Prepared for:

British Waterways

Hydraulic aspects of the Montgomery Canal Restoration

Report

March, 2006

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Contents

1 Introduction

1.1 Background

The Montgomery Canal extends from the popular Llangollen Canal at Frankton Junction to Newtown, 35 miles to the South and passing the counties of Shropshire and Powys. The canal is a declared Site of Special Scientific Interest. Of particular interest are the floating water plants. Together with the banks it forms the habitat of many birds and animals; it has international value for its wildlife.
The Montgomery Canal Partnership wishes to restore the Montgomery Canal, which is an ongoing campaign since 1969, as a flagship of sustainable canal restoration by protecting its unique environment and heritage and by increasing access for all. Therefore, the Partnership has prepared a Conservation Management Strategy in which the restoration plans are lain out. In order to combine sometimes conflicting interests, such as nature conservation and navigation, research is required to optimize the levels of navigation possible, while maintaining and achieving nature conservation standards.

British Waterways commissioned WL | DELFT HYDRAULICS (WL) to carry out a desk study on the water motions induced by navigation (purchase order no 4500046071 dated 14th of July, 2005). The study is part of a larger research project comprising also ecology and boat design research and partly funded by the European Interreg III Crosscut project.
The study has been carried out by Mr. Henk Verheij, whereas from the side of British Waterways and Inland Waterways Association respectively Mr. Stephen Lees and Mr. Tony Harrison were involved.

1.2 Objective

Plants can be damaged by moving boats: indirectly by the hydraulic effects such as flow velocities or waves, or by direct contact between the plants and the boat, for instance with the propeller. More insight into the damaging mechanisms and the relative importance of different mechanisms, will aid the design of channels, the development of boat modifications and the development of boat management techniques in ways that minimise damage to plants.
Based on the foregoing the objective of the proposed study is:

> *A thorough investigation of the hydraulic effects of boat passage on canal plant communities by means of reviewing literature on ship-induced water motions, reviewing case-studies on boat management, and integrating those results into an advice regarding optimising channel design, boat design and boat management.*

The results will be assessed in the light of their benefits to aquatic macrophyte and marginal plant communities, their implementation costs and their applicability not only to the Montgomery Canal, but also to other canals in the UK and the EU.

Figure 1.1
Map of the Montgomery Canal (Current State).

1.3 Scope and approach of the study

The Montgomery Canal is a much-loved place and, subsequently, a popular destination for walkers, anglers and recreational boats, among which narrow boats. It is believed that maximum 5,000 annual boat movements in England and 2,500 in Wales are possible (Conservation Management Strategy), but the real environmental carrying capacity is unknown. The actual capacity will be revealed, and the limits kept within, through a process of staged build up of boat numbers and detailed ecological monitoring.

Canal plant communities are known to be vulnerable to a combination of factors related to water quality and water currents, pressures and waves due to boats. Considering navigation it is essential to understand the physics of the processes by which plant damage may occur: the reverse or return currents generated in confined channels, the jets created by the propeller / rudder systems, the turbidity caused by the propeller, or the direct cutting action of the propeller.
Combining this with knowledge on the impact on marginal and aquatic plant communities enables to propose optimum channel profiles, development of boat modifications and boat management. For instance, on the most vulnerable canal sections all craft might have to comply with local speed limits.

The approach of this project was as follows: first, a literature review on ship-induced water motions (Chapter 2) and a review of case-studies on boat management (Chapter 3) were carried out, after which, secondly, the findings were integrated into an advice (Chapter 4). Chapter 5 presents the conclusions and recommendations.

2 Literature review on ship-induced water motions

2.1 General

Research on ship-induced water motions in confined channels started already a century ago in different countries. In principle, three phenomena can be distinguished:

- Primary ship wave consisting of a water level depression alongside the ship along with a return current, bow wave and transverse stern wave;
- Secondary ship waves (e.g. short waves comparable with wind waves which start at the bow and the stern of a boat travelling to the bank);
- Propeller jet(s).

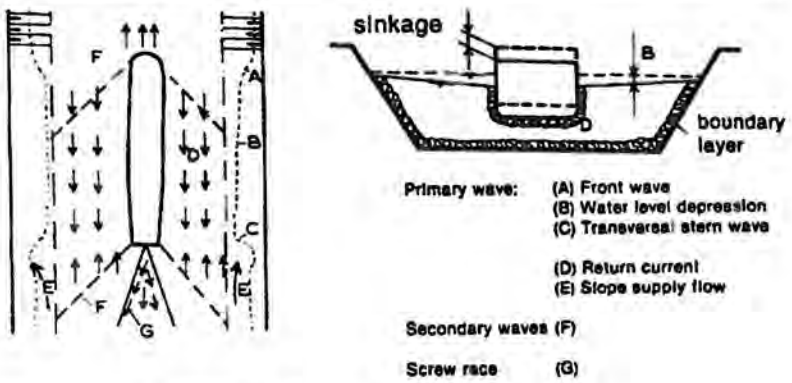

Figure 2.1 Definition sketch ship-induced water motions

PIANC (2000) distinguishes three categories of small waterways for recreational crafts: RA, RB and RC, but the typical English narrow boat does not belong to any of the categories. According to the information in the PIANC report which is based on 22,000 narrow boats this recreational boat type can be defined as:

- Beam 7 ft (2.13 m)
- Length 35 ft (10.67 m)
- Draught 3 ft (0.91 m)

However, a more average value for the draught is in the range of 0.50 to 0.75 m, with an average of 0.65 m. Hames (1989) presents data based on the majority of British canals: beam B = 2.083 m and draught T = 0.762 m. Nowadays the boat length is about 55 ft (16.5 m) and the length is increasing slowly.

A typical canal cross-section has the dimensions (Eaton & Willby, 2004):

- Canal depth 0.8 to 1.2 m (although 1.5 m can be considered as the maximum depth and 1.2 m as the average);
- Water surface width 10 to 15 m;
- Canal cross section: about 11.5 m^2.

For the Montgomery Canal the figures are:
- Canal depth 1.5 m, but in practice it is less in nearly all places due to silt;
- Water surface width 9 to 12 m;
- Canal cross section: optimum about 15 m^2.

The existing literature has been examined, in particular related to narrow boats in canals. Special attention has been paid to jets of propulsion systems, in particular the main propulsion systems. However, modern systems such as water jets will not be addressed, because they are not expected on the UK canals.

The effects of recreational boat traffic on aquatic vegetation are:

- Direct effects:
  1. physical contact between boats and vegetation: moving hulls, propeller
  2. generated water motions: flows, turbulence, pressure changes, waves

- indirect effects:
  1. turbidity
  2. bed disturbance
  3. silt deposition on leaves

In this study direct effects only will be considered.

Note: Aquatic vegetation comprises (Eaton & Willby, 2004): submersed rooted species (e.g. most pondweeds), floating-leaved rooted species (e.g. water lilies) and free-floating species (e.g. duckweeds).
Marginal vegetation comprises shallow water species which emerge from the water surface sufficiently to bear leaves wholly in the atmosphere, e.g. Sweet Reed Grass and associated species.

2.2 Primary ship wave

Thiele (1901), Kreij (1913) and Kreitner (1934) developed the first analytical methods to calculate return current and water level depression (Figure 2.2). Applying Bernoulli's theorem and the continuity equation they result in a simple set of equations based on hydraulic principles, i.e. an energy based approach. The method has been improved by Schijf (1949) by adding correction coefficients to assess for irregular flow distribution.
Schijf also demonstrated clearly the existence of natural speed limits, although it is likely that Russell was one of the first engineers to experience the onset of the speed limit during the 1834-5 steamboat trials for the Edinburgh & Glasgow Union Canal Company (Schofield, ??). The limit speed occurs because the return flow reaches a maximum value

when the depth reduces to the minimum (critical) depth. Flow onto the propeller can then no longer increase and neither can the thrust increase the boat's speed.
Schofield (2003) stated that if the propeller should be placed under the bow of the boat, the speed will increase beyond the limits of the barrier speed, because the flow to the propeller is not restricted and not depending on the minimum water depth downstream.

Nevertheless, the energy method computes only average values valid for the whole cross-section. As long as the ratio of canal cross-section to midship-section is small this approach is allowed. For large ratios corrections should be used to take into account two-dimensional effects. The formulas read:

$$A_C V_s = A_W \left(V_s + u_r\right) \tag{2.1}$$

$$\frac{1}{2}\rho V_s^2 + \rho g h_0 = \frac{1}{2}\rho\left(V_s + u_r\right)^2 + \rho g\left(h_0 - z\right) \tag{2.2}$$

$$A_W = b_b\left(h_0 - z\right) + m\left(h_0 - z\right)^2 - A_M \tag{2.3}$$

V_s = boat speed (m/s)
V_c = critical speed (m/s)
h_0 = water depth (m)
A_c = cross-section canal (m^2)
A_M = wetted midship section (m^2)
A_W = wetted cross-section of the canal during a boat passage (m^2)
b_b = canal width at the bottom (m)
u_r = return current (m/s)
m = canal side slope (horizontal:vertical) (-)
z = water level depression (m)
ρ = density of water (kg/m^3)
g = acceleration of gravity (m/s^2)

All methods aiming at a prediction of the water motions assume the sinkage or squat of a ship is equal to the water level depression z. In general, this is about true. However, the sinkage at the bow and the stern can be different depending on the ship type and the boat speed. For most ships the sinkage at the stern equals the sinkage at the bow for moderate speeds. For boat speeds close to the critical speed the stern sinkage will become larger than the average sinkage.

In addition, a momentum-based approach has been developed by Bouwmeester (1977), which gives almost identical results.
Nowadays, mathematical models have been developed. In Section 2.4 some attention will be paid to these models.

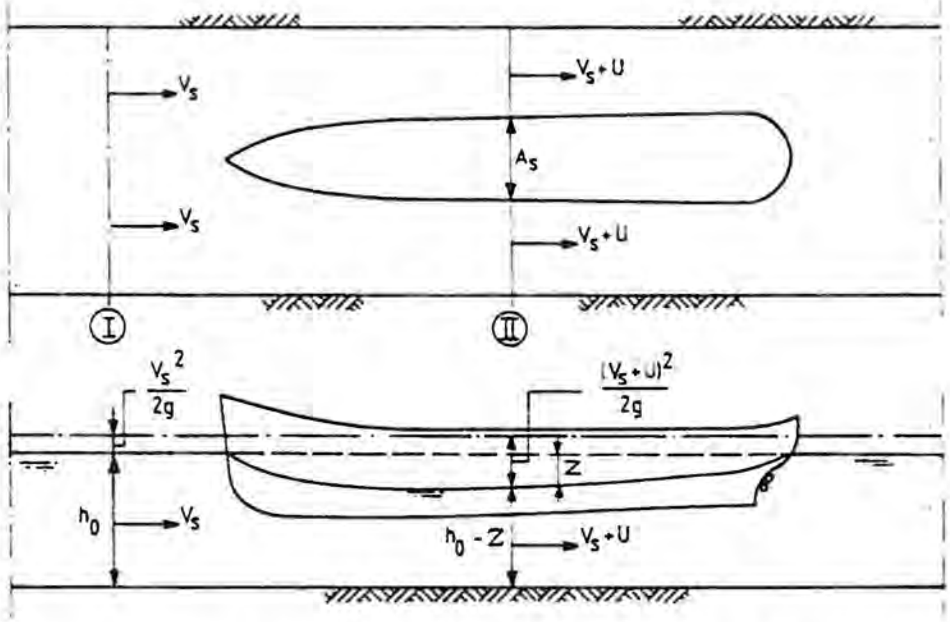

Figure 2.2 Average flow velocities and water level depression in the primary ship wave system next and underneath a boat (co-ordinate system related to the boat).

Flow velocities underneath the keel

The energy method as well as the momentum method has been developed for predicting the water motions near the banks of a canal. In the situation of the Montgomery Canal the flow velocities at the bed are more important in relation to the aquatic vegetation.
Neither the energy method nor the momentum method predicts the flow velocities underneath the hull of the boat correctly. Nowadays, the draught of commercial vessels is increasing and the keel clearance becomes smaller. Subsequently, the influence on bed material increases. Therefore, research is going on to develop proper formulas, although in literature some equations have already been presented.

Maynord (1990) proposes to compute the return current underneath the boat with the equation:

$$\frac{U_b}{V_s} = 0.16\left(\frac{B}{h_0}\right)^{0.54}\left(\frac{T}{h_0}\right)^{0.68} \quad \text{for } T/h_0 = 0.1 \text{ to } 0.6 \text{ and } N > 6 \qquad (2.4)$$

where
U_b = maximum flow velocity beneath the bow at 3 to 4 times the keel clearance (m/s)
V_s = boat speed (m/s)
B = boat's beam (m)
T = boat's draught (m)
h_0 = water depth (m)
N = ratio of A_C/A_M (-)
A_c = cross-section canal (m^2)
A_M = wetted midship section (m^2)

The equation has been calibrated with model tests, whereas the relevant parameters were given already by Fuehrer & Romisch (1977).

Based on research at Delft Hydraulics in the 70s the following equation has been presented (CUR, 1995; CUR/CIRIA, 2005):

$$\frac{U_b}{U_r} = 1.5 \; to \; 2.0 \tag{2.5}$$

where

U_r = average return flow velocity calculated with the energy or Schijf method, e.g. eq.(2.1) to (2.3) (m/s)

Recent research at WL | Delft Hydraulics resulted in the functional relationship (Verheij, 2005):

$$\frac{U_b}{U_r} = f\left(\frac{h_0 - T}{h_0}, \frac{V_s}{\sqrt{gh_0}}, \frac{A_C}{A_M}\right) \tag{2.6}$$

It is expected that an equation will be available before the end of 2005. Compared to eq.(2.5) the new equation can be considered as an improvement.

breaking stern wave

Relevant for the canal bed is also the stern wave between boat and bank. This holds in particular for the breaking stern wave which is accompanying a ship travelling in a canal with a speed close to the speed limit. The breaking wave causes extra turbulence.

The height of the stern wave z_{max} can be computed as a function of the water level depression dh:

$$z_{max} = 1.5 \cdot z \tag{2.7}$$

In order to avoid misunderstanding: breaking waves may occur (1) directly adjacent to the boat and in case of canals with a small surface width, will continue to the bank, or (2) near the bank in case of a sloping bank. The second type is related to the decreasing water depth above the slope. The front of this wave moves in the same direction and with the same speed as the boat. Flow velocities in the wave front decrease very rapidly from a value almost equal to the boat speed to a value about equal to the flow velocity in the wake behind the ship. This breaking wave also occurs for low ship speeds, lower than the critical boat speed. The only condition is that the water level depression as a result of the moving ship reaches the bank, which in general is the situation for canals with a surface width less than 10 times the boat's beam.

The first type of breaking wave is related to the critical boat speed, which depends on the ratio of the cross-sections of ship and canal. In practice, displacement ships can not exceed a speed of about 0.9 times the theoretical critical speed. Most boats will sail with a speed of about 0.7 times the critical speed which is considered as a compromise because above this speed the engine is consuming a lot of fuel, makes a lot of noise and the boat generates waves whereas the speed does not increase.

bottom shear stress

The flow velocities create shear stresses at the bed. Admiraal et al (1999) present results of laboratory experiments carried out at the Waterways Experiment Station of the US Corps of Engineers at Vicksburg, USA, with US push-tow barges for Mississippi conditions on a scale 1:25 (prototype water depths between 3.4 m and 7.0 m). In Figure 2.3 an example of measured shear stresses are shown. Observed maximum characteristic values for the return current were (translated to prototype conditions):

$\tau < 20$ Pa
$d\tau/dt < 10$ Pa/s

where:
τ = shear stress (Pa = N/m^2)
t = time (s)

It should be noted that the shear stresses induced by the propeller jet are about 5 times higher (see next Section).

$\tau < 125$ N/m^2
$d\tau/dt < 30$ Pa/s

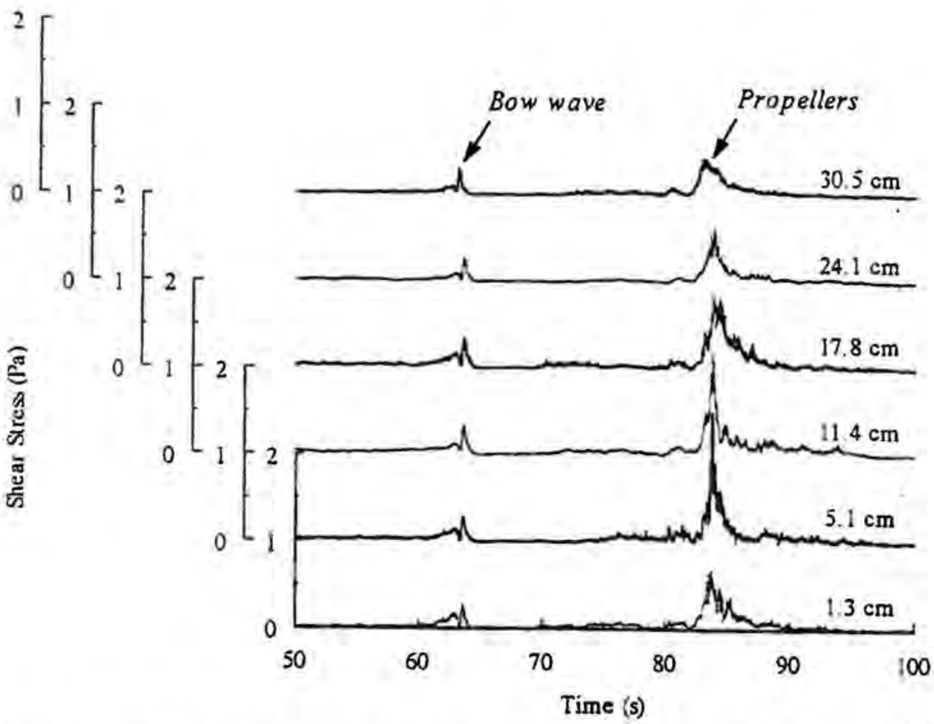

Figure 2.3 Example of measured average model shear stress distributions beneath a scale model of a barge tow; water depth 4.3 m (Admiraal et al, 1999)
Note: distance of measurements from tow centreline are given on the right side

In addition to the shear stress measurements the entrainment of sediment was calculated. The Garcia-Parker equation proved to predict quite well for the sediment used with a diameter of 0.5 mm:

$$E = \frac{AZ_u^5}{1+\frac{A}{0.3}Z_u^5} \tag{2.8}$$

with

$$Z_u = \frac{u_*}{w_s}R_p^{0.6} \quad with \quad R_p = \frac{D\sqrt{gRD}}{\upsilon} \tag{2.9}$$

where

E = sediment entrainment (-)
A = constant; A = 1.3 10^{-7}
w_s = sediment fall velocity (m/s)
u_* = shear velocity; $u_* = (\tau/\rho)^{0.5}$ (m/s)
τ = shear stress related to particle diameter D (N/m2)
R_p = particle Reynolds number (-)
D = particle diameter (m)
R = submerged specific gravity; R = 1.65
υ = kinematic viscosity of water (m^2/s)

Finally, Admiraal et al computed the total suspended sediment load induced by the navigation traffic. Therefore, they combined the observed shear stresses and the entrainment function of Garcia-Parker. For example, the quantities for the return flow and the propeller flow are 4 m^3/s and 37 m^3/s respectively.

