which provoke difficulties in riparian margins for establishment of helophyte and aquatic vegetation (Haslam, 1987; Coops *et al.*, 1991) and can result in physical damage (Vermaat and De Bruyne, 1993; Asplund and Cook, 1997) or uprooting of vegetation (Murphy *et al.*, 1995). Equally important, moving vessels cause sediment resuspension and an increase in water turbidity (Smarts *et al.*, 1985; Hofmann *et al.*, 2008). As a result, reduction of photosynthesis occurs which may be further inhibited by settlement of fine sediments on plant leaves (Murphy *et al.*, 1995).

When constructing shallow water zones, the defence dam can reduce hydraulic forces induced by navigation (Weber *et al.*, 2012), allowing a suitable condition for helophytes. However, careful construction design of the defence dam is needed since a case study with timber piling as defence dam still notes hydraulic forces and subsequent erosion in the shallow water zone (De Roo *et al.*, 2012). In the present study, the observed development of helophytes

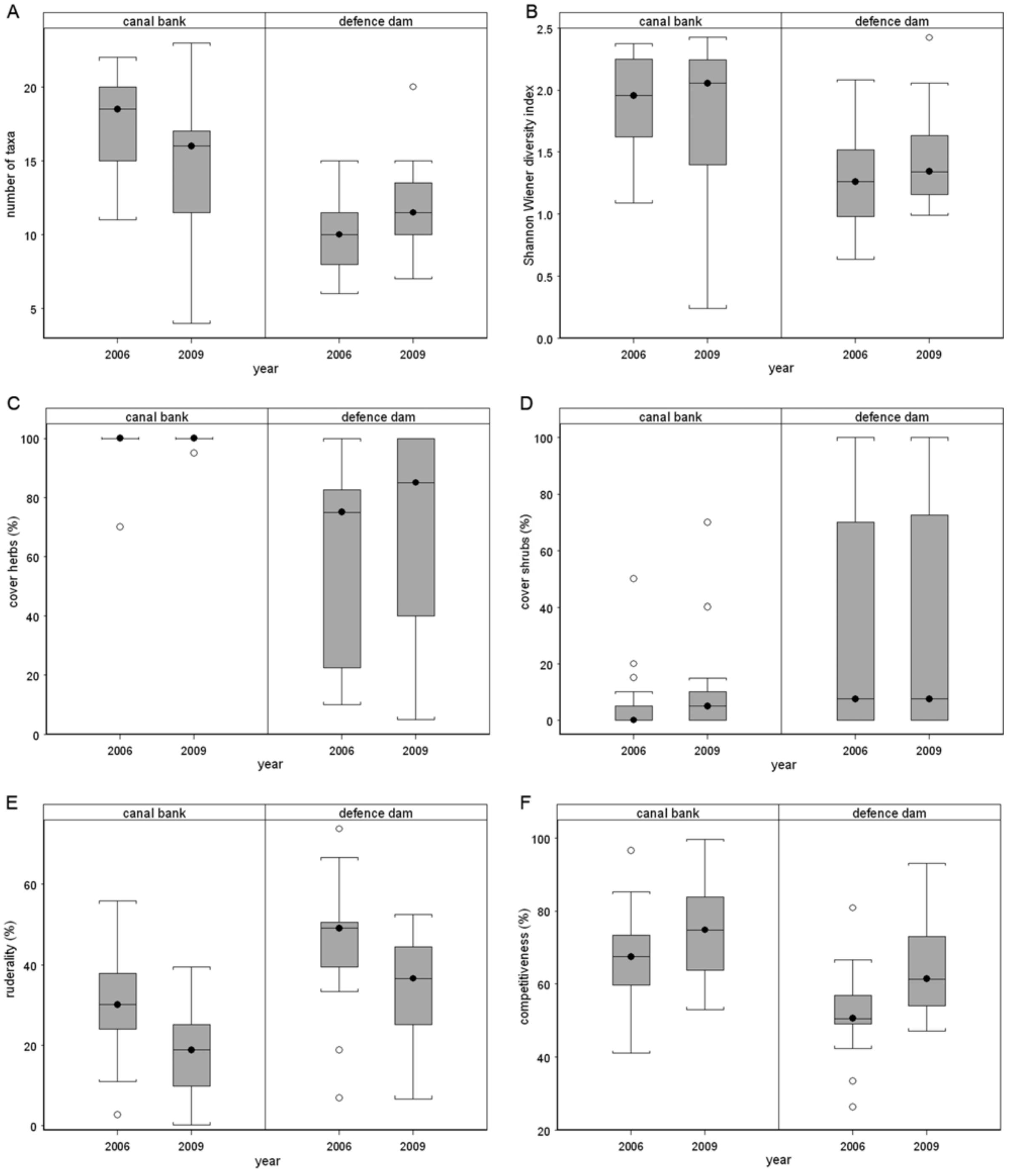

Fig. 3. Boxplot for the number of taxa (A), Shannon–Wiener diversity (B), cover by herbs (C), cover by shrubs (D), ruderality (E) and competitiveness (F) per plot site (canal bank or defence dam) and per year of investigation (2006 or 2009). Intersection line with filled circles = median; box = first and third quartiles; whiskers = largest and smallest observations falling within a distance of 1.5 times the box size from the nearest quartile; open circles = outliers, observations with values between 1.5 and 3 box lengths from the upper or lower edge of the box.

in the shallow zone suggests sheltered conditions, which indicates that the defence dam inhibits hydraulic forces.

The linear mixed-effect model analysis revealed significant effects of plot site (Table 4). Furthermore, in plots located on the canal bank side, cover by herbs was almost always 100%. In plots from the defence dam side, cover by herbs had lower values (Fig. 3). A possible explanation is a difference in construction materials. The defence dams are made by riprap covered with mastic asphalt and the canal banks by rock-filled gabion baskets. The size (0.3 m diameter) and form of the stones used in gabion baskets provide abundant interstitial spaces. Mastic asphalt as

Table 4. Coefficient (standard error within brackets) of linear mixed-effect models examining effect of year of investigation (2006 *vs.* 2009) and plot site (canal bank *vs.* defence dam) and their interaction to different response variables. **$P \leq 0.01$, ***$P \leq 0.001$.

Response variable	Intercept	Plot site (defence dam = 1; canal bank = 0)	Year of investigation (2009 = 1; 2006 = 0)	Interaction of plot site and year of investigation
Number of taxa	– 17.6 (0.86)***	– 7.5 (1.07)**	– 3.1 (1.07)***	4.7 (1.51)**
Shannon–Wiener diversity	1.8 (0.09)***	– 0.5 (0.09)***		
Logit (cover by shrubs)	– 2.8 (0.79)***	1.5 (0.31)***		
Cover phreatophytes	78.8 (5.77)***	– 20.2 (6.40)**	17.4 (6.40)**	
Competitiveness	66.1 (4.17)***	– 13.1 (2.16)***	9.6 (2.16)***	
Ruderality	29.7 (4.45)***	15.7 (2.21)***	– 11.3 (2.21)***	