Direct impacts of the ship's hull

No literature has been found on direct impacts of boat hulls on aquatic vegetation. Obviously, groundings will disturb the canal bottom and damage the present vegetation.

2.3 Propeller jets

Flamm (1913) was probably the first who recognized the effect of a propeller jet on a canal bottom. Later in the second half of the 20th century, as the ship dimensions increased, many researchers investigated the effect of the flow velocities induced. For instance, Oebius & Schuster (1975, 1979), Robakiewicz (1966), Römisch (1975), Blaauw & van de Kaa (1978), Verheij (1983), Maynord (1990), Prosser (1986) and, more recently, Hamill et al (1993 - 2004).

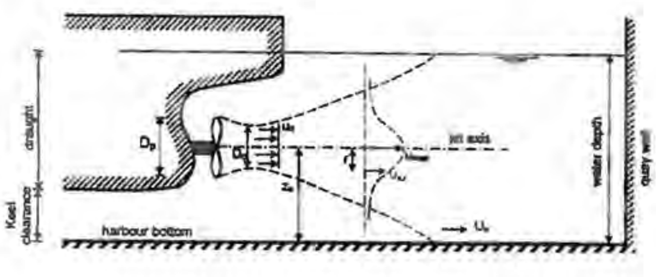

Figure 2.4 Sketch of propeller jet behind a ship

The older research is all based on the actuator disc theory assuming the propeller jet can be schematized as a submerged free jet discharging out of an orifice into an infinite fluid and using the relevant equations presented by Albertson et al (1950):

$$V_{axis} = \frac{1}{2C} V_0 \left(D_0 / x \right) \tag{2.10}$$

and

$$\frac{V_{r,x}}{V_{axis}} = \exp\left[-\frac{1}{2C^2} \frac{r^2}{x^2} \right] \tag{2.11}$$

where

V_{axis} = flow velocity in the axis of the jet (m/s)
V_0 = efflux velocity (m/s)
$V_{r,x}$ = flow velocity in the jet at location x,r (m/s)
D_0 = diameter of a free jet (e.g. effective propeller diameter) (m)
x = horizontal distance from the propeller (m)
r = radial distance from the jet axis (m)
C = coefficient (-)

Albertson et al (1950) determined a value of 0.081 for the coefficient C. The presented formulas assume a normal or Gaussian distribution of the flow around the axis and are valid in the zone of established flow. Closer to the orifice the flow has not been established yet and different formulas should be used.

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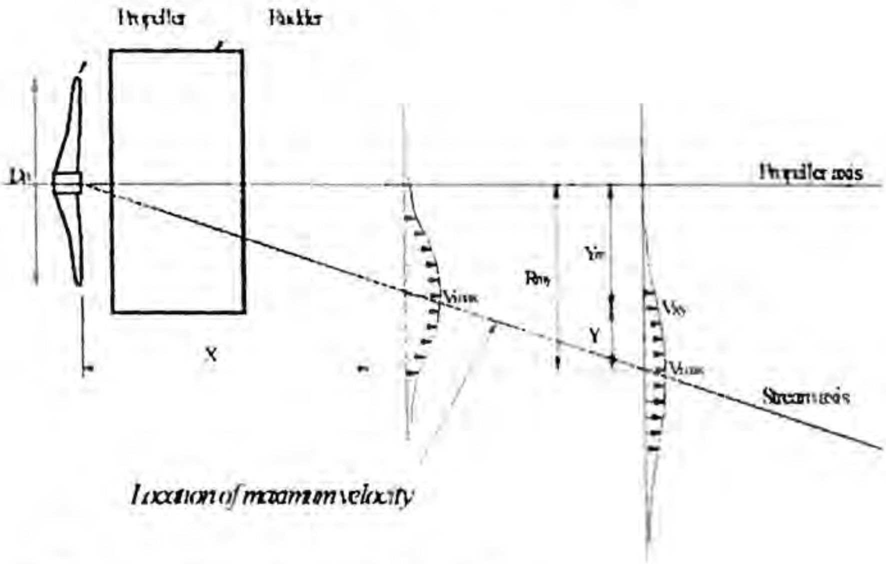

Figure 2.5 Velocity distribution in the z-plane

Before discussing the applicable propeller jet studies, the underlying assumptions of the Albertson theory are mentioned:

- hydrostatic pressure throughout the flow;

- dynamically similar diffusion under all conditions;
- varying of the longitudinal component of the velocity according to a normal or Gaussian probability function.

It is important to note that propeller jets behind moving boats differ from the conditions addressed by Albertson et al in the following way:

- the channel bottom and water surface inhibit jet spreading;
- a moving jet is discharging into a moving flow field;
- the propeller jet has a radial component of velocity;
- the rudder splits the jet into two jets;
- the Kort nozzle (propeller placed in a tube) and open wheel (free propeller) are different from a free jet out of an orifice.

The present methods are derived mostly for manoeuvring boats, i.e. boat speed V = 0. This assumption of manoeuvring greatly simplifies the problem, because wake effects are eliminated. For vessels underway ($V \neq 0$), Führer, Römisch & Engelke (1981) stated: "Consequently, a marked reduction of bottom velocities occurs. Furthermore, the maximum bottom velocity takes place in an ever-increasing distance behind the ship." Schäle (1977) found that "the propeller jet of moving freight motor ships, even with a high propeller loading, never comes in contact with the canal bottom but always rises along the shortest path to the surface of the water."

Schäle states that the propeller jet strikes the channel bottom only under the following conditions (not necessarily occurring at the same time):

- start-up from a stationary condition;
- whenever the water depth/draught ratio is less than 1.2;
- manoeuvring with hard rudder.

Schäle's observation of the jet rising to the surface is consistent with the findings of Maxwell & Pazwash (1973) for shallow, submerged, axisymmetric jets.

Governing equations

In principle, all methods can be presented by:

$$V_0 = c_1 n D_p \sqrt{K_T} \qquad (2.12)$$

and

$$V_{x,r} = A\left(\frac{D_0}{x}\right)^{\gamma} V_0 \exp\left(-\frac{1}{C_2^2}\frac{r^2}{x^2}\right) f\left(rudder, confinement\right) \qquad (2.13)$$

where

V_0 = efflux velocity (m/s)
$V_{x,r}$ = flow velocity at location x,r (m/s)
n = number of revolutions (s^{-1})
D_p = propeller diameter (m)
D_0 = effective propeller diameter (m); $D_0 = 0.7\ D_p$
K_T = thrust coefficient or dimensionless relationship between propulsive force, number

of revolutions and diameter of the propeller (-)

r = radial distance to the propeller axis (m)

x = distance to the propeller (m)

Blaauw & Van de Kaa (1978) and Verheij (1983) derived the following values for the variables: $c_1 = 1.6$, $C_2 = 0.18$, $A = 2.8$ and $\gamma = 1$. This results in:

Efflux velocity $$V_0 = 1.6 n D_p \sqrt{K_T} \qquad (2.14)$$

Flow velocity along the axis $$V_{axis} = 2.8\, V_0 \left(D_0/x\right) \qquad (2.15)$$

Flow distribution $$V_{x,r} = V_{axis} \cdot \exp\left[-15.4 r^2/x^2\right] \qquad (2.16)$$

With eq.(2.16) the flow velocities at the bed can be calculated by substituting for r the distance from the propeller axis to the bed. Obviously, given the particular function, the maximum flow velocity at the bed can be expected below the propeller jet axis and the flow velocities will decrease slowly as one moves away from the propeller jet axis in the direction of the bank. The flow velocities at the bed can be characterized as a Gaussian or normal distribution.

Fuehrer, Römisch & Engelke (1981) presented other values for equation 2.15 and 2.16: 2.6 and 22.2 in stead of 2.8 and 15.4 respectively. Furthermore, they presented an equation for the flow velocity near the bed:

$$\frac{V_b}{V_0} = A\left(\frac{x}{D_p}\right)^{-a} \qquad (2.17)$$

with a = 0.6 spreading is limited by bottom and water surface and A is a function of h/D_p and z_p/D_p (z_p = distance from propeller axis to canal bed). For the Montgomery Canal conditions: A ~1.5

Führer & Römisch (1977) mention the deflection of the jet to the bed under an angle of 12 degrees.

Hamill et al (1993) present instead of equation 2.15:

$$\frac{V_{axis}}{V_0} = 0.87\left(\frac{x}{D_p}\right)^{-0.25\beta} \qquad (2.18)$$

where

β = propeller blade area ratio (-)

Hamill et al (2004) showed that the coefficient c_1 is not a constant:

$$c_1 = \left(\frac{D_p}{D_h}\right)^{-0.403} K_T^{-1.79} \beta^{0.744} \qquad (2.19)$$

where
K_T = thrust coefficient (-)
D_h = diameter propeller axle or hub (m)

However, Hamill et al (1996) present also the equation from a PhD study by Stewart:

$$V_0 = c_1 n D_p \sqrt{K_T} \tag{2.20}$$

$$c_1 = \left(\frac{D_p}{D_h}\right)^{-0.323} K_T^{-0.1459} P^{0.44} \beta^{0.513} \tag{2.21}$$

where
P = pitch ratio (-)

Note the differences in the exponents in equations 2.19 and 2.21. Moreover, in PIANC Bulletin 89 also an exponent of -0.179 for the K_T parameter has been presented.

Earlier, Hamill presented (1993):

$$V_0 = 1.33 n D_p \sqrt{K_T} \tag{2.22}$$

This formula was presented originally in Hamill's PhD study at the Queens University of Belfast.

Hamill et al also re-introduced the presence of the hub:

$$R_{m0} = 0.67 R_p - R_h \tag{2.23}$$

where
R_{mo} = location of maximum flow velocity (m)
R_p = propeller radius (m)
R_h = radius of propeller hub (m)

The maximum flow velocities were measured at about 0.7 times R_h whereas the other methods assume a maximum at 0.5 times R_p.
However, Oebius et al (1975) and Verheij (1983) suggested the use of equation 2.23 earlier, based on the work of naval architects in the 50s, among which Lerbs (1952).

Finally, Hamill presented the following equation for the flow field:

$$\frac{V_x}{V_{max}} = \exp\left[-\frac{1}{2}\frac{(r - R_{m0})^2}{(0.5R_{m0})^2}\right] \tag{2.24}$$

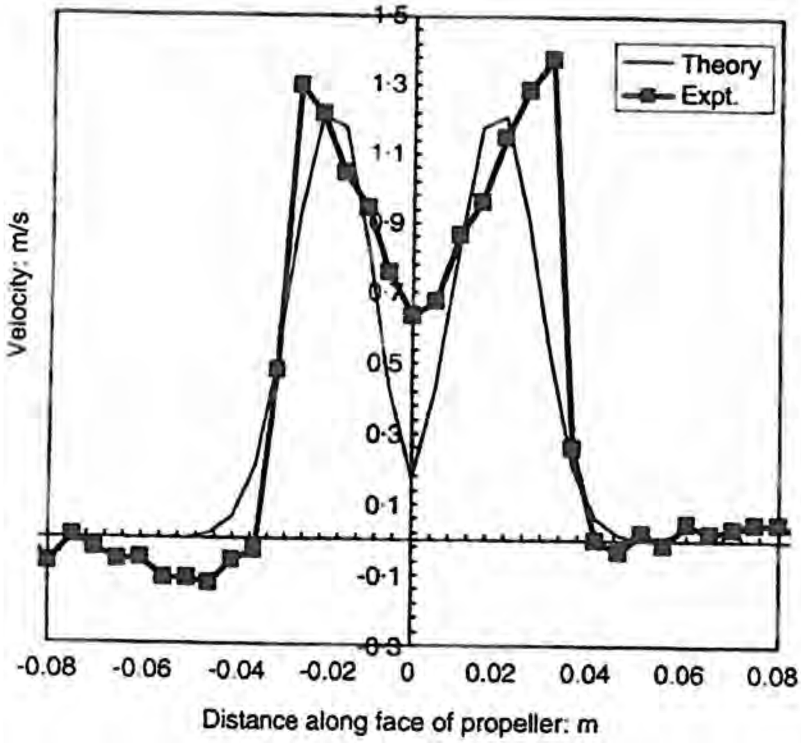

Figure 2.6 Axial velocity distribution along the propeller face (Hamill et al, 2004)

All research mentioned above aimed at commercial ships. OSTEC carried out tests with a narrow boat for British Waterways in order to find improvements with respect to hull shape and propulsion system to reduce the induced water motions. The results are summarized by Hames (1989) as far as they concern the small-scale tests and in OSTEC (1991) results of full scale tests are reported. A significant improvement with respect to induced pressures can be obtained by a shrouded propeller, where the shroud is constructed around the existing propeller. The pressures reduce by 50% compared to a narrow boat with a free propeller.

Very often no information is available on the thrust coefficient K_T. Blaauw & Van de Kaa (1978) presented an equation known in maritime engineering:

$$V_0 = C_3 \left(\frac{P_D}{\rho D_p^2} \right)^{0.33} \qquad (2.25)$$

where
P_D = applied engine power (W)

Values for the coefficient C_3 are:
C_3 = 1.17 for ducted propellers
C_3 = 1.48 for free propellers
Hamill & Johnston (1993) presented a value of C_3 = 1.23 for free propellers (with C_1 = 1.33 in equation (2.14) instead of C_1 = 1.6).
Maynord (1999) found for Mississippi tow boats values in between: C_3 = 1.06 to 1.10 for propellers with a nozzle and C_3 = 1.29 to 1.34 for free propellers.

Since $D_0 = 0.7\ D_p$ equation (2.25) can also be written as:

$$V_0 = 0.79\,C_3\left(\frac{P_D}{\rho D_0^2}\right)^{0.33} \tag{2.26}$$

Substituting a value of $C_3 = 1.48$ for a free propeller then results in 1.17, which equals the value of $C_3 = 1.17$ for a ducted propeller. Therefore, Blaauw & Van de Kaa (1978) presented one equation for both types of propellers:

$$V_0 = 1.15\left(\frac{P_D}{\rho D_0^2}\right)^{0.33} \tag{2.27}$$

moving boats

Limited information is available on the flow velocities in the propeller jet of moving boats. In general, they are of less importance compared to the flow velocities induced by a manoeuvring boat. Nevertheless, moving boats do generate a propeller jet. Some researchers have presented methods to compute the flow velocities behind moving boats.

Fuehrer, Römisch & Engelke (1981) presented a method in which the advance coefficient J plays a role:

$$J = \frac{V_s}{nD_p} \tag{2.28}$$

$$V_{b,\max} = V_{b,\max,J=0}\left(1-J\right) \tag{2.29}$$

$$V_{b,\max,J=0} = E\left(\frac{z_p}{D_p}\right)^{-1.0} V_0\left(1-J\right) \tag{2.30}$$

with E = 0.71 for boats with a fine stern shape with a central rudder;
E = 0.25 for inland vessels with a tunnel stern and a twin rudder configuration.

Where:
V_s = boat speed (m/s)
$V_{b,max}$ = maximum flow velocity in the propeller jet at bed level (m/s)

Fuehrer & Römisch (1977) simplify equation 2.12 to:

$$V_0 = 0.95nD_p \tag{2.31}$$

As the advance coefficient very often cannot be determined with eq.(2.28), because n or D_p is unknown, equation 2.31 gives a solution:

$$J = \frac{V_s}{V_o/0.95} \tag{2.32}$$

However, the coefficient 0.95 is based on a thrust coefficient of about 0.4 which holds for V_s = 0 m/s. For moving boats (V_s > 0 m/s) the value of 0.4 decreases and, subsequently, the value of 0.95. Moreover, the value of will probably change.

Verheij (1983) presented a method for determining the flow velocity in the propeller jet behind a moving boat in which also the wake behind the boat is taken into account as well:

$$V_{0,moving} = \sqrt{V_a^2 + V_{0,manoeuvring}^2} \tag{2.33}$$

$$V_a = \left(V + u_r\right)\left(1 - w\right) \tag{2.34}$$

where
V_a = wake velocity (m/s)
w = wake coefficient; w = 0.3 to 0.5 (-)
u_r = average return flow velocity (m/s)

The Verheij method is pretty complicated and the uncertainty in the results is large.

In general, these methods reduce the flow velocities with a factor related to (1 – J).

Finally, other methods simply reduce the flow velocities in the jet with half of the boat speed.

influence of the rudder

The influence of the rudder on the flow field has been shown by various researchers, for instance by Fuehrer, Römisch & Engelke (1981); see equation (2.13). In essence, the rudder acts as an obstacle to the propeller jet, however due to the rotational nature of the jet, the rudder also acts as a lifting surface. The jet splits into two different jets, one directed towards the free surface and the other directed towards the canal bottom which after hitting the bottom changes into a wall jet (see Figure 2.5).

In general, the presence of the rudder does not influence the flow velocities, although Hamill et al (1998) reported a 30% increase compared to the situation without a rudder.
Hamill & Johnston (1993) reported also that the axial component is 10 times any other component, i.e. radial and tangential velocities. Thus, the rudder has a straightening effect on a propeller jet, and reduces the radial velocities significantly.
Hamill, Garvey & Hughes (2001) show clearly that the presence and operation of a rudder does not result in any significant differences in the values of the efflux velocities for rudder angles up to 35 degrees.

Hamill et al (1998) present an equation with the rudder angle θ (in degrees) included:

$$R_{\sigma z} = -0.8 R_{m0} - \left(-0.322 + 0.0012\theta\right) x \tag{2.35}$$

However, behind the rudder the flow field is affected by the rudder. Hamill & Garvey (1996)(1998) presented equations for the location of the maximum jet velocities as well as an equation to calculate the flow velocity in the propeller axis.
According to Verheij (1983) a rudder effect can be accounted for by a reduction factor, for instance 25% reduction for a rudder angle of 30 degrees.

discharge, shear stresses and turbulence

Maynord (1999) presents an equation to compute the total discharge due to the propeller:

$$Q_0 = \frac{C_3 \left(\frac{P_D}{\rho D_p^2} \right)^{1/3} \pi D_p^2}{4z} \qquad (2.36)$$

where
z = factor for type of propeller (-); z = 2 free propeller, z = 1 propeller with a nozzle

Maynord states that for moving boats ($V_s \neq 0$) the discharge Q is at most about 10% larger compared to manoeuvring boats. Substituting $D_p = 1.4D_0$, z = 2 and $C_3 = 1.48$ for a free propeller or $D_p = 1.0D_0$, z = 1 and $C_3 = 1.17$ for a nozzled propeller the equation reads:

$$Q_0 = 0.29 \left(\frac{P_D}{\rho D_0^2} \right)^{1/3} \pi D_0^2 \qquad (2.37)$$

An identical result can be obtained with eq.(2.27) and $Q_0 = v_0 A = 0.25\, v_0 \pi D_0$.

Admiraal et al (1999) present results of laboratory experiments carried out at the Waterways Experiment Station of the US Corps of Engineers at Vicksburg, USA, with US push-tow barges for Mississippi conditions on a scale 1:25 (prototype water depths between 3.4 m and 7.0 m). In Figure 2.3 an example of measured shear stresses are shown. Observed maximum characteristic values for the propeller jet in the model (translated to prototype conditions):

$\tau < 125$ N/m^2
$d\tau/dt < 30$ Pa/s

It should be noted that the shear stress induced by the propeller jet are about 5 times higher than those induced by the return current.