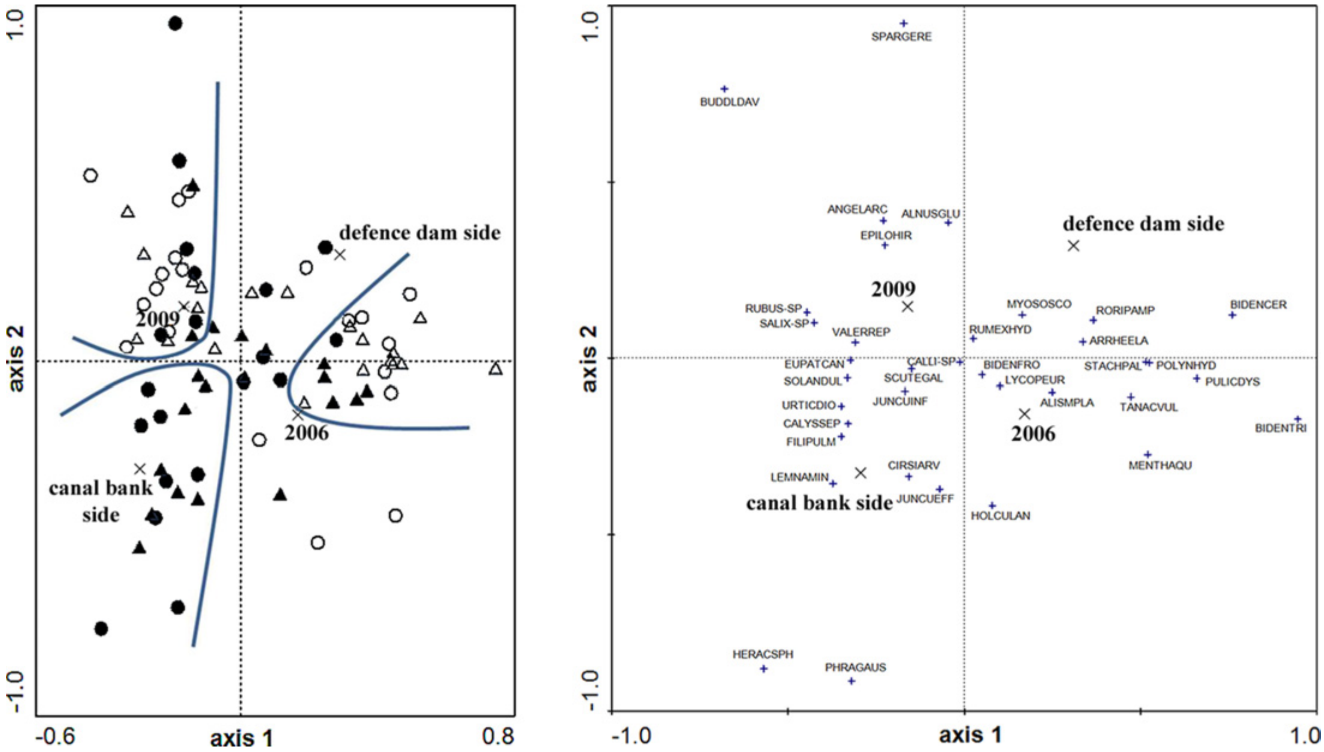

Fig. 4. CA-ordination diagram (first and second axis) of plots on the sides of the shallow water zone with nominal variables year (2006, 2009) and plot site (canal bank or defence dam side) passively projected into the ordination space and shown by their centroids. Ordination was performed with the most abundant taxa (taxa having cover values of at least 4% in at least one plot). The eigenvalues for axis 1 and axis 2 are 0.38 and 0.27 respectively; the total inertia is 3.15. The full names of the taxa together with the abbreviations are listed in Table 3. Plot symbols: ▲: plot at canal bank side and surveyed in 2006; △: plot at defence dam side and surveyed in 2006; ●: plot at canal bank side and surveyed in 2009; ○: plot at defence dam side and surveyed in 2009. The clusters marked on the diagram are discussed in the text.

a cover of riprap limits interstitial spaces. The presence of interstitial spaces is an important factor for helophyte vegetation development (CUR, 2003; Fischenich, 2003; Steiger *et al.*, 2005). As a consequence vegetation colonization and succession may occur faster on the canal bank side compared with the defence dam side. Indeed, the observed higher number of taxa, more diverse vegetation and higher herb cover on the canal bank side are in agreement. Higher competitiveness in plots on the canal bank side compared with plots on the defence dam side also indicates a later succession stage. This is in accordance with Grime (2001) who describes a shift in vegetation from high ruderality to high competitiveness during the early stages of succession under conditions of high productivity.