Dargahi (2003) computed the shear stress at the bottom with the equation:

$$\tau = c\rho_w \left(u_h + 3\sigma_u \right)^2 \qquad (2.38)$$

where:
σ_u = standard deviation of the average flow velocity which is a measure for the turbulence (m/s)

With c = 0.015 the results fit well with computed results (Figure 2.7). However, it is believed that Dargahi did not include rotational effects in his model.
Verheij (1983) proposes a factor c = 0.08, but with an extra factor of 0.5:

$$\tau = 0.5 c \rho_w \left(u_b + 3\sigma_u\right)^2 \tag{2.39}$$

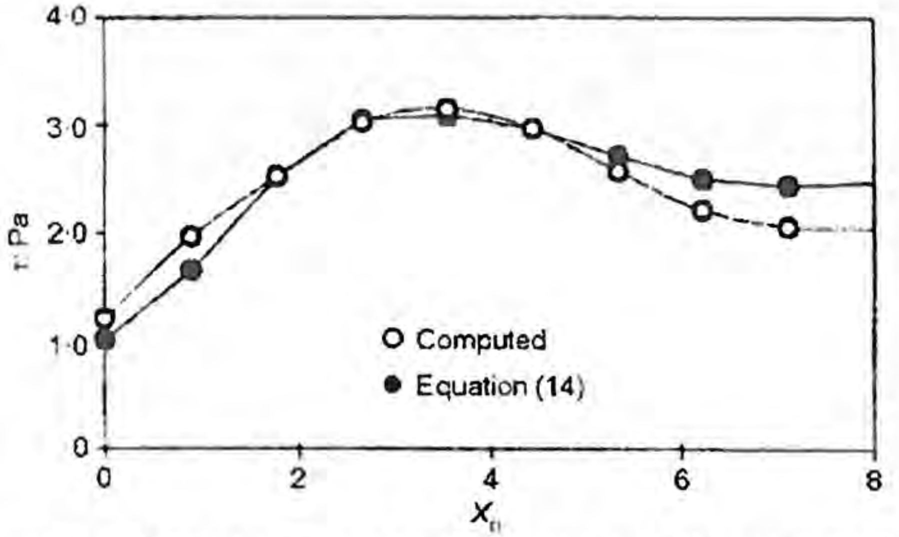

Figure 2.7 Wall shear stress at y = 0 (Dargahi, 2003); note: equation (14) = equation (2.38)

Blaauw & Van de Kaa (1978) and Dargahi (2003) presented results on turbulence in the propeller jet (Figures 2.8 and 2.9 respectively). Relative turbulence intensities up to 40% have been measured. This means maximum flow velocities of about two times the average flow velocities.
Note that Dargahi computed equal intensities compared to Blaauw & Van de Kaa for z = 0 but much lower values at the bed.

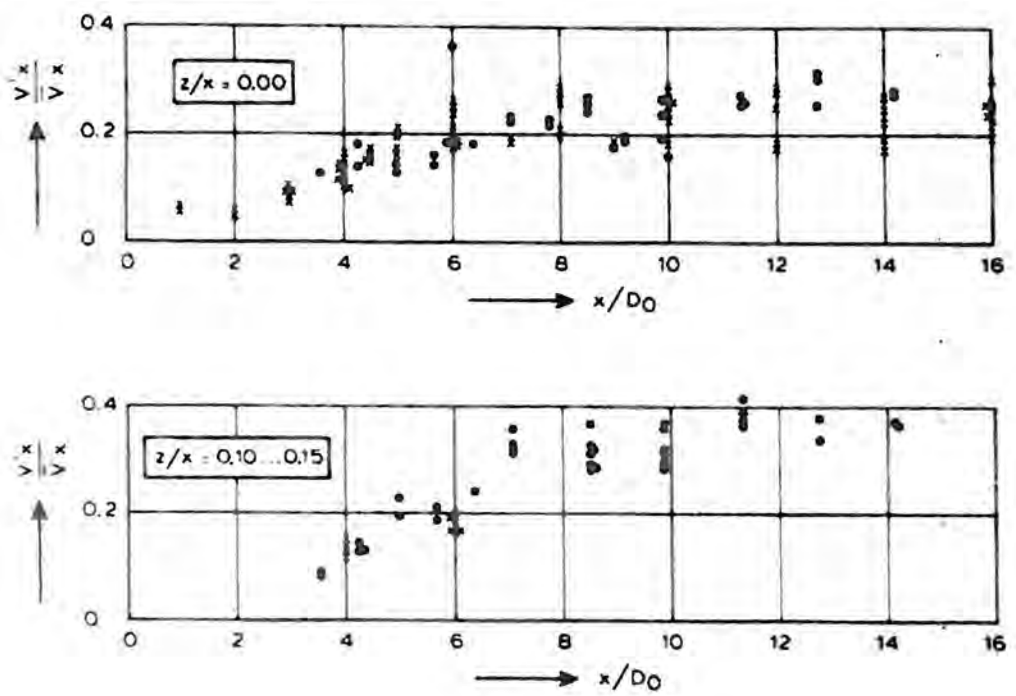

Figure 2.8 Relative turbulence intensity (Blaauw & van de Kaa, 1978)

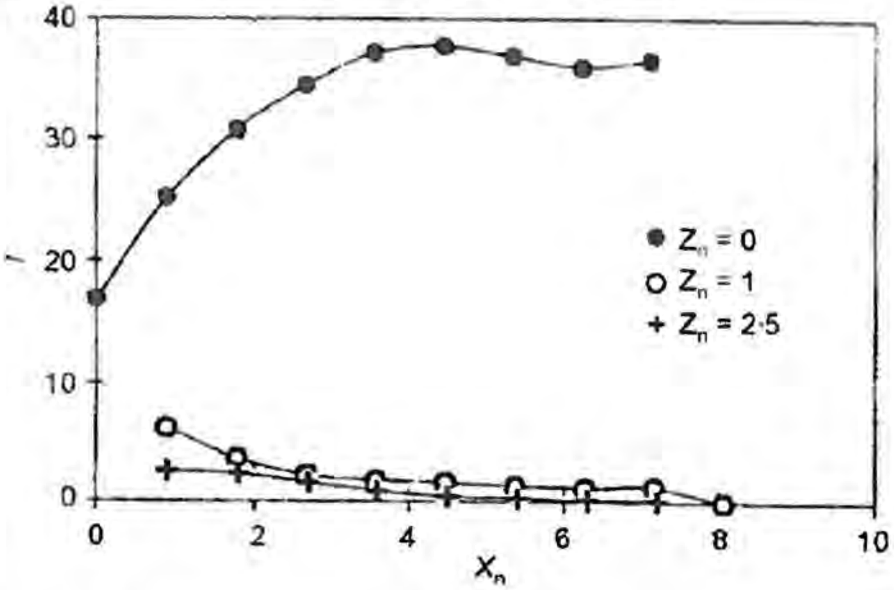

Figure 2.9 Relative streamwise turbulence intensities (Dargahi, 2003)

Maynord (1990) presented the pressures induced by a jet produced by push-tow units, but he also mentions suction at the bed in front of the propeller.

All research mentioned above aimed at commercial ships. As mentioned before, OSTEC carried out tests with a narrow boat for British Waterways in order to find improvements with respect to hull shape and propulsion system to reduce the induced water motions (1985)(1988). The results are summarized by Hames (1989) as far as they concern the small-scale tests and in OSTEC (1991) results of full scale tests are reported. A significant improvement with respect to induced pressures can be obtained by a shrouded propeller, where the shroud is constructed around the existing propeller. The pressures reduce by 50% compared to a narrow boat with a free propeller for a 2 m/s boat speed:

OSTEC shrouded propeller	0.75 kN/m^2
Traditional narrow boat	1.50 kN/m^2

Hames mentions maximum pressure differences of 1.0 psi which is 6.895 kN/m^2. However, these values are full scale predictions from model results.
It should be noted that the pressures presented by Hames are much larger than the results presented by Dargahi and Maynord (taking also into account that pressures are about 2 to 3 times larger than shear stresses). The reason of this different result is not known.

Other types, such as outboard engines and hydro jets are not considered. The propellers of outboard engines mostly are below the keel level. Hydro jets induce very high flow velocities which are directed to the canal bed.

Finally, in Figure 2.10 the relationships between different parameters in a canal are shown. In principle, the parameters can be expressed in each other.

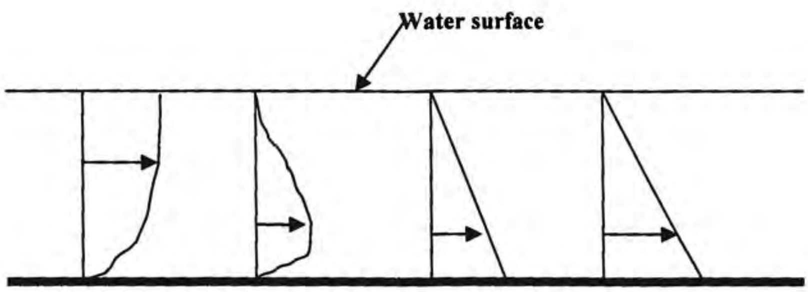

Figure 2.10 Relationships between different parameters in a flow

Direct impacts of the propeller

Propeller scars cause tremendous damage to SAV beds (SAV = Submerged Aquatic Vegetation). The damage occurs when boats sail in shallow water where the propeller might come in contact with the vegetation. The contact might destroy the blades, but can also tear up the rhizome system. In particular, outboard systems where the propeller is located mostly below the keel, endanger SAV's more than inboard systems.
In Figure 2.11 the sailed track route of a recreational craft can be deduced from the damage to SAV bed.

Figure 2.11 Propeller scars on SAV beds (Turner et al, 2005)

2.4 Numerical and small-scale physical modelling

Propeller jets

Amongst others, Hamill et al (1993) and Dargahi (2003) presented results of numerical computations of propeller jet velocities. In principle, numerical computations are possible nowadays, however with respect to propeller jets it is essential that the rotational and tangential components are included. Also the influence of the rudder and the presence of the canal bottom should be taken into account. At the moment research on these aspects is going on at Delft University of Technology.

However, the literature considered did not reveal an overall model including all aspects. Moreover, the models should be calibrated and verified thoroughly.

With respect to small-scale modelling various researchers have shown that accurate results can be obtained. WL | DELFT HYDRAULICS has carried out earlier tests to propeller jet induced flow velocities (Blaauw & Van de Kaa, 1978) Verheij (1983), showing its capability to do this type of research.
It is essential to use a real propeller with a rudder.

Primary ship induced water motions

The ship induced water motions along side a ship can be modelled very well with modern CFD tools. Thus, the average and local return current velocities and water level depressions next to the ship can be computed very accurate. However, flow velocities and pressure fluctuations underneath the ship are more difficult, due to the boundary layers near the bottom of the canal and near the ship. In particular, in conditions with small keel clearances the flow conditions can not be predicted at the moment.
It is also difficult to model the breaking wave.

Therefore, WL | DELFT HYDRAULICS still carries out tests in its unique experimental facilities that include a variety of flumes as well as wave, current and tidal basins. Considering the Montgomery Canal and narrow boats, physical tests with respect to water motions may be carried out in the structures facility (indicated as Flume 4; see www.wldelft.nl). This flume is provided with a zigzag-weir for a fast and accurate steering of the water levels and for the elimination of possible translatory waves. Moreover, it is possible to tow model ships with a maximum (model) speed of 0.5 m/s. The flume characteristic dimensions are: length = 30 m, width = 5 m, maximum water depth = 1.0 m, maximum discharge = 1 m^3/s.

A disadvantage of small-scale modelling is the cost of building a model ship.

2.5 Conclusions

The literature survey has resulted in information on:

- Available formulas to estimate the flow velocities in the return current underneath the keel and in the propeller jet behind the boat;
- Measured shear stresses and pressure differences due to return current and propeller jet;

- Turbulence intensities in the propeller jet;

These results may help to determine the conditions in the Montgomery Canal. Very important in this respect are the results of the OSTEC studies, because these studies are the only known research related to narrow boats.

No information has been found on direct contacts between the boat's hull or propeller and the aquatic vegetation.

3 Review of case studies on boat management

3.1 General

Navigation will sometimes have a negative influence on nature conservation. Appropriate counter measures may reduce such influences, such as boat speed limits, reduced numbers of boat passages, or increased passing distances of protected zones.
The experiences at other canals with boat management have been examined. Therefore, relevant case studies have been collected. Recreational authorities have been asked to explain their boat management policy, for instance, to prohibit mooring in reed zones.
Some information on boat management has been published by working group 12 of the Recreational Navigation Commission of PIANC in its report "Recreational Navigation and Nature" (PIANC, 2002).

3.2 Findings on boat management

Authorities in the Netherlands have been contacted by telephone and asked to explain their boat management policy. The findings have been summarized below.
Originally, it was the idea to e-mail an inquiry to the authorities but it was expected that the response would be minimal due to the summer holidays and earlier experiences with an inquiry by e-mail to harbour authorities. An inquiry by telephone was expected to give better results. The e-mail questions are summarized below; not all of them were discussed during the telephone inquiry.

Inquiry questions

SHIP TYPES
- Give description of boat types: small motor cabins, canoes, et cetera
- Inboard or outboard propulsion system
- Dimensions of the recreational yachts

CANAL CHARACTERISTICS
- Depth and width at water surface
- Profile: rectangular or trapezoidal
- Protected or unprotected bank; type of protection

VEGETATION (IN PARTICULAR AQUATIC)
- Type of vegetation: bank zone or related to bed
- Species
- Damage due to navigation (direct by propeller or grounding or indirect by water motions)

- Recovery of the vegetation after damage

BOAT MANAGEMENT
- Navigation intensity; related to weekends ? summer months ?
- Any restriction of the number of yachts
- Speed limits ?
- Are some canal sections not accessible ? or during some part of the year ?
- Do you have regulations ?
- How do you inform people ?

Findings of telephone inquiry

Recreational authorities, nature conservation organizations and provincial governments in the Netherlands have been contacted and their experiences with boat management have been discussed. Important organizations were:

- Natuurmonumenten
- Staatsbosbeheer, in particular Nieuwkoopse Plassen
- Natural Park De Biesbosch
- De Marrekrite
- Natural Park De Weerribben
- Provinces Friesland, Brabant and Zuidholland

Boat management in the Netherlands deals with: speed limit, access to vulnerable small canals, berthing options, control of behaviour, and information and education. All aspects are described in rules and regulations of local authorities responsible for the management of the area, provincial laws with respect to recreational navigation, and regulations for the whole country.

Speed limits

In general, there is no speed limit, except (i) that it is not allowed to induce water motions that may endanger other ships, or cause damage to banks, and (ii) that for some vulnerable small waterways, to be mentioned in provincial laws, a speed limit of 6 km/h exist. The speed limit is not related to damage to aquatic vegetation, but to marginal vegetation at the banks. Aquatic vegetation hardly plays a role, because most canal bottoms consist of mud and because the maintenance of sufficient depth requires regular dredging.

The speed limit of 6 km/h applies for the whole country. This rule is written down along with many other navigational rules in the BPR (police regulations for inland waterways). Provincial and local authorities do not play a role, other than to select/specify the waterways for which they want a speed limit, and to provide a basis for maintaining this policy[1].

Access to small waterways

[1] Note: the official speed limit on UK canals is 4 mph, but 3 mph is a more common speed in practice. On the southern length of the England section of the Montgomery Canal an advisory speed limit of 2 mph exists.

Provincial and local authorities determine the access to waterways. Three different levels can be distinguished:

1. access allowed for ships sailing less than 6 km/h;
2. access prohibited for motorized ships, but not for canoes, rowing boats, etcetera;
3. access prohibited for all ship types.

The Water Almanac specifies which situation is applicable for a particular waterway. Moreover, at the entrance it is shown on displays. In nature reserves waterways are sometimes also blocked by a floating beam to prevent ships from sailing into the waterways. No information has been collected about seasonal waterways closures.

Berths

Most of the regulations deal with berths in order to prevent undesired berthing, for instance in reed banks (Duyve, 1986). Local authorities have created many berthing sometimes including temporary toilet facilities, waste disposal, etcetera.

Control of regulations

The (water) police and provincial officers have a task in controlling the behaviour of the public. They have the possibility to give a penalty. Personnel of local authorities do not have this option, they can only ask the public to obey the regulations.
In general, the authorities are satisfied with the behaviour of the public. However, they emphasize it is necessary to bring the rules under the public's attention regularly.

Information and education

The rules and regulations are published in brochures and on displays at the entrances of recreational areas. People hiring a ship or canoe receive a brochure along with the hiring contract.

Summarizing: boat management in the Netherlands is mainly focused on berthing facilities, however for some waterways rules and regulations exist about maximum boat speed and accessibility but these restrictions are related to marginal vegetation at the banks and not to aquatic vegetation on the canal bottom.

4 Interpretation and application

4.1 Introduction

The present state-of-the-art with respect to ship-induced water motions has been summarized as well as the knowledge on boat management in recreational areas. In this chapter the results will be translated to the Montgomery Canal. First, the water motions will be calculated for narrow boats in small canals under various conditions. Second, the results will be interpreted taking into account the experiences with boat management elsewhere.
The integrated results should enable advice to be given on optimising boat design, channel design and/or boat management, in particular minimum sailing distances or limited boat speed. In this respect also some attention has been paid to the following aspects:

- Water depth: is there an optimum depth, which reduces effects of boat traffic on turbidity and physical stresses (related to natural light penetration)?
- Channel profile: benefits for aquatic communities can be affected by reviewing the standard trapezoidal section with the following potential ideas: steeper sides, to maximise aquatic area and minimise marginal zone; ledges on channel off-side that are deep enough for aquatic plants, but too shallow for boats.

4.2 Water motions due to narrow boats

Two phenomena are responsible for high flow velocities, turbulence and pressure changes near the bed:

- Return current or displacement flow underneath the hull.
- Propeller jet behind the ship.

As a consequence bed material may be brought into suspension, increasing the turbidity, and the current may cause the uprooting of biomass of the aquatic vegetation. The two phenomena will be discussed below. In addition, pressure changes and direct contacts with the ship or the ship propeller are dealed with.

Return current or displacement flow

The flow velocities in the return current underneath the hull amidships are a function of the mean return flow velocities according to the one-dimensional method of Schijf[2]. In order to compute the flow velocities, ships and canal cross-sections have to be defined. The following narrow boats have been selected:

N1: 0.91 m draught (maximum draught mentioned in PIANC, 2000)
N2: 0.80 m draught (draught mentioned by Hames, 1989)

[2] *see Chapter 2: eq.(2.1) to (2.3) and eq.(2.5).*

N3: 0.65 m draught (average draught mentioned by British Waterways)

The length and beam for the narrow boats are: 15 m length x 2.13 m beam.

In Table 4.1 an overview of the ship characteristics is presented.

Table 4.1 Principal dimensions for narrow boats

Ship type	Name	Dimensions	cross-sectional area
narrow boat	N1	15 x 2.13 x 0.91 m^3	1.938 m^2
narrow boat	N2	15 x 2.13 x 0.80 m^3	1.704 m^2
narrow boat	N3	15 x 2.13 x 0.65 m^3	1.385 m^2

Regarding the canal cross-sections PIANC (2000) presented guidelines for small waterways for recreational purposes:

- Water depth $h \geq 1.2$ times draft T;
- Bed width $b_b \geq 2.8$ times beam B (assuming the meeting of two ships);
- Canal cross-section $A_C \geq 5.5$ times midship cross-section A_M

Note that for a rectangular canal profile the width and depth requirements result in a smaller canal cross-section than the separate requirement for A_C.