The linear mixed-effect models also revealed significant effects of year of investigation (2006 *vs.* 2009) on competitiveness and ruderality (Table 4). A vegetation indicating higher competitiveness and lower ruderality was observed in plots of 2009 compared with 2006. These findings also seem to indicate vegetation succession (Grime, 2001). The decrease of the number of species in the plots of the canal bank during the period 2006–2009 can be the result of outcompeting pioneer species (with high ruderality) by a lower number of species with a competitive strategy. Apparently, although the shallow water zones were constructed in 1998, vegetation succession was still noted in the period 2006–2009.

In waterways hydrochory (water dispersal) may play an important role for establishment of new plant populations. Hydrochory may supply propagules of many species from elsewhere, sometimes from far upstream (Merritt and Wohl, 2002). As a consequence, quick colonization of margins of newly constructed river channels was noted by Gurnell *et al.* (2006a) and Goodson *et al.* (2004). Our results also show an almost complete helophyte vegetation cover in the canal bank side 8 years after its construction. Artificial seeding or planting of bare waterway margins often seems unnecessary (Gurnell *et al.*, 2006a).

Rooted aquatic vegetation

The shallow water zones along the canal Ghent-Bruges are of little importance for rooted aquatic plant species. Concordantly, Boeters *et al.* (1997) hardly found any rooted aquatic plants in 4–6-year-old shallow zones with porous defence dams or with openings in the defence dam. On the other hand, Weber *et al.* (2012) observed abundant rooted aquatic vegetation in 5-year-old shallow zones with defence dams constructed from sheet-piles and equipped with openings. Also, Boedeltje *et al.* (2001) found abundant rooted aquatic vegetation in 3–5-year-old shallow water zones.

A possible explanation for the absence of rooted aquatic vegetation in the shallow water zones along the canal Ghent-Bruges are unfavourable abiotic conditions. During fieldwork a thick (>10 cm) and soft substrate was observed at the bottom of the shallow water zone. Boedeltje *et al.* (2001) observed that the occurrence of rooted submerged macrophytes in shallow water zones was clearly related to a thin (<2 cm) sediment layer with a low amount of organic matter and low concentrations of ammonium in the water layer and the pore water. When a sediment layer with high organic matter content is present and low water exchange between shallow water zone and main channel occurs, increased O_2 consumption rates during summer (as a result of decomposition) can cause anoxia of the water layer and enhanced concentrations of soluble sulphides and H_2S (Rolletschek, 1999). As a result, among others because of sulphide toxicity, rooted aquatic vegetation is hampered (Smolders and Roelofs, 1993). Anoxia and increased nutrient releases from the sediment can cause development and domination of free floating aquatic taxa (*Lemna* spp., Boedeltje *et al.*, 2005) giving no change to rooted aquatic vegetation. Domination of free floating aquatic species was noticed in 5.5-year-old shallow water zones (Boedeltje *et al.*, 2001).

A possible high organic content in sediments of the studied shallow water zone can originate from the main channel by fertilizer run-off from agricultural activities, untreated sewage effluents or dead biomass. The relative importance of these sources remains unknown.

Sedimentation

Sedimentation seems to occur in the shallow water zones along the canal Ghent-Bruges. Deposition and accumulation of sediments were observed in shallow water zones along navigable canals (Boeters *et al.*, 1997; Boedeltje *et al.*, 2001), in backwaters along navigable canals (Willby and Eaton, 1996), in backwaters along navigable rivers (Smarts *et al.*, 1985; Bornette *et al.*, 1998) and in shallow water zones bordering lakes (Rolletschek, 1999). In a navigable canal with a defence dam of metal sheet-piles with openings, Boeters *et al.* (1997) described accumulation of sediments at a rate of 3–4.5 cm per year. The sedimentation in shallow water zones or backwaters along navigable waterways originates from vessel traffic. The explanation is that moving vessels induce bank and bed erosion in the main channel leading to high loads of suspended sediment in the water column (Murphy *et al.*, 1995; Hofmann *et al.*, 2008; Söhngen *et al.*, 2008). These sediments can enter shallow water zones by means of openings in the defence dam. With every vessel passage, sediment rich water enters the shallow zone while sediment poor water flows out (Hooimeijer, 1997). Furthermore, when helophytes develop in the shallow water zone sedimentation is expected to accelerate (Tabacchi *et al.*, 2000; Gurnell *et al.*, 2006b).