For commercial ships the following dimensions are advised:

- $h/T \geq 1.4$ normal profile (or 1.3 small profile);
- $b_T/B \geq 4$ (or 3);
- $b_b/B \geq 2$ (or 2);
- in addition: $A_c/A_M \geq 7$ (minimum 5).

(b_T = canal width at the level of a boats maximum draught)

In Table 4.2 canals are defined based on the guidelines for recreational boats.

Table 4.2 Required minimum canal dimensions based on the narrow boats

Ship type	Water depth	Surface width	cross-sectional area
N1	1.092 m	5.964 m	10.66 m^2
N2	0.960 m	5.964 m	9.37 m^2
N3	0.780 m	5.964 m	7.62 m^2

However, these canals are not realistic and based on desired dimensions in Table 4.3 more realistic canals are defined.

Table 4.3 Selected canals with the relevant dimensions

Canal	type	water depth	Surface width	Cross-section
C1	Rectangular	1.0 m	8.0 m	8.00 m^2
C2	(Slope m = 0)		10.0 m	10.00 m^2

C3			12.0 m	12.00 m^2
C4 C5 C6	Rectangular (Slope m = 0)	1.2 m	8.0 m 10.0 m 12.0 m	9.60 m^2 12.00 m^2 14.40 m^2
C7 C8 C9	Rectangular (Slope m = 0)	1.5 m	8.0 m 10.0 m 12.0 m	12.00 m^2 15.00 m^2 18.00 m^2
C10 C11 C12	Trapezoidal (Slope m = 2)	1.0 m	10.0 m 12.0 m 15.0 m	8.00 m^2 10.00 m^2 13.00 m^2
C13 C14 C15	Trapezoidal (Slope m = 2)	1.2 m	10.0 m 12.0 m 15.0 m	9.12 m^2 11.52 m^2 15.12 m^2
C16 C17 C18	Trapezoidal (Slope m = 2)	1.5 m	10.0 m 12.0 m 15.0 m	10.50 m^2 13.50 m^2 18.00 m^2

Note: $A_c = bh - mh^2$

For boat speeds of 0.5 m/s, 1.0 m/s and 1.5 m/s the mean return flow u_r and the average squat z (assumed to be equal to the average water level depression dh) has been computed for the 18 canals and 3 narrow boats.
However, a limiting condition is that the ship speed will not exceed 0.7 times the critical ship speed. In the annex for each combination the limit speed V_c and the maximum 0.7 times V_c are shown.
Note: In British canals the allowed maximum speed is 4 mph, whereas the theoretical maximum speed of narrow boats is believed to be about 3.6 mph.
The average speed is about 3 mph or 1.35 m/s (based on a mile of 1609 m, although a nautical mile of 1852 m is an alternative).

In the Annex A the average return flow velocities and the under hull bow velocities (twice the return flow velocity) are presented. The under hull bow velocities are the maximum flow velocities below a moving boat, whereas the return flow velocities are the average values of flow velocities passing below and to the sides of the moving boats.
In the annex also the average water level depression or squat z in m is presented. As can be seen the average squat is always less than 0.10 m, however, at the stern the squat might be more than the figures mentioned in the table.

In the next Figures some results regarding the flow velocities are shown. More results are presented in Annex B.

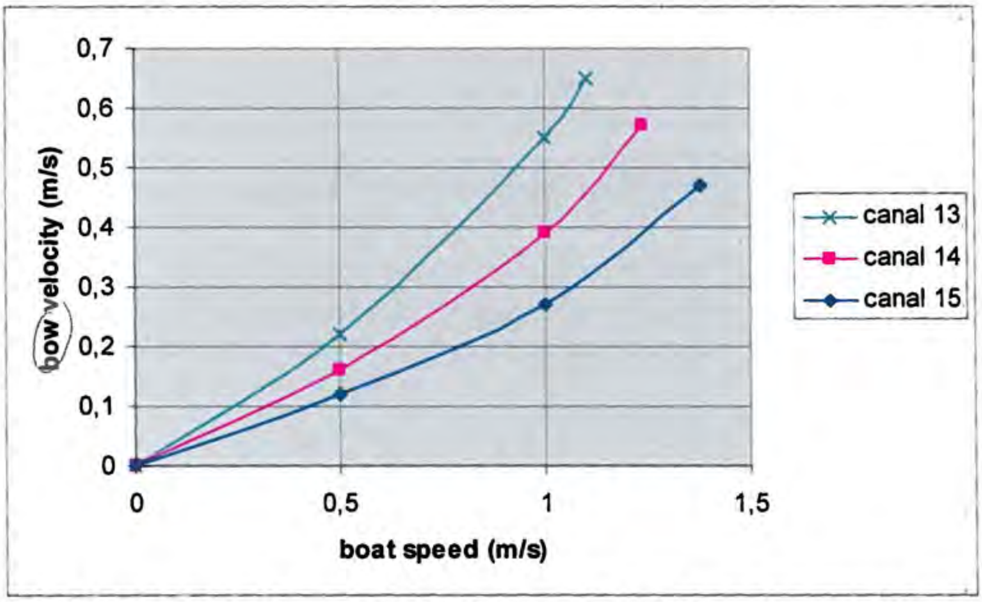

Figure 4.1 Narrow boat N2: Influence surface width for a water depth of 1.2 m

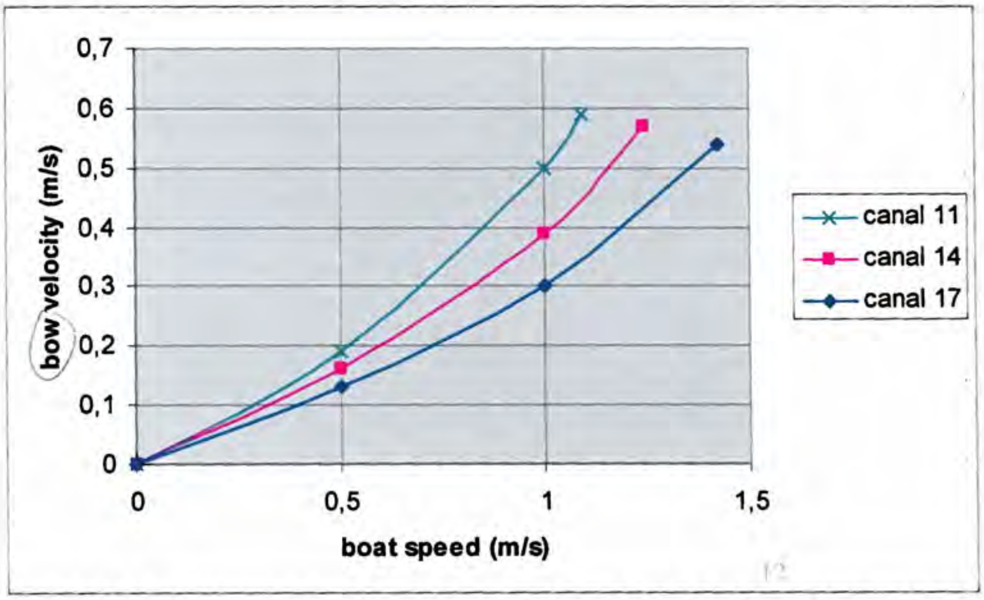

Figure 4.2 Influence water depth h for a surface width b of 10 m for narrow boat N2

conclusions

The flow velocities underneath the bow for conditions in accordance with the PIANC recommendations are:

$V_s = 0.5$ m/s: $U_{bow} < 0.30$ m/s
$V_s = 1.0$ m/s: $U_{bow} < 0.45$ m/s
$V_s = \max$ m/s: $U_{bow} < 0.60$ m/s

For smaller canals maximum flow velocities can be expected up to 0.8 m/s.

Regarding the flow velocities next to a sailing ship values can be expected of:

$V_s = 0.5$ m/s: $U_{bow} < 0.15$ m/s
$V_s = 1.0$ m/s: $U_{bow} < 0.25$ m/s
$V_s = $ max m/s: $U_{bow} < 0.30$ m/s

These flow velocities are 0.5 times the bow velocities and equal to the average return flow velocity.
In principal, these velocities will hardly affect material of the canal bed. Whether or not they will cause uprooting of biomass is outside the remit of this study.

It can be concluded that the flow velocities in a trapezoidal canal are about 10 to 20 % larger than in a rectangular canal.

Maynord (1990) proposes equation 2.4 to compute the return current underneath the ship. However, this equation cannot be applied because the conditions are not fulfilled ($h/T < 1.6$).

Propeller jet

In section 2.3 many methods and many equations are presented to calculate the flow velocities in the propeller jet. In this Section the method according to Verheij will be applied[3].
The method according to Hamill will not be applied because there is uncertainty about the value of the exponents (different values are mentioned in the available papers). However, results will be presented taking into account the influence of the hub[4].

For moving ships the flow velocity will be reduced by 50% of the ship's speed, but also by a factor $(1\text{-}J)^5$.
The actual value of J will be less, because the thrust coefficient K_T decreases with the speed for moving ships and thus the factor 0.95 decreases compared to manoeuvring ships.

These results will be compared with results according to the Führer & Römisch (1977) method[6] with $E = 0.71$ for ships with a fine stern shape with a central rudder.

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[3] *equations (2.15), (2.16) and (2.27)*

[4] $R_{m0} = 0.67 R_p - R_h$

[5] $J = \dfrac{V}{V_o / 0.95}$

[6] *equations (2.29) and (2.30)*

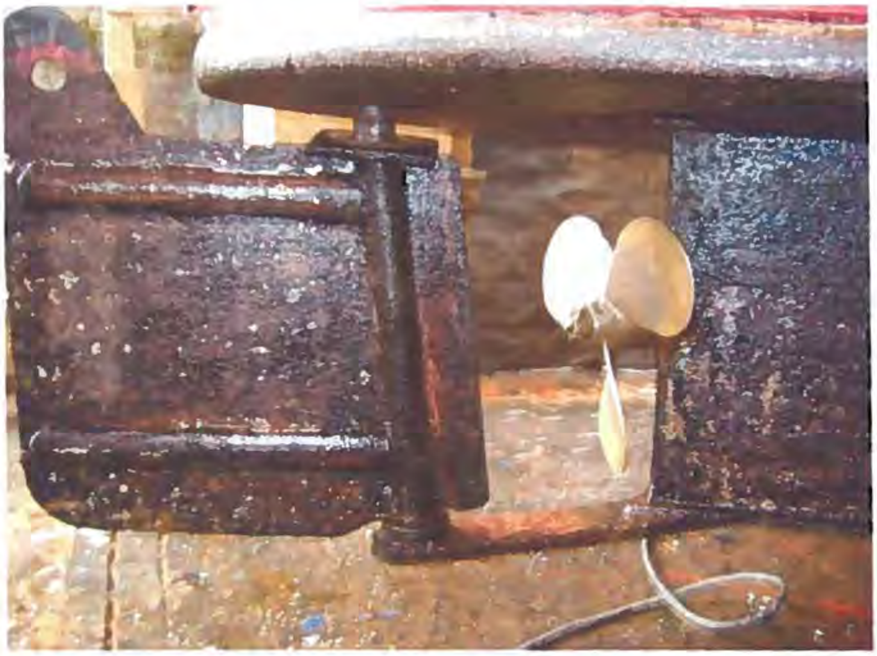

Figure 4.3 Narrow boat with propeller and rudder configuration

The British Waterways provided the following data on propellers

Diameter: average $D_p = 0.22$ to 0.24 m (range: 0.20 to 0.35 m)
Distance between blade tip and keel : 0.10 m (sometimes 0.05 m)

Hames (1989) presented a value of 0.30 m used in the OSTEC model tests.

No information was available on the hub diameter and the engine power. Estimated values are:

Hub diameter	0.05 m
Installed engine power	5 to 10 kW

Applying these values the flow velocities in the propeller jet have been determined for a propeller diameter of 0.25 m. First, the efflux velocity V_0 has been determined with equation 2.27:

$P = 5$ kW: $V_0 = 6.3$ m/s
$P = 10$ kW: $V_0 = 7.9$ m/s

As the installed engine power is not known an average efflux velocity is assumed of 7.0 m/s for the further calculations.

Table 4.4 Flow velocities in the propeller jet behind a ship

ship	Water depth h = 1.0 m				Water depth h = 1.2 m				Water depth h = 1.5 m			
	Ship speed (m/s)				Ship speed (m/s)				Ship speed (m/s)			
	0	0.5	1.0	max	0	0.5	1.0	max	0	0.5	1.0	max
N1	1.39	1.14	0.89	-	0.79	0.54	0.29	0.27	0.48	0.23	0	0
N2	0.98	0.73	0.48	-	0.64	0.39	0.14	0.09	0.42	0.17	0	0
N3	0.70	0.45	0.20	0.12	0.51	0.26	0.01	0	0.36	0.11	0	0

In Figure 4.4 the flow velocities for narrow boat N2 are presented. For the other boats the velocities are presented in Appendix B.

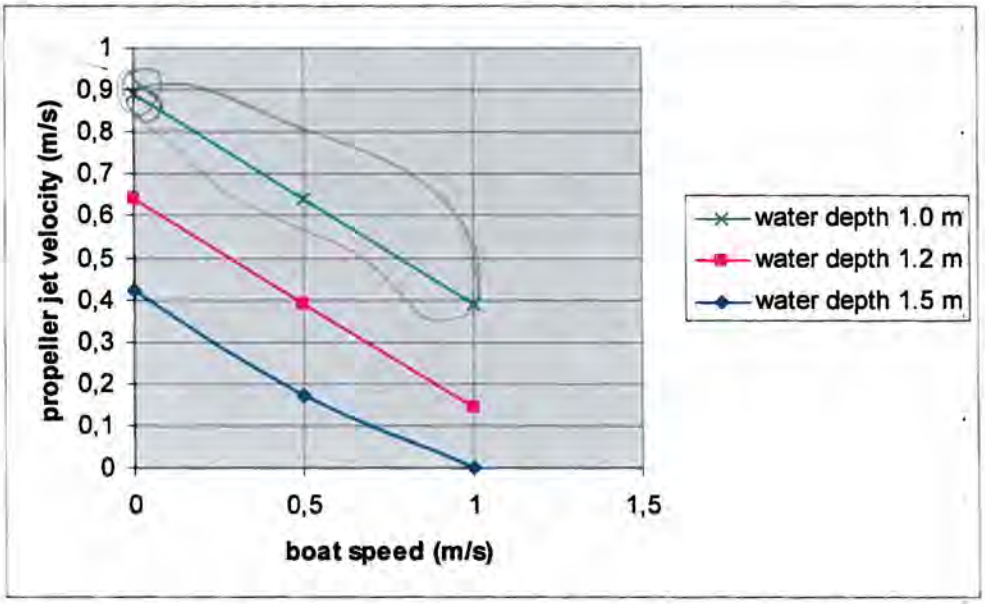

Figure 4.4 Flow velocities at the canal bed in the propeller jet of narrow boat N2 (draft 0.80 m)

It can be concluded based on the above results that flow velocities up to 1 m/s (exclusive N1) are possible for manoeuvring narrow boats and in the range up to 0.75 m/s for sailing boats.

However, the above results do not take into account the jet deflection towards the canal bed. Results taking into account these deflection are presented in Table 4.5. The presented flow velocities are the flow velocities in the jet axis computed with equation 2.15.

Table 4.5 Flow velocities in the propeller jet behind a moving boat taking into account the jet deflection

	T = 0.65 m and h = 0.80 m (x = 1.53 m)		T = 0.65 m and h = 0.95 m (x = 2.24 m)	
	V_s = 0.5 m/s	V_s = 1.0 m/s	V_s = 0.5 m/s	V_s = 1.0 m/s
$V_{moving} = V_{man} - 0.5\ V_s$	1.99 m/s	1.74 m/s	1.28 m/s	1.03 m/s
Hamill with eq.(2.23)	2.50 m/s	2.25 m/s	1.50 m/s	1.25 m/s
V_{moving} with eq.(2.30)	3.56 m/s	3.30 m/s	2.44 m/s	2.27 m/s

The flow velocities in Table 4.5 are much higher than those in Table 4.4. It is believed that these flow velocities are not realistic, because in case of a moving ship the return flow underneath the keel will not allow the propeller jet to deflect to the bed. On the contrary, the jet will be pushed upwards.
Obviously, blocking the jet in the direction of the bed, for instance with a horizontal apron below propeller and rudder will reduce the flow velocities.

Finally, the flow velocities at the bed underneath the bow and in the propeller jet of a narrow boat N2 (draught 0.80 m) sailing in a trapezoidal canal are presented for surface widths 10 m, 12 m and 15 m in Figure 4.5.

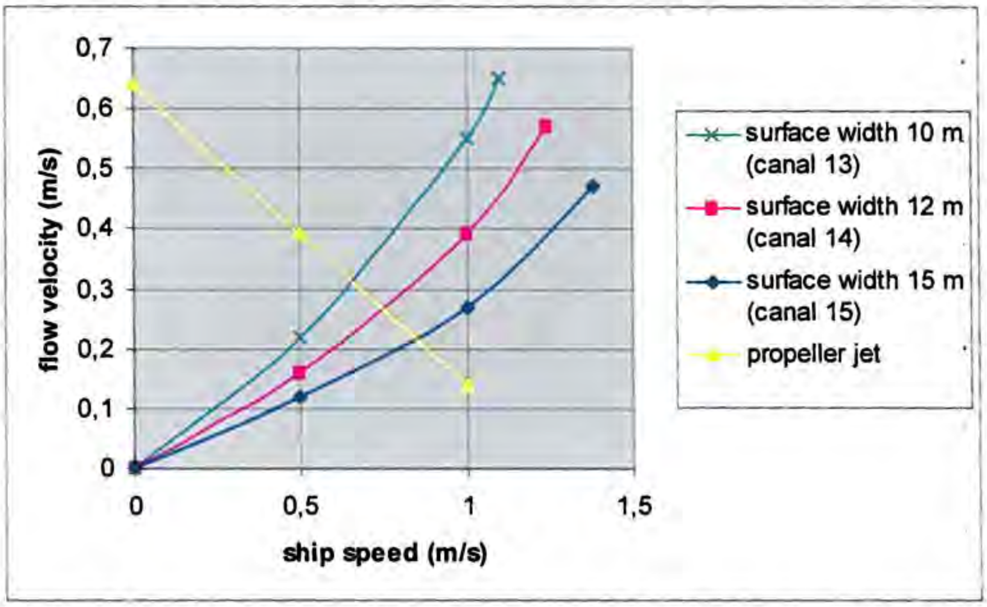

Figure 4.5 Flow velocities at the canal bed underneath the bow and in the propeller jet of narrow boat N2 (draught 0.80 m)

In Figure 4.6 is, as an example, the flow distribution for boat N2 in canal C13 presented for a boat speed of 1.0 m/s (other results are presented in Appendix C). The duration of the flow velocities can be easily determined by dividing a particular distance by the boat speed.

	Y-distance from boat centerline [m]					
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50
0.00	.00	.00	.00	.00	.00	.00
1.00	.55	.55	.55	.27	.27	.27
2.00	.55	.55	.55	.27	.27	.27
3.00	.55	.55	.55	.27	.27	.27
4.00	.27	.27	.27	.27	.27	.27
5.00	.27	.27	.27	.27	.27	.27
6.00	.27	.27	.27	.27	.27	.27
7.00	.27	.27	.27	.27	.27	.27
8.00	.27	.27	.27	.27	.27	.27
9.00	.27	.27	.27	.27	.27	.27
10.00	.27	.27	.27	.27	.27	.27
11.00	.27	.27	.27	.27	.27	.27

12.00	.27	.27	.27	.27	.27	.27
13.00	.27	.27	.27	.27	.27	.27
14.00	.27	.27	.27	.27	.27	.27
15.00	.27	.27	.27	.27	.27	.27
16.00	.00	.00	.00	.00	.00	.00
17.00	.00	.00	.00			
18.00	.14	.00	.00	.00		
19.00	.12	.00	.00	.00	.00	
20.00	.05	.00	.00	.00	.00	.00
21.00	.00	.00	.00	.00	.00	.00
22.00	.00	.00	.00	.00	.00	.00
23.00	.00	.00	.00	.00	.00	.00
24.00	.00	.00	.00	.00	.00	.00
25.00	.00	.00	.00	.00	.00	.00

Figure 4.6 Distribution flow velocities over the canal width for boat N2 with a boat speed of 1.0 m/s in canal C13 (depth 1.2 m, width 10 m and slope 1:2)

Based on the flow distributions the flow velocities over the canal cross-section at a certain location are be derived. For boat speeds of 0,5 m/s and 1.0 m/s the results are shown in Figures 4.7 and 4.8 for a cross-section about 2 m behind the boats bow. Similar figures can be mad using the flow distributions in Appendix C.

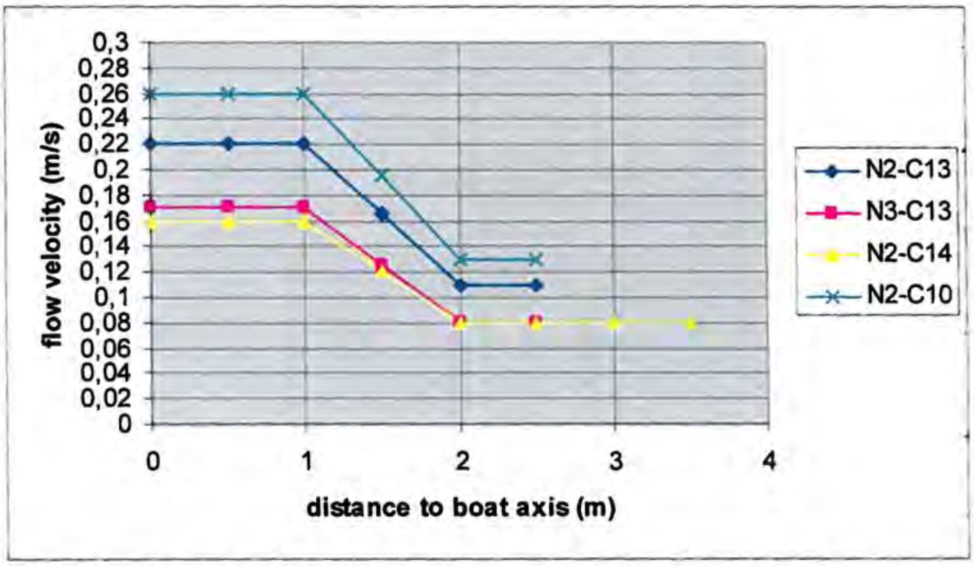

Figure 4.7 Flow velocities in a cross-section at 2 m from the bow for $V_s = 0.5$ m/s

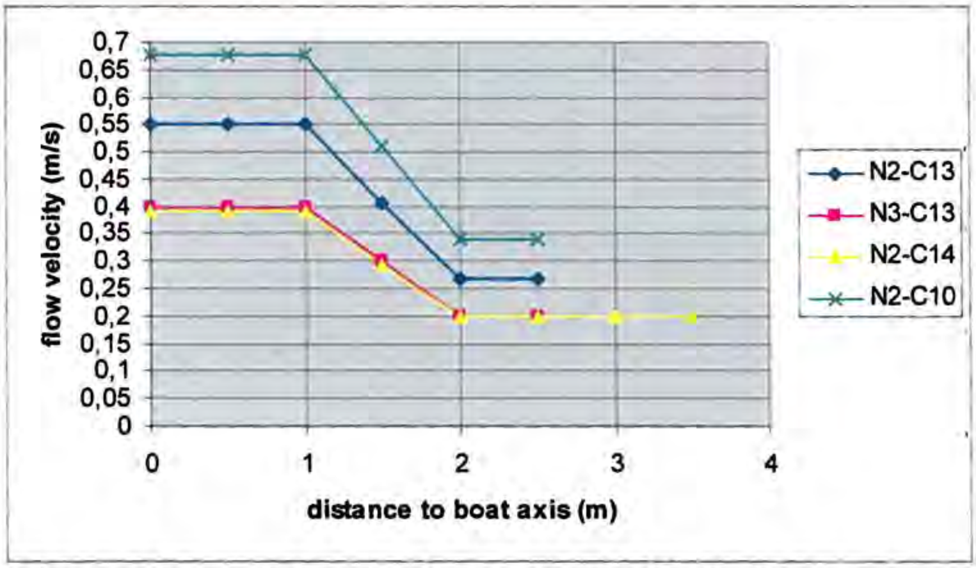

Figure 4.8 Flow velocities in a cross-section at 2 m from the bow for $V_s = 1.0$ m/s

Pressure changes and shear stresses

Different sources have published data on induced pressures and shear stresses by propeller jets:

Admiraal:	$\tau_{max} < 125$ N/m^2 and $d\tau_{max}/dt < 30$ Pa/s	
Dargahi:	$\tau_{max} = 3$ N/m^2	
OSTEC:	shrouded propeller	dp = 0.75 kN/m^2
	traditional narrow boat	dp = 1.50 kN/m^2
Hames:	model tests narrow boat	dp = 6.895 kN/m^2

Note: the shear stresses induced by the propeller jet are about 5 times higher than those induced by the return current.

The shear stresses can be calculated with equation (2.39)[7]. Verheij (1983) proposes a factor c = 0.08 whereas Dargahi proposes c = 0.015 with a coefficient equal to 1.0.
Substituting a flow velocity of 1.0 m/s and a relative turbulence of 40% the shear stress becomes: 195 N/m^2 according to Verheij and 36 N/m^2 according to Dargahi. The value of 195 N/m^2 is larger than measured by Admiraal, but the distance between propeller and bed is also much smaller. Dargahi computed less turbulence close to the bed, and then the shear stress reduces to about 10 N/m^2.

The pressure differences as measured by OSTEC for full scale tests are much larger than the shear stresses, whereas the presented data by Hames (upgraded model results) are very large. The reason for the difference between shear stresses and pressure differences are not clear.

[7] $\tau = 0.5 c \rho_w (u_b + 3\sigma_u)^2$

Obviously, the shear stresses and pressure differences will endanger the stability of bed material, i.e. bed material will erode, and probably also biomass will be damaged.

Direct contacts

Direct contacts between the vegetation and the ship's hull or the propeller of narrow boats are not mentioned in literature. However, it cannot be excluded considering the limited draught/depth ratios.

Contacts between the ship's hull and the bed will damage the biomass of vegetation, but contacts between the hull and the stems of vegetation above the bed will probably not harm the stems.

It is expected that the suction in front of the propellers might wash-out biomass, taking into account the small depth-draught ratio. On the other hand, the shape and the small depth-draught ratio will force the flow to enter the propeller plane from the areas next to the ~~ship's~~ boat's hull. Maynord has shown that the discharge underneath the keel for limited depth-draught ratios decreases to 20% compared to common depth-draught ratios. hull

4.3 Recreational navigation options

The results in Section 4.2 show high flow velocities with high turbulence levels and significant pressure changes.

Reduction of these levels might be realized by:

- Boat management;
- Modification of the narrow boat design;
- Adjustment of the canal dimensions.

The last item will not be discussed in this section, because it has already been discussed in Section 4.2.

Boat management

Boat management is not a new issue. Hames (1989) mentions already a speed limit of 4 statute miles per hour (= 6.4 km/h) for canals of British Waterways. For many years already positive experiences with a speed limit of 6 km/h exist in recreational areas in the Netherlands. The question is whether or not a speed limit is sufficient or whether additional measures should be considered, such as limiting the number of ships or prohibited access in the growing season.

The calculation results presented in Section 4.2 clearly show that a larger water depth in combination with a speed limit, for instance 0.5 m/s results in reduced flow velocities due to return current. However, a speed limit means higher flow velocities due to the propeller jet.

Taking into account all aspects, it is recommended to increase the water depth to a depth-draught ratio larger than 1.5, i.e. a water depth of 1.0 m for an average draught of 0.65 m, in combination with a limit speed of 0.5 m/s. This will limit the flow velocities at the bed.

Furthermore, at some locations with vulnerable aquatic vegetation, for instance at the aqueduct site (Figure 4.9), it might be considered to allow sailing in one part of the canal width and blocking the other part of the canal. At other canal locations a bypass might be considered or an enlargement of the canal with 5 to 10 m to allow boats to sail around the vulnerable sites.

Figure 4.8 Montgomery Canal

Boat design

hull

The most dangerous impacts on the canal bottom are the pressures induced by the displacement flow underneath the ship's ~~bow~~ and the flow velocities in the propeller jet. A more streamlined bow reduces the pressures considerably as has been proven by the OSTEC tests. However, it is difficult to change the existing narrow boats.

The most realistic option is to reduce the flow velocities near the canal bed due to the propeller jet, for instance with a shrouded propeller. OSTEC carried out tests with positive results, but implementation in the fleet of narrow boats was no success. The reason was that debris in the canals frequently blocked the shrouded propeller. This was confirmed in a telephone call on the 16th of April 2004 between Mr. Graham Newman and a representative of Alvechurch Boats Ltd. This company built narrow boats for hire fleet and for private use according to the OSTEC prototype.
However, nowadays the canals are cleaner, subsequently, a new attempt can be considered.
Note that a shrouded propeller is not identical to a propeller with a Kort nozzle.

Another option is to build below the propeller a plate with a length up to the rudder and a width of about 0.5 m. This horizontal plate or apron blocks the jet in the direction to the canal bed.

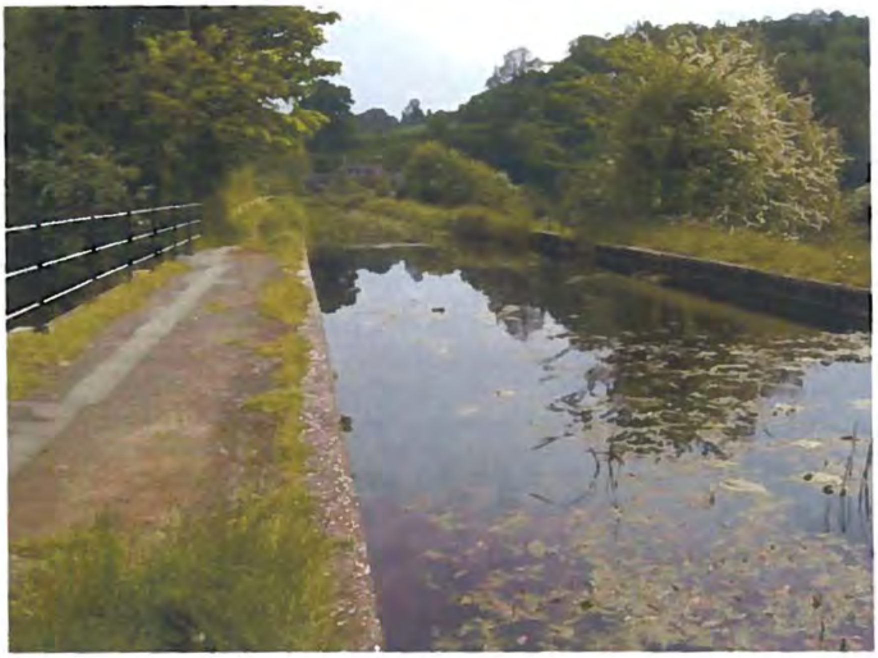

Figure 4.9 Aqueduct in the Montgomery Canal

5 Conclusions and recommendations

The flow velocities underneath the hull and in the propeller jet of narrow boats are computed, because they may endanger rare species of submerged aquatic vegetation. Therefore, the relevant calculation methods have been summarized. In addition, experiences with boat management, i.e. speed limits for ships, passing distances and limited access, in recreational areas have been reviewed.
Based on the results the following conclusions are presented:

- Minimum flow velocities in the propeller jet behind the ship and underneath the hull at the bow will be in the range of 0.3 m/s to 0.5 m/s, but will decrease with depth-draught ratios larger than 1.2. However, dredging may imply damaging the aquatic vegetation. Relative high turbulence levels up to 40% are possible.
- A speed limit of 0.5 m/s to 1.0 m/s might be considered. Note: a lower ship speed induces lower bow velocities, but higher flow velocities in the propeller jet.
- At some locations with vulnerable aquatic vegetation, for instance at the aqueduct site, it might be considered to allow sailing in one half of the canal width and blocking the other half of the canal. At other canal locations a bypass might be considered.
- A reduction of the propeller jet velocities can be realized by a fixed apron below the propeller and the rudder which prevents jet deflection towards the canal bed. Full scale tests with a shrouded propeller have proven the effect of this type of measure.

Examples of computed flow velocities under the hull at the bow, in the propeller jet and over the canal cross-section are presented in Figures 5.1 and 5.2.

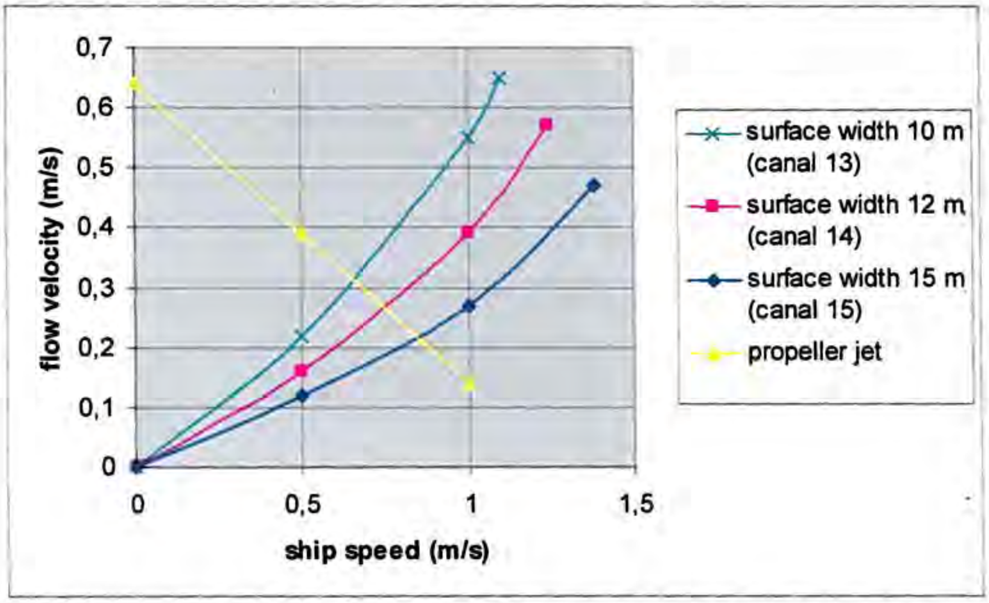

Figure 5.1 Flow velocities at the canal bed underneath the bow and in the propeller jet of narrow boat N2 (draught 0.80 m)

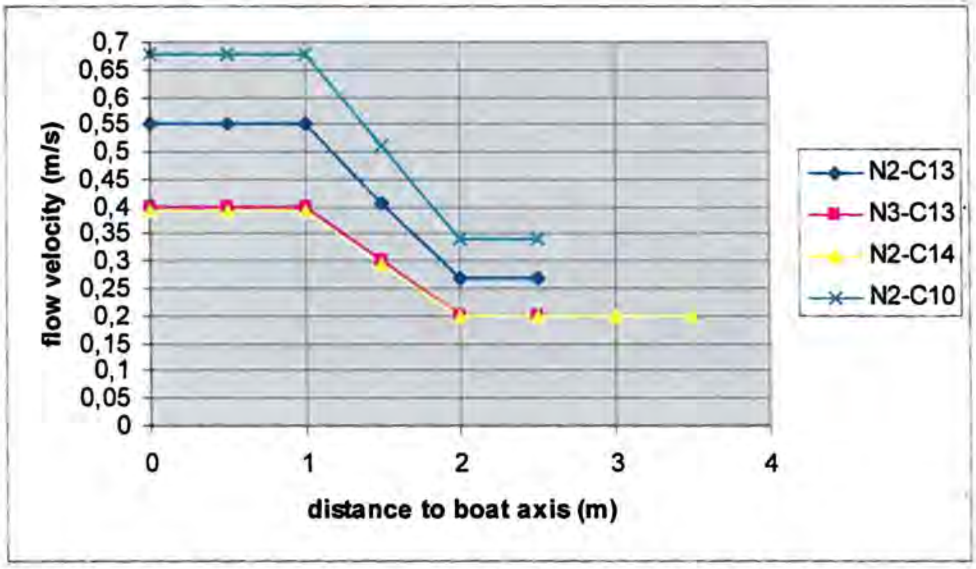

Figure 5.2 Flow velocities in a cross-section at 2 m from the bow for $V_s = 1.0$ m/s

Regarding boat management a telephone inquiry in the Netherlands showed that boat management is mainly focussed on berthing facilities. However, for some waterways rules and regulations exist about maximum boat speed and accessibility but these restrictions are related to marginal vegetation at the banks and not to aquatic vegetation on the canal bottom.

Based on the above conclusions it is recommended:

- To maintain a minimum water depth of 1.2 m, but if possible to increase the water depth to 1.5 m;
- To implement a speed limit of about 1.0 m/s at all sections of the canal;
- To realize bypasses and one-way traffic at vulnerable locations;
- To ask boat owners to fix a plate below the propeller and the rudder in order to prevent direct damage by the propeller jet;
- To ask boat owners to install slowly rotating propellers as they result in lower flow velocities compared to fast rotating propellers;
- To implement changes of the boats hulls according to the OSTEC recommendations as they clearly demonstrated the positive effects on the flow velocities, although the present study did not investigate this aspect.