It is expected that a reduction of the sediment input in shallow water zones can be achieved by constructing a defence dam without openings. However, when the defence dam is made up of porous stones considerable water exchange with accumulation of sediments in shallow zones is described by Boeters *et al.* (1997). Shallow water zones constructed with a hydrologically impermeable defence dam without openings can inhibit sedimentation (Boedeltje *et al.*, 2001). Pipes can be installed in the defence dam especially to allow fish migration between the main channel and the shallow water zone. However, additional experience and studies are needed to quantify sedimentation rates in shallow water zones in relation to porosity of the defence dam and the number, location and width of openings or pipes in the defence dam. Also, it may be possible that when planting helophytes in shallow water zones near the openings or pipes, sedimentation is forced to these areas thereby inhibiting sedimentation in other areas of the shallow zone. Furthermore, sedimentation rates in shallow water zones are expected to be influenced by navigation variables (like vessel speed, number of passages, vessel types and distance of vessel passage to defence dam) and by channel variables (like channel width and depth, bed-sediment composition and channel geometry).

Conclusions and recommendations

A constructed marginal shallow water zone can allow the establishment and development of a native helophyte vegetation and thus enhance biodiversity along navigable canals. Artificial seeding or planting is not needed because sufficient propagules are supplied by water dispersal. To improve conditions for helophyte vegetation an unprotected slope or a temporal protection (biological geotextiles) of the canal bank can be considered on the condition that the defence dam largely reduces the waves and currents of passing vessels. However, if bank stabilizing material is needed it is advisable to apply materials that provide interstitial spaces, like riprap or rock-filled gabion baskets. Covering these materials with, for example, mastic asphalt will negatively affect helophyte vegetation establishment. Furthermore, if enough space is available gentle profiles of the sides are recommended to enhance opportunities for helophyte vegetation (CUR, 1999a; Schiereck, 2004).

Along navigable canals deposition and accumulation of sediments in shallow water zones can inhibit the development of rooted aquatic vegetation. Therefore, if rooted aquatic vegetation is to be achieved, study of construction designs that reduce sediment input in the shallow water zone is needed. A balance seems to be chosen between isolation, which inhibits hydraulic forces, and water exchange, which inhibits anoxia of the water layer, prevents domination of free floating aquatic vegetation and provides ecological connectivity.

Achieving or conserving good ecological potential for artificial waterways according to the WFD may require mitigation of navigation impacts. The construction of marginal shallow water zones along navigable canals may be necessary to achieve ecological goals. In closing, a mosaic of bank types along navigable canals can be recommended as a realistic solution with varying stretches of steep slopes of concrete or metal sheet-piles (limited to sites where this is necessary), more gentle slopes with coarse material (like riprap or rock-filled gabion baskets, allowing riparian vegetation), wave absorbing structures in front of canal banks, shallow water zones and natural unprotected slopes. Furthermore, if appropriate, the application or enforcement of navigation rules (like speed limits) or adaptation of vessel or propulsion design may also reduce impact of hydraulic forces on banks (Söhngen *et al*., 2008). Such ecologically orientated engineering will not severely constrain commercial navigation and their socioeconomic benefits, but it will substantially enhance biodiversity and ecological processes in navigable canals (Wolter and Arlinghaus, 2003).

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