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A Flow velocities induced by narrow boats

return flow velocities between ship and bank

			N1					N2					N3
canal	b x h (m)	Ac	Vl	0.7xVl	Vs = 0.5 m/s	Vs = 1.0 m/s	Vs=1.5m/s of 0.7Vl	Vl	0.7xVl	Vs = 0.5 m/s	Vs = 1.0 m/s	Vs=1.5m/s of 0.7Vl	Vl
C1	8x1.0 (0)	8,00	1,42	1,00	0,15	0,40	n.a.	1,52	1,06	0,13	0,32	0,35	1,67
C2	10x1.0 (0)	10,00	1,59	1,11	0,11	0,28	0,34	1,68	1,18	0,10	0,23	0,31	1,82
C3	12x1.0 (0)	12,00	1,72	1,20	0,09	0,22	0,30	1,80	1,26	0,08	0,18	0,27	1,93
C4	8x1.2 (0)	9,60	1,71	1,20	0,12	0,28	0,38	1,81	1,27	0,10	0,23	0,34	1,96
C5	10x1.2 (0)	12,00	1,88	1,32	0,09	0,21	0,32	1,98	1,38	0,08	0,17	0,29	2,11
C6	12x1.2 (0)	14,40	2,01	1,41	0,07	0,16	0,29	2,10	1,47	0,06	0,14	0,26	2,23
C7	8x1.5 (0)	12,00	2,11	1,47	0,09	0,20	0,35	2,21	1,55	0,08	0,17	0,30	2,36
C8	10x1.5 (0)	15,00	2,28	1,60	0,07	0,15	0,27	2,37	1,66	0,06	0,13	0,23	2,51
C9	12x1.5 (0)	18,00	2,41	1,69	0,06	0,12	0,21	2,50	1,75	0,05	0,10	0,18	2,63
C10	10x1.0 (2)	8,00	1,29	0,90	0,16	0,38	n.a.	1,38	0,90	0,13	0,34	n.a.	1,52
C11	12x1.0 (2)	10,00	1,47	1,03	0,12	0,31	0,33	1,56	1,09	0,10	0,25	0,30	1,68
C12	15x1.0 (2)	13,00	1,67	1,17	0,08	0,21	0,28	1,74	1,22	0,07	0,17	0,25	1,86
C13	10x1.2 (2)	9,12	1,48	1,04	0,13	0,34	0,37	1,57	1,10	0,11	0,27	0,33	1,71
C14	12x1.2 (2)	11,52	1,68	1,18	0,10	0,24	0,32	1,77	1,24	0,08	0,20	0,28	1,90
C15	15x1.2 (2)	15,12	1,90	1,33	0,07	0,16	0,27	1,97	1,38	0,06	0,14	0,24	2,09
C16	10x1.5 (2)	10,50	1,70	1,19	0,11	0,26	0,35	1,80	1,26	0,09	0,21	0,32	1,93
C17	12x1.5 (2)	13,50	1,94	1,36	0,08	0,18	0,30	2,03	1,42	0,07	0,15	0,27	2,15
C18	15x1.5 (2)	18,00	2,19	1,53	0,06	0,13	0,24	2,27	1,59	0,05	0,11	0,20	2,38

note: m = slope (2 = 2vertical:1horizontal; 0 = vertical)
n.a.: 0.7 Vl < 1.0 m/s
(yellow) Ac < 5.5 x Am

N1 and C10 with h = 1.0 m: Vs =0.90 m/s
N2 and C10 with h = 1.0 m: Vs =0.97 m/s

N1 with C1, C2, C3, C10, C11 and C12: h < 1.2 T or

return flow velocities under the bow of the ship

canal	b x h (m)	Ac	N1 Vl	0.7xVl	Vs = 0.5 m/s	Vs = 1.0 m/s	Vs=1.5m/s of 0.7Vl	N2 Vl	0.7xVl	Vs = 0.5 m/s	Vs = 1.0 m/s	Vs=1.5m/s of 0.7Vl	N3 Vl
C1	8x1.0 (0)	8,00	1,42	1,00	0,30	0,80	n.a	1,52	1,06	0,25	0,64	0,71	1,67
C2	10x1.0 (0)	10,00	1,59	1,11	0,23	0,56	0,68	1,68	1,18	0,19	0,46	0,62	1,82
C3	12x1.0 (0)	12,00	1,72	1,20	0,18	0,44	0,60	1,80	1,26	0,15	0,37	0,54	1,93
C4	8x1.2 (0)	9,60	1,71	1,20	0,23	0,55	0,75	1,81	1,27	0,20	0,46	0,68	1,96
C5	10x1.2 (0)	12,00	1,88	1,32	0,18	0,41	0,65	1,98	1,38	0,15	0,35	0,58	2,11
C6	12x1.2 (0)	14,40	2,01	1,41	0,14	0,33	0,57	2,10	1,47	0,13	0,28	0,51	2,23
C7	8x1.5 (0)	12,00	2,11	1,47	0,18	0,39	0,70	2,21	1,55	0,15	0,33	0,60	2,36
C8	10x1.5 (0)	15,00	2,28	1,60	0,14	0,30	0,54	2,37	1,66	0,12	0,25	0,45	2,51
C9	12x1.5 (0)	18,00	2,41	1,69	0,11	0,24	0,43	2,50	1,75	0,10	0,21	0,36	2,63
C10	10x1.0 (2)	8,00	1,29	0,90	0,31	0,75	n.a.	1,38	0,90	0,26	0,68	n.a.	1,52
C11	12x1.0 (2)	10,00	1,47	1,03	0,23	0,63	0,67	1,56	1,09	0,19	0,50	0,59	1,68
C12	15x1.0 (2)	13,00	1,67	1,17	0,17	0,42	0,57	1,74	1,22	0,14	0,35	0,50	1,86
C13	10x1.2 (2)	9,12	1,48	1,04	0,26	0,68	0,73	1,57	1,10	0,22	0,55	0,65	1,71
C14	12x1.2 (2)	11,52	1,68	1,18	0,19	0,47	0,64	1,77	1,24	0,16	0,39	0,57	1,90
C15	15x1.2 (2)	15,12	1,90	1,33	0,14	0,32	0,53	1,97	1,38	0,12	0,27	0,47	2,09
C16	10x1.5 (2)	10,50	1,70	1,19	0,21	0,51	0,70	1,80	1,26	0,18	0,43	0,63	1,93
C17	12x1.5 (2)	13,50	1,94	1,36	0,16	0,36	0,60	2,03	1,42	0,13	0,30	0,54	2,15
C18	15x1.5 (2)	18,00	2,19	1,53	0,11	0,25	0,48	2,27	1,59	0,10	0,21	0,40	2,38

B Flow velocities under the hull and in the propeller jet

1 Flow velocities beneath the boat

Rectangular canal

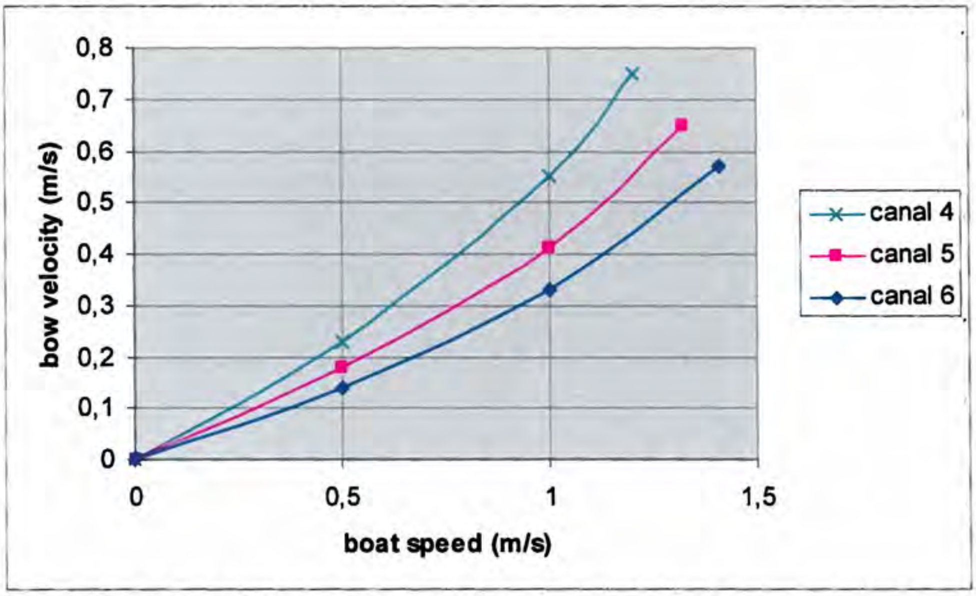


Figure 1a Narrow boat N1: Influence surface width for a water depth of 1.2 m

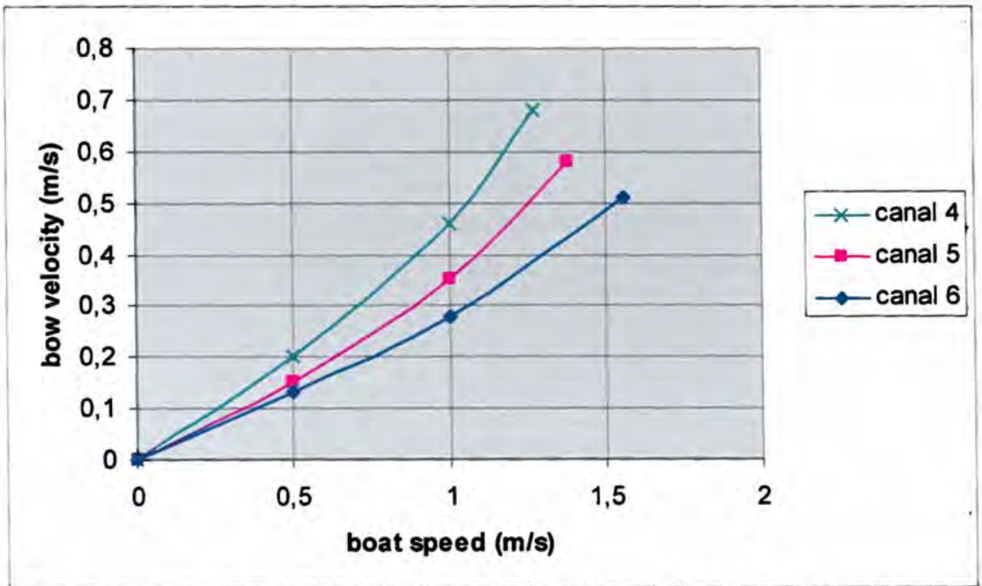


Figure 1b Narrow boat N2: Influence surface width for a water depth of 1.2 m

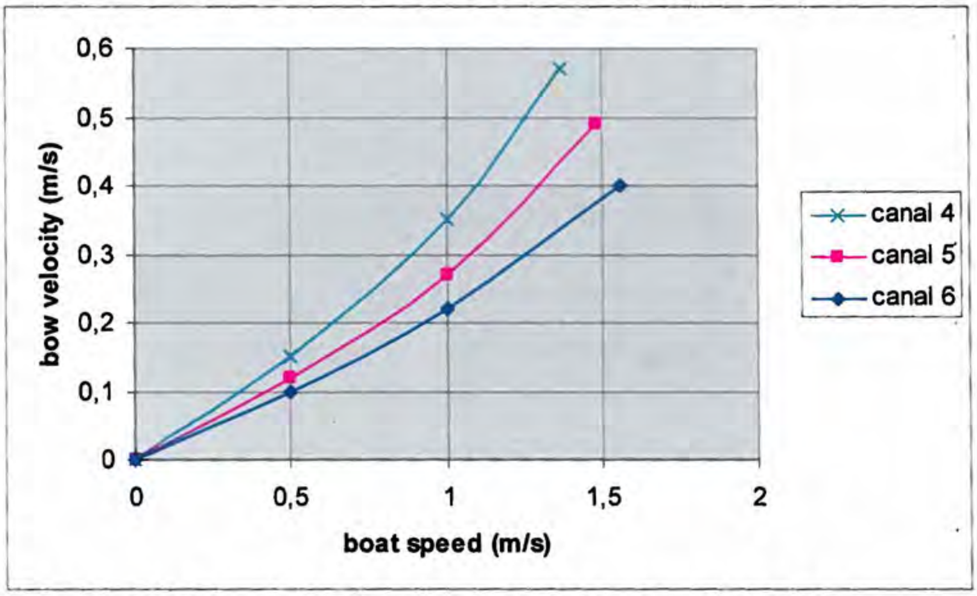


Figure 1c Narrow boat N3: Influence surface width for a water depth of 1.2 m

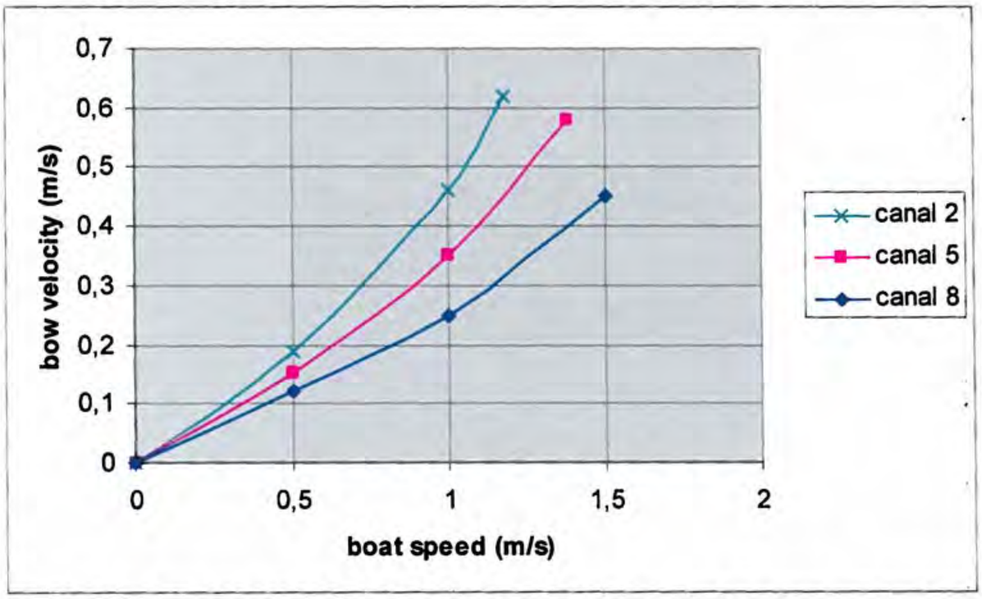


Figure 2 influence water depth h for a surface width b of 10 m for narrow boat N2

Trapezoidal canal

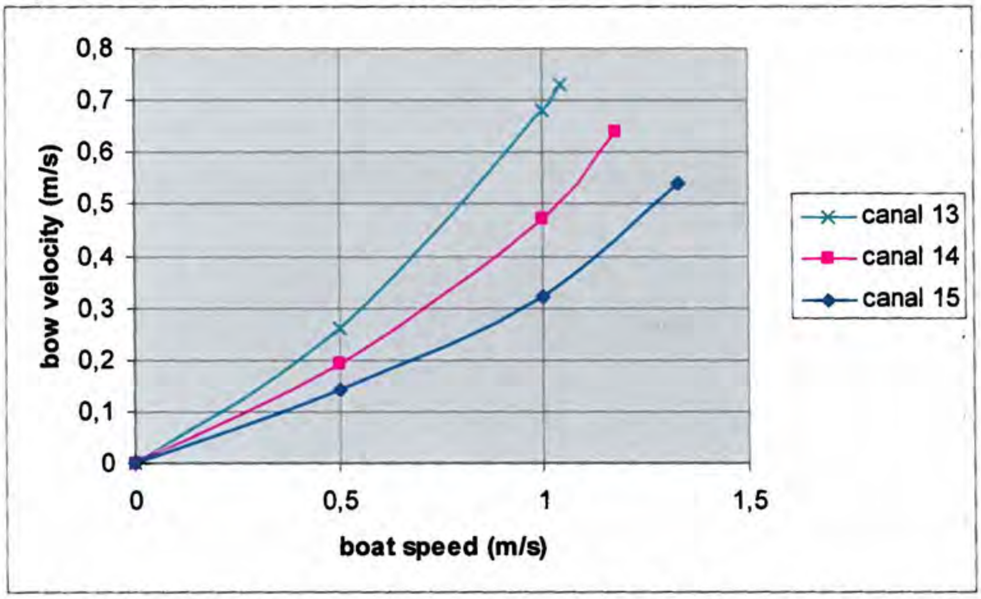


Figure 3a Narrow boat N1: Influence surface width for a water depth of 1.2 m

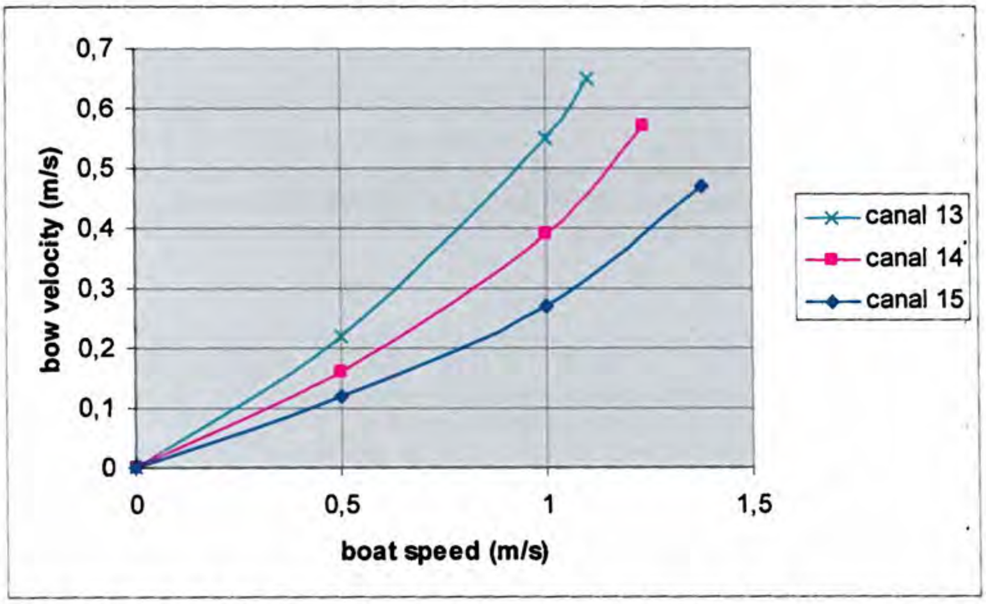


Figure 3b Narrow boat N2: Influence surface width for a water depth of 1.2 m

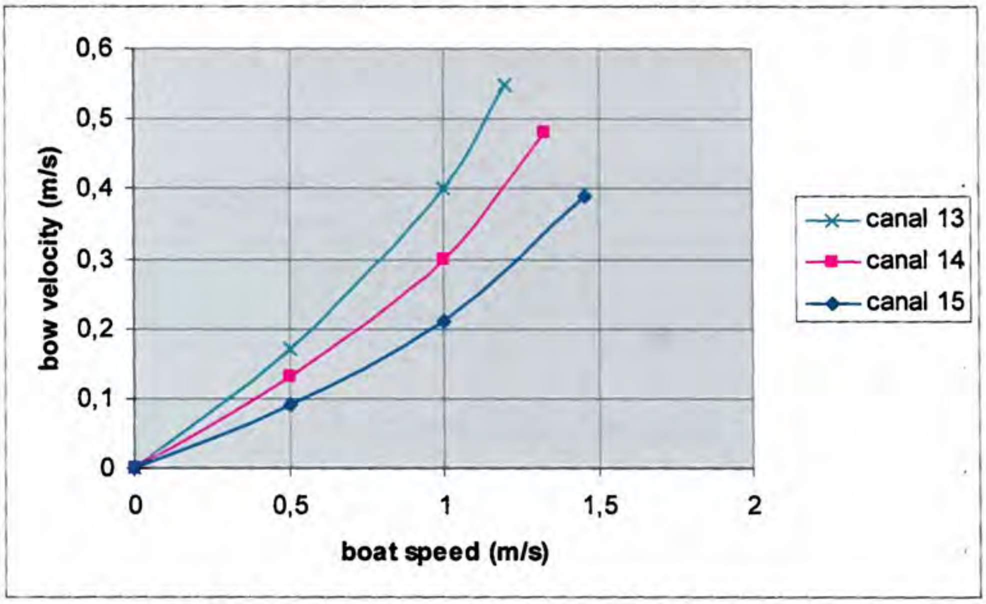


Figure 3c Narrow boat N3: Influence surface width for a water depth of 1.2 m

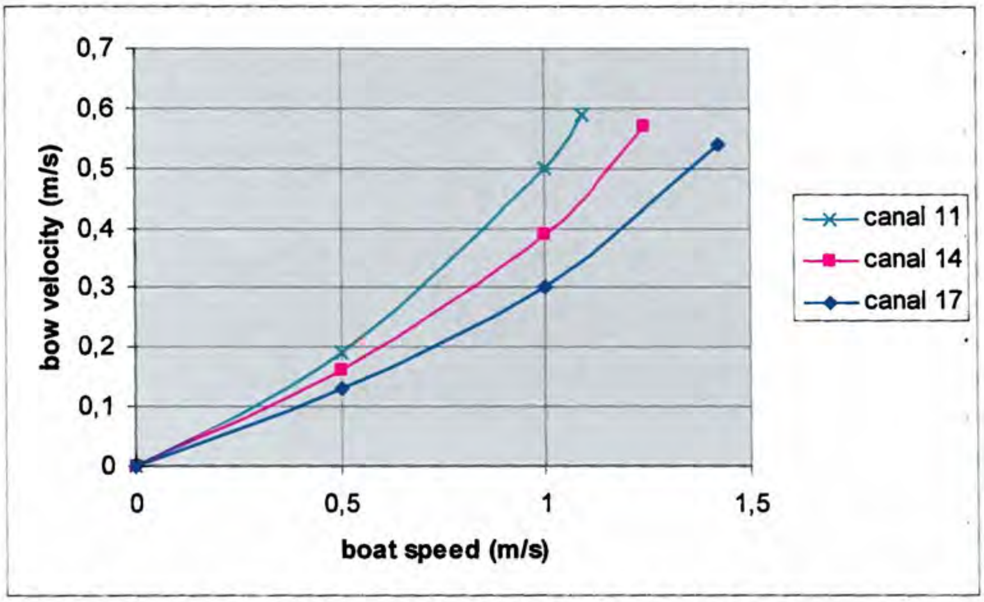


Figure 4 influence water depth h for a surface width b of 10 m for narrow boat N2

2 Flow velocities in propeller jet

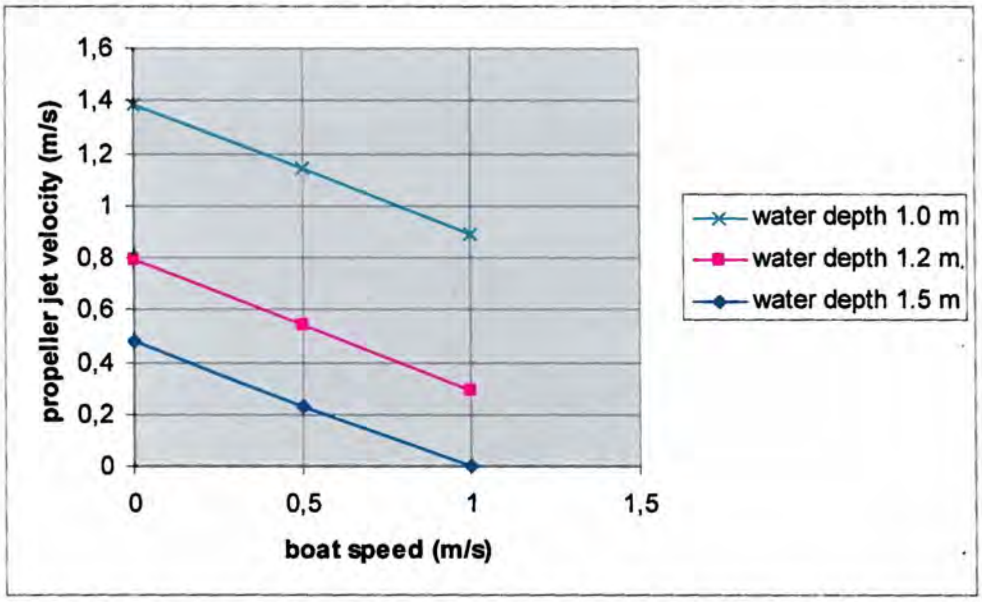


Figure 5a Flow velocities at the canal bed in the propeller jet of narrow boat N1 (draft 0.91 m)

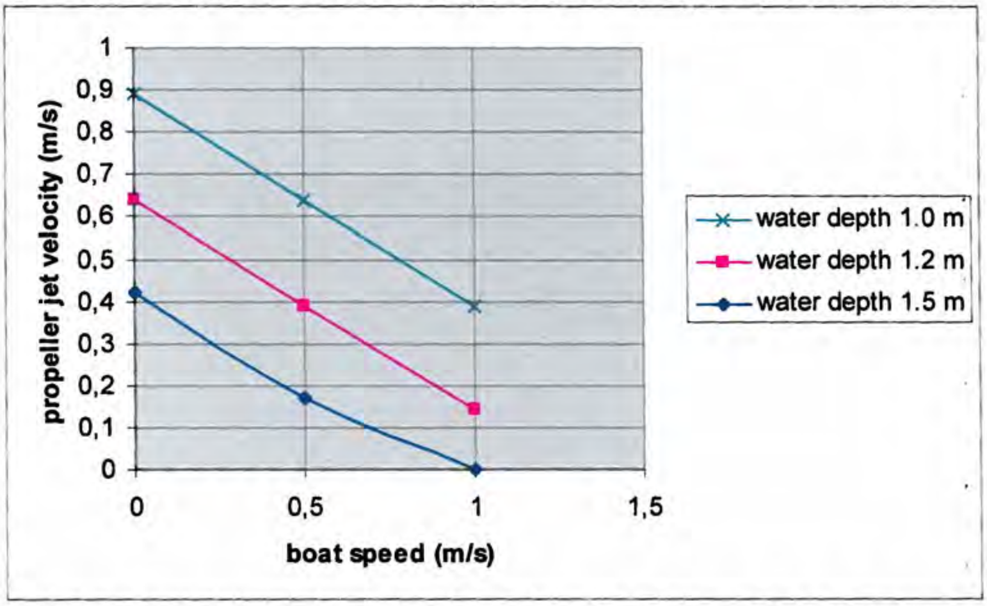


Figure 5b Flow velocities at the canal bed in the propeller jet of narrow boat N2 (draft 0.80 m)

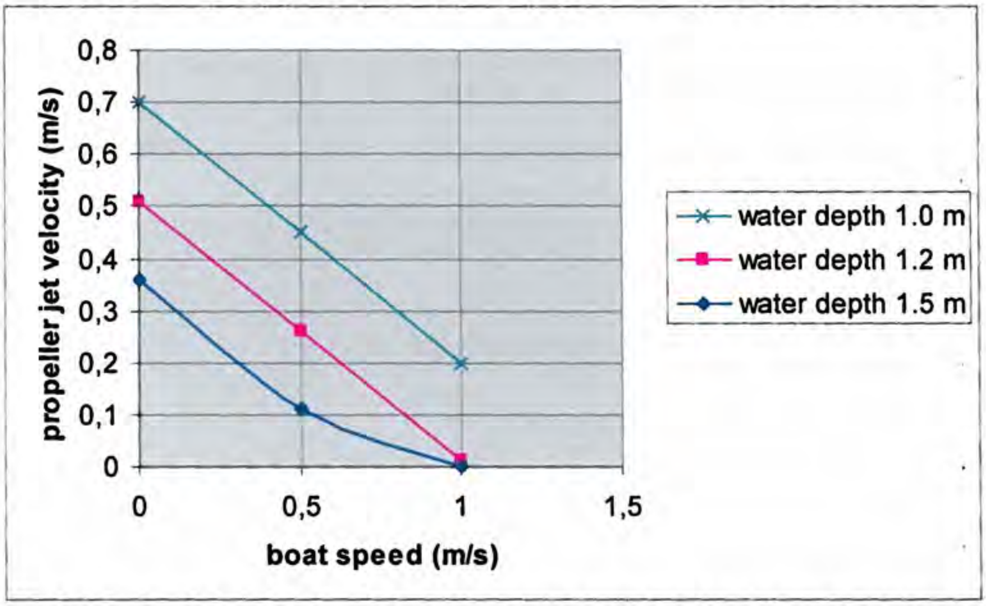
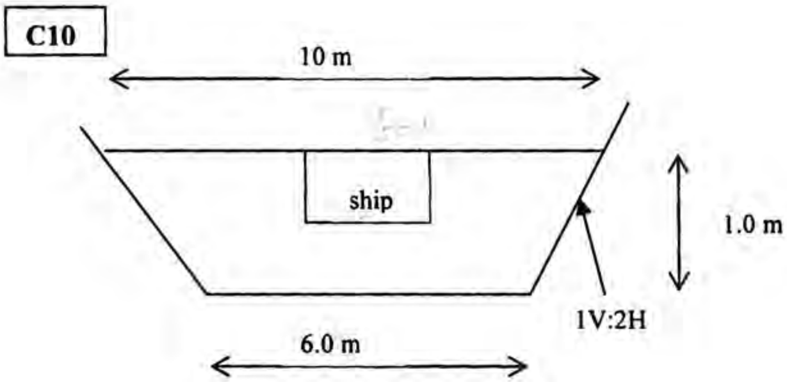
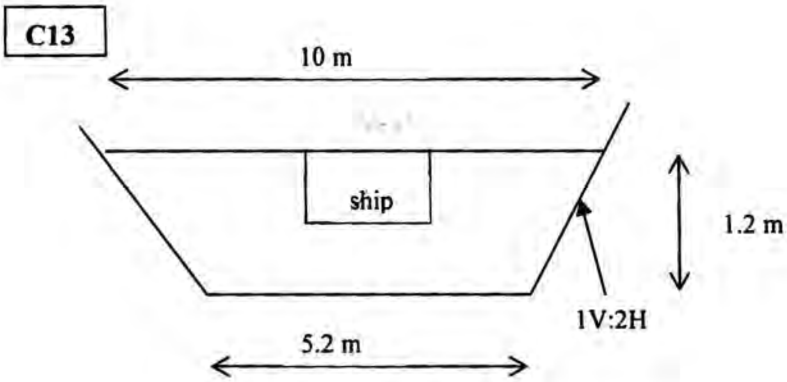


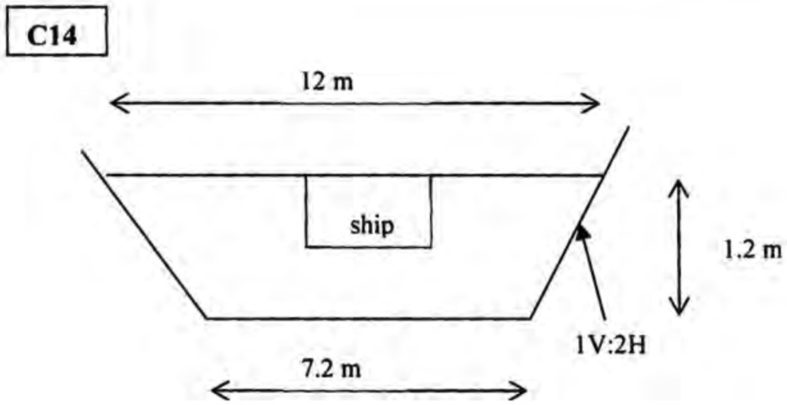
Figure .5c Flow velocities at the canal bed in the propeller jet of narrow boat N3 (draft 0.65 m)

C Flow distributions over the cross-section

1 canals






C14
12 m
ship
1.2 m
1V:2H
7.2 m

2 flow distributions behind the propeller jet

2.1 boat N2

V_s = 0 m/s and water depth 1.0 m (canal C10)

X-distance[m] from propeller	Y-distance from boat centerline [m] .00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00	.36							
2.00	.97	.37	.02					
3.00	.88	.57	.16	.02				
4.00	.73	.58	.28	.08	.02			
5.00	.62	.53	.33	.15	.05	.01		
6.00	.53	.47	.34	.20	.10	.04	.01	
7.00	.46	.42	.34	.23	.13	.06	.03	
8.00	.41	.38	.32	.24	.16	.09	.05	.02
9.00	.36	.35	.30	.24	.17	.11	.07	.04
10.00	.33	.32	.28	.23	.18	.13	.08	.05
11.00	.30	.29	.26	.23	.18	.14	.10	.06
12.00	.28	.27	.25	.22	.18	.14	.11	.07
13.00	.26	.25	.23	.21	.18	.14	.11	.08
14.00	.24	.23	.22	.20	.17	.15	.12	.09
15.00	.22	.22	.21	.19	.17	.14	.12	.10
16.00	.21	.21	.20	.18	.16	.14	.12	.10
17.00	.20	.19	.19	.17	.16	.14	.12	.10
18.00	.19	.18	.18	.17	.15	.14	.12	.10
19.00	.18	.17	.17	.16	.15	.13	.12	.10
20.00	.17	.17	.16	.15	.14	.13	.12	.10
21.00	.16	.16	.15	.15	.14	.13	.12	.10
22.00	.15	.15	.15	.14	.13	.12	.11	.10
23.00	.15	.14	.14	.14	.13	.12	.11	.10
24.00	.14	.14	.14	.13	.13	.12	.11	.10
25.00	.13	.13	.13	.13	.12	.12	.11	.10

V_s = 0 m/s and water depth 1.2 m (canals C13 and C14)

X-distance[m] from propeller	Y-distance from boat centerline [m] .00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00								
2.00	.48	.18	.01					
3.00	.64	.42	.12	.01				
4.00	.62	.48	.24	.07	.01			
5.00	.55	.47	.30	.14	.05	.01		
6.00	.49	.44	.32	.19	.09	.03	.01	
7.00	.43	.40	.32	.21	.12	.06	.03	
8.00	.39	.37	.31	.23	.15	.09	.04	
9.00	.35	.34	.29	.23	.16	.11	.06	.03
10.00	.32	.31	.27	.23	.17	.12	.08	.05
11.00	.29	.28	.26	.22	.18	.13	.09	.06
12.00	.27	.26	.24	.21	.18	.14	.10	.07
13.00	.25	.25	.23	.20	.17	.14	.11	.08
14.00	.23	.23	.22	.20	.17	.14	.12	.09

15.00	.22	.22	.21	.19	.17	.14	.12	.09
16.00	.21	.20	.19	.18	.16	.14	.12	.10
17.00	.19	.19	.18	.17	.16	.14	.12	.10
18.00	.18	.18	.18	.17	.15	.14	.12	.10
19.00	.17	.17	.17	.16	.15	.13	.12	.10
20.00	.17	.16	.16	.15	.14	.13	.12	.10
21.00	.16	.16	.15	.15	.14	.13	.12	.10
22.00	.15	.15	.15	.14	.13	.12	.11	.10
23.00	.15	.14	.14	.14	.13	.12	.11	.10
24.00	.14	.14	.14	.13	.12	.12	.11	.10
25.00	.13	.13	.13	.13	.12	.11	.11	.10

V_s = 0.5 m/s and water depth 1.0 m (canal C10)

	Y-distance from boat centerline [m]							
X-distance[m] from propeller	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00	.11							
2.00	.72	.12	.00					
3.00	.63	.32	.00					
4.00	.48	.33	.03	.00				
5.00	.37	.28	.08	.00	.00	.00	.00	.00
6.00	.28	.22	.09	.00	.00	.00	.00	.00
7.00	.21	.17	.09	.00	.00	.00	.00	.00
8.00	.16	.13	.07	.00	.00	.00	.00	.00
9.00	.11	.10	.05	.00	.00	.00	.00	.00
10.00	.08	.07	.03	.00	.00	.00	.00	.00
11.00	.05	.04	.01	.00	.00	.00	.00	.00
12.00	.03	.02	.00	.00	.00	.00	.00	.00
13.00	.01	.00	.00	.00	.00	.00	.00	.00
14.00	.00	.00	.00	.00	.00	.00	.00	.00
15.00	.00	.00	.00	.00	.00	.00	.00	.00

V_s = 0.5 m/s and water depth 1.2 m (canals C13 and C14)

	Y-distance from boat centerline [m]							
X-distance[m] from propeller	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00								
2.00	.23	.00	.00					
3.00	.39	.17	.00	.00				
4.00	.37	.23	.00	.00	.00			
5.00	.30	.22	.05	.00	.00	.00		
6.00	.24	.19	.07	.00	.00	.00	.00	
7.00	.18	.15	.07	.00	.00	.00	.00	
8.00	.14	.12	.06	.00	.00	.00	.00	
9.00	.10	.09	.04	.00	.00	.00	.00	.00
10.00	.07	.06	.02	.00	.00	.00	.00	.00
11.00	.04	.03	.01	.00	.00	.00	.00	.00
12.00	.02	.01	.00	.00	.00	.00	.00	.00
13.00	.00	.00	.00	.00	.00	.00	.00	.00
14.00	.00	.00	.00	.00	.00	.00	.00	.00
15.00	.00	.00	.00	.00	.00	.00	.00	.00

V_s = 1.0 m/s and water depth 1.0 m (canal C10)

	Y-distance from boat centerline [m]							
X-distance[m] from propeller	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00	.00							
2.00	.47	.00	.00					
3.00	.38	.07	.00					
4.00	.23	.08	.00	.00				
5.00	.12	.03	.00	.00	.00	.00	.00	.00
6.00	.03	.00	.00	.00	.00	.00	.00	.00
7.00	.00	.00	.00	.00	.00	.00	.00	.00
8.00	.00	.00	.00	.00	.00	.00	.00	.00
9.00	.00	.00	.00	.00	.00	.00	.00	.00
10.00	.00	.00	.00	.00	.00	.00	.00	.00

V_s = 1.0 m/s and water depth 1.2 m (canals C13 and C14)

	Y-distance from ship centerline [m]							
X-distance[m] from propeller	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00								
2.00	.00							
3.00	.14	.00						
4.00	.12	.00	.00	.00	.00			
5.00	.05	.00	.00	.00	.00	.00	.00	
6.00	.00	.00	.00	.00	.00	.00	.00	
7.00	.00	.00	.00	.00	.00	.00	.00	
8.00	.00	.00	.00	.00	.00	.00	.00	
9.00	.00	.00	.00	.00	.00	.00	.00	.00
10.00	.00	.00	.00	.00	.00	.00	.00	.00

2.2 boat N3

V_s = 0 m/s and water depth 1.0 m (canal C10)

	Y-distance from boat centerline [m]							
X-distance[m] from propeller	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00	.05							
2.00	.59	.23	.01					
3.00	.71	.46	.13	.02				
4.00	.65	.51	.25	.07	.01			
5.00	.57	.49	.31	.14	.05	.01		
6.00	.50	.45	.33	.19	.09	.03	.01	
7.00	.44	.41	.32	.22	.13	.06	.03	.
8.00	.39	.37	.31	.23	.15	.09	.05	.02
9.00	.36	.34	.29	.23	.17	.11	.06	.03
10.00	.32	.31	.28	.23	.17	.12	.08	.05
11.00	.30	.29	.26	.22	.18	.13	.09	.06
12.00	.27	.27	.24	.21	.18	.14	.10	.07
13.00	.25	.25	.23	.21	.18	.14	.11	.08

14.00	.24	.23	.22	.20	.17	.14	.12	.09
15.00	.22	.22	.21	.19	.17	.14	.12	.10
16.00	.21	.20	.19	.18	.16	.14	.12	.10
17.00	.20	.19	.19	.17	.16	.14	.12	.10
18.00	.18	.18	.18	.17	.15	.14	.12	.10
19.00	.18	.17	.17	.16	.15	.13	.12	.10
20.00	.17	.17	.16	.15	.14	.13	.12	.10
21.00	.16	.16	.15	.15	.14	.13	.12	.10
22.00	.15	.15	.15	.14	.13	.12	.11	.10
23.00	.15	.14	.14	.14	.13	.12	.11	.10
24.00	.14	.14	.14	.13	.13	.12	.11	.10
25.00	.13	.13	.13	.13	.12	.11	.11	.10

V_s = 0 m/s and water depth 1.2 m (canals C13 and C14)

	Y-distance from boat centerline [m]							
X-distance[m] from propeller	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00								
2.00	.22	.08						
3.00	.45	.29						
4.00	.50	.40	.19	.06				
5.00	.49	.42	.26	.12	.04			
6.00	.45	.40	.29	.17	.08	.03		
7.00	.41	.38	.30	.20	.12	.06	.02	
8.00	.37	.35	.29	.22	.14	.08	.04	.02
9.00	.34	.32	.28	.22	.16	.10	.06	.03
10.00	.31	.30	.27	.22	.17	.12	.08	.05
11.00	.29	.28	.25	.21	.17	.13	.09	.06
12.00	.27	.26	.24	.21	.17	.14	.10	.07
13.00	.25	.24	.23	.20	.17	.14	.11	.08
14.00	.23	.23	.21	.19	.17	.14	.11	.09
15.00	.22	.21	.20	.19	.16	.14	.12	.09
16.00	.20	.20	.19	.18	.16	.14	.12	.10
17.00	.19	.19	.18	.17	.16	.14	.12	.10
18.00	.18	.18	.17	.16	.15	.14	.12	.10
19.00	.17	.17	.17	.16	.15	.13	.12	.10
20.00	.16	.16	.16	.15	.14	.13	.12	.10
21.00	.16	.16	.15	.15	.14	.13	.11	.10
22.00	.15	.15	.15	.14	.13	.12	.11	.10
23.00	.14	.14	.14	.14	.13	.12	.11	.10
24.00	.14	.14	.13	.13	.12	.12	.11	.10
25.00	.13	.13	.13	.13	.12	.11	.11	.10

V_s = 0.5 m/s and water depth 1.0 m (canal C10)

	Y-distance from boat centerline [m]							
X-distance[m] from propeller	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00	.00							
2.00	.34	.00						
3.00	.46	.21	.00					
4.00	.40	.26	.00	.00				

5.00	.32	.24	.06	.00	.00			
6.00	.25	.20	.08	.00	.00	.00		
7.00	.19	.16	.07	.00	.00	.00	.00	.00
8.00	.14	.12	.06	.00	.00	.00	.00	.00
9.00	.11	.09	.04	.00	.00	.00	.00	.00
10.00	.07	.06	.03	.00	.00	.00	.00	.00
11.00	.05	.04	.01	.00	.00	.00	.00	.00
12.00	.02	.02	.00	.00	.00	.00	.00	.00
13.00	.00	.00	.00	.00	.00	.00	.00	.00
14.00	.00	.00	.00	.00	.00	.00	.00	.00
15.00	.00	.00	.00	.00	.00	.00	.00	.00

V_s = 0.5 m/s and water depth 1.2 m (canals C13 and C14)

	Y-distance from boat centerline [m]							
X-distance[m] from propeller	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00								
2.00	.00	.0						
3.00	.20	.04						
4.00	.25	.15	.00	.00				
5.00	.24	.17	.01	.00	.00			
6.00	.20	.15	.04	.00	.00	.00		
7.00	.16	.13	.05	.00	.00	.00	.00	
8.00	.12	.10	.04	.00	.00	.00	.00	.00
9.00	.09	.07	.03	.00	.00	.00	.00	.00
10.00	.06	.05	.02	.00	.00	.00	.00	.00
11.00	.04	.03	.00	.21	.00	.00	.00	.00
12.00	.02	.01	.00	.00	.00	.00	.00	.00
13.00	.00	.00	.00	.00	.00	.00	.00	.00
14.00	.00	.00	.00	.00	.00	.00	.00	.00
15.00	.00	.00	.00	.00	.00	.00	.00	.00

V_s = 1.0 m/s and water depth 1.0 m (canal C10)

	Y-distance from boat centerline [m]							
X-distance[m] from propeller	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
1.00	.00							
2.00	.09	.00						
3.00	.21	.00	.00					
4.00	.15	.01	.00	.00				
5.00	.07	.00	.00	.00	.00			
6.00	.00	.00	.00	.00	.00	.00		
7.00	.00	.00	.00	.00	.00	.00	.00	.00
8.00	.00	.00	.00	.00	.00	.00	.00	.00
9.00	.00	.00	.00	.00	.00	.00	.00	.00
10.00	.00	.00	.00	.00	.00	.00	.00	.00

V_s = 1.0 m/s and water depth 1.2 m (canals C13 and C14)

	Y-distance from boat centerline [m]							
X-distance[m]	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50

from propeller								
1.00	.00							
2.00	.00	.00						
3.00	.00	.00	.00					
4.00	.00	.00	.00	.00				
5.00	.00	.00	.00	.00	.00			
6.00	.00	.00	.00	.00	.00	.00		
7.00	.00	.00	.00	.00	.00	.00	.00	.00
8.00	.00	.00	.00	.00	.00	.00	.00	.00
9.00	.00	.00	.00	.00	.00	.00	.00	.00
10.00	.00	.00	.00	.00	.00	.00	.00	.00

3 flow velocity distributions over the canal width for moving boats

3.1 boat N2

Distribution flow velocities over the canal width for boat N2 with a boat speed of 0.5 m/s in canal C10 (depth 1.0 m, width 10 m and slope 1:2)

	Y-distance from boat centerline [m]					
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50
0.00	.00	.00	.00	.00	.00	.00
1.00	.26	.26	.26	.13	.13	.13
2.00	.26	.26	.26	.13	.13	.13
3.00	.26	.26	.26	.13	.13	.13
4.00	.13	.13	.13	.13	.13	.13
5.00	.13	.13	.13	.13	.13	.13
6.00	.13	.13	.13	.13	.13	.13
7.00	.13	.13	.13	.13	.13	.13
8.00	.13	.13	.13	.13	.13	.13
9.00	.13	.13	.13	.13	.13	.13
10.00	.13	.13	.13	.13	.13	.13
11.00	.13	.13	.13	.13	.13	.13
12.00	.13	.13	.13	.13	.13	.13
13.00	.13	.13	.13	.13	.13	.13
14.00	.13	.13	.13	.13	.13	.13
15.00	.13	.13	.13	.13	.13	.13
16.00	.11					
17.00	.72	.12	.00			
18.00	.63	.32	.00			
19.00	.48	.33	.03	.00		
20.00	.37	.28	.08	.00	.00	.00
21.00	.28	.22	.09	.00	.00	.00
22.00	.21	.17	.09	.00	.00	.00
23.00	.16	.13	.07	.00	.00	.00
24.00	.11	.10	.05	.00	.00	.00
25.00	.08	.07	.03	.00	.00	.00
26.00	.05	.04	.01	.00	.00	.00
27.00	.03	.02	.00	.00	.00	.00
28.00	.01	.00	.00	.00	.00	.00
29.00	.00	.00	.00	.00	.00	.00
30.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N2 with a boat speed of 0.5 m/s in canal C13 (depth 1.2 m, width 10 m and slope 1:2)

	Y-distance from boat centerline [m]					
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50
0.00	.00	.00	.00	.00	.00	.00
1.00	.22	.22	.22	.11	.11	.11
2.00	.22	.22	.22	.11	.11	.11
3.00	.22	.22	.22	.11	.11	.11
4.00	.11	.11	.11	.11	.11	.11
5.00	.11	.11	.11	.11	.11	.11

6.00	.11	.11	.11	.11	.11	.11
7.00	.11	.11	.11	.11	.11	.11
8.00	.11	.11	.11	.11	.11	.11
9.00	.11	.11	.11	.11	.11	.11
10.00	.11	.11	.11	.11	.11	.11
11.00	.11	.11	.11	.11	.11	.11
12.00	.11	.11	.11	.11	.11	.11
13.00	.11	.11	.11	.11	.11	.11
14.00	.11	.11	.11	.11	.11	.11
15.00	.11	.11	.11	.11	.11	.11
16.00	.00	.00	.00	.00	.00	.00
17.00	.23	.00	.00			
18.00	.39	.17	.00	.00		
19.00	.37	.23	.00	.00	.00	
20.00	.30	.22	.05	.00	.00	.00
21.00	.24	.19	.07	.00	.00	.00
22.00	.18	.15	.07	.00	.00	.00
23.00	.14	.12	.06	.00	.00	.00
24.00	.10	.09	.04	.00	.00	.00
25.00	.07	.06	.02	.00	.00	.00
26.00	.04	.03	.01	.00	.00	.00
27.00	.02	.01	.00	.00	.00	.00
28.00	.00	.00	.00	.00	.00	.00
29.00	.00	.00	.00	.00	.00	.00
30.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N2 with a boat speed of 0.5 m/s in canal C14 (depth 1.2 m, width 12 m and slope 1:2)

	Y-distance from boat centerline [m]							
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
0.00	.00	.00	.00	.00	.00	.00	.00	.00
1.00	.16	.16	.16	.08	.08	.08	.08	.08
2.00	.16	.16	.16	.08	.08	.08	.08	.08
3.00	.16	.16	.16	.08	.08	.08	.08	.08.
4.00	.08	.08	.08	.08	.08	.08	.08	.08
5.00	.08	.08	.08	.08	.08	.08	.08	.08
6.00	.08	.08	.08	.08	.08	.08	.08	.08
7.00	.08	.08	.08	.08	.08	.08	.08	.08
8.00	.08	.08	.08	.08	.08	.08	.08	.08
9.00	.08	.08	.08	.08	.08	.08	.08	.08
10.00	.08	.08	.08	.08	.08	.08	.08	.08
11.00	.08	.08	.08	.08	.08	.08	.08	.08
12.00	.08	.08	.08	.08	.08	.08	.08	.08
13.00	.08	.08	.08	.08	.08	.08	.08	.08
14.00	.08	.08	.08	.08	.08	.08	.08	.08
15.00	.08	.08	.08	.08	.08	.08	.08	.08
16.00	.00	.00	.00	.00	.00	.00	.00	.00
17.00	.23	.00	.00					
18.00	.39	.17	.00	.00				
19.00	.37	.23	.00	.00	.00			
20.00	.30	.22	.05	.00	.00	.00		

21.00	.24	.19	.07	.00	.00	.00	.00	
22.00	.18	.15	.07	.00	.00	.00	.00	
23.00	.14	.12	.06	.00	.00	.00	.00	
24.00	.10	.09	.04	.00	.00	.00	.00	.00
25.00	.07	.06	.02	.00	.00	.00	.00	.00
26.00	.04	.03	.01	.00	.00	.00	.00	.00
27.00	.02	.01	.00	.00	.00	.00	.00	.00
28.00	.00	.00	.00	.00	.00	.00	.00	.00
29.00	.00	.00	.00	.00	.00	.00	.00	.00
30.00	.00	.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N2 with a boat speed of 1.0 m/s in canal C10 (depth 1.0 m, width 10 m and slope 1:2)

	Y-distance from boat centerline [m]					
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50
0.00	.00	.00	.00	.00	.00	.00
1.00	.68	.68	.68	.34	.34	.34
2.00	.68	.68	.68	.34	.34	.34
3.00	.68	.68	.68	.34	.34	.34
4.00	.34	.34	.34	.34	.34	.34
5.00	.34	.34	.34	.34	.34	.34
6.00	.34	.34	.34	.34	.34	.34
7.00	.34	.34	.34	.34	.34	.34
8.00	.34	.34	.34	.34	.34	.34
9.00	.34	.34	.34	.34	.34	.34
10.00	.34	.34	.34	.34	.34	.34
11.00	.34	.34	.34	.34	.34	.34
12.00	.34	.34	.34	.34	.34	.34
13.00	.34	.34	.34	.34	.34	.34
14.00	.34	.34	.34	.34	.34	.34
15.00	.34	.34	.34	.34	.34	.34
16.00	.11					
17.00	.47	.00	.00			
18.00	.38	.07	.00			
19.00	.23	.08	.00	.00		
20.00	.12	.03	.00	.00	.00	.00
21.00	.03	.00	.00	.00	.00	.00
22.00	.00	.00	.00	.00	.00	.00
23.00	.00	.00	.00	.00	.00	.00
24.00	.00	.00	.00	.00	.00	.00
25.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N2 with a boat speed of 1.0 m/s in canal C13 (depth 1.2 m, width 10 m and slope 1:2)

	Y-distance from boat centerline [m]					
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50
0.00	.00	.00	.00	.00	.00	.00
1.00	.55	.55	.55	.27	.27	.27
2.00	.55	.55	.55	.27	.27	.27

3.00	.55	.55	.55	.27	.27	.27
4.00	.27	.27	.27	.27	.27	.27
5.00	.27	.27	.27	.27	.27	.27
6.00	.27	.27	.27	.27	.27	.27
7.00	.27	.27	.27	.27	.27	.27
8.00	.27	.27	.27	.27	.27	.27
9.00	.27	.27	.27	.27	.27	.27
10.00	.27	.27	.27	.27	.27	.27
11.00	.27	.27	.27	.27	.27	.27
12.00	.27	.27	.27	.27	.27	.27
13.00	.27	.27	.27	.27	.27	.27
14.00	.27	.27	.27	.27	.27	.27
15.00	.27	.27	.27	.27	.27	.27
16.00	.00	.00	.00	.00	.00	.00
17.00	.00	.00	.00			
18.00	.14	.00	.00	.00		
19.00	.12	.00	.00	.00	.00	
20.00	.05	.00	.00	.00	.00	.00
21.00	.00	.00	.00	.00	.00	.00
22.00	.00	.00	.00	.00	.00	.00
23.00	.00	.00	.00	.00	.00	.00
24.00	.00	.00	.00	.00	.00	.00
25.00	.00	.00	.00	.00	.00	.00
26.00	.00	.00	.00	.00	.00	.00
27.00	.00	.00	.00	.00	.00	.00
28.00	.00	.00	.00	.00	.00	.00
29.00	.00	.00	.00	.00	.00	.00
30.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N2 with a boat speed of 1.0 m/s in canal C14 (depth 1.2 m, width 12 m and slope 1:2)

	Y-distance from boat centerline [m]							
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
0.00	.00	.00	.00	.00	.00	.00	.00	.00
1.00	.39	.39	.39	.20	.20	.20	.20	.20
2.00	.39	.39	.39	.20	.20	.20	.20	.20
3.00	.39	.39	.39	.20	.20	.20	.20	.20
4.00	.20	.20	.20	.20	.20	.20	.20	.20
5.00	.20	.20	.20	.20	.20	.20	.20	.20
6.00	.20	.20	.20	.20	.20	.20	.20	.20
7.00	.20	.20	.20	.20	.20	.20	.20	.20
8.00	.20	.20	.20	.20	.20	.20	.20	.20
9.00	.20	.20	.20	.20	.20	.20	.20	.20
10.00	.20	.20	.20	.20	.20	.20	.20	.20
11.00	.20	.20	.20	.20	.20	.20	.20	.20
12.00	.20	.20	.20	.20	.20	.20	.20	.20
13.00	.20	.20	.20	.20	.20	.20	.20	.20
14.00	.20	.20	.20	.20	.20	.20	.20	.20
15.00	.20	.20	.20	.20	.20	.20	.20	.20
16.00	.00	.00	.00	.00	.00	.00	.00	.00

17.00	.00	.00	.00					
18.00	.14	.00	.00	.00				
19.00	.12	.00	.00	.00	.00			
20.00	.05	.00	.00	.00	.00	.00		
21.00	.00	.00	.00	.00	.00	.00	.00	
22.00	.00	.00	.00	.00	.00	.00	.00	
23.00	.00	.00	.00	.00	.00	.00	.00	
24.00	.00	.00	.00	.00	.00	.00	.00	.00
25.00	.00	.00	.00	.00	.00	.00	.00	.00
26.00	.00	.00	.00	.00	.00	.00	.00	.00
27.00	.00	.00	.00	.00	.00	.00	.00	.00
28.00	.00	.00	.00	.00	.00	.00	.00	.00
29.00	.00	.00	.00	.00	.00	.00	.00	.00
30.00	.00	.00	.00	.00	.00	.00	.00	.00

3.2 boat N3

Distribution flow velocities over the canal width for boat N3 with a boat speed of 0.5 m/s in canal C10 (depth 1.0 m, width 10 m and slope 1:2)

	Y-distance from boat centerline [m]					
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50
0.00	.00	.00	.00	.00	.00	.00
1.00	.20	.20	.20	.10	.10	.10
2.00	.20	.20	.20	.10	.10	.10
3.00	.20	.20	.20	.10	.10	.10
4.00	.10	.10	.10	.10	.10	.10
5.00	.10	.10	.10	.10	.10	.10
6.00	.10	.10	.10	.10	.10	.10
7.00	.10	.10	.10	.10	.10	.10
8.00	.10	.10	.10	.10	.10	.10
9.00	.10	.10	.10	.10	.10	.10
10.00	.10	.10	.10	.10	.10	.10
11.00	.10	.10	.10	.10	.10	.10
12.00	.10	.10	.10	.10	.10	.10
13.00	.10	.10	.10	.10	.10	.10
14.00	.10	.10	.10	.10	.10	.10
15.00	.10	.10	.10	.10	.10	.10
16.00	.00	.00	.00	.00	.00	.00
17.00	.34	.00				
18.00	.46	.21	.00			
19.00	.40	.26	.00	.00		
20.00	.32	.24	.06	.00	.00	
21.00	.25	.20	.08	.00	.00	.00
22.00	.19	.16	.07	.00	.00	.00
23.00	.14	.12	.06	.00	.00	.00
24.00	.11	.09	.04	.00	.00	.00
25.00	.07	.06	.03	.00	.00	.00
26.00	.05	.04	.01	.00	.00	.00
27.00	.02	.02	.00	.00	.00	.00
28.00	.00	.00	.00	.00	.00	.00
29.00	.00	.00	.00	.00	.00	.00

30.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N3 with a boat speed of 0.5 m/s in canal C13 (depth 1.2 m, width 10 m and slope 1:2)

	Y-distance from boat centerline [m]					
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50
0.00	.00	.00	.00	.00	.00	.00
1.00	.17	.17	.17	.08	.08	.08
2.00	.17	.17	.17	.08	.08	.08
3.00	.17	.17	.17	.08	.08	.08
4.00	.08	.08	.08	.08	.08	.08
5.00	.08	.08	.08	.08	.08	.08
6.00	.08	.08	.08	.08	.08	.08
7.00	.08	.08	.08	.08	.08	.08
8.00	.08	.08	.08	.08	.08	.08
9.00	.08	.08	.08	.08	.08	.08
10.00	.08	.08	.08	.08	.08	.08
11.00	.08	.08	.08	.08	.08	.08
12.00	.08	.08	.08	.08	.08	.08
13.00	.08	.08	.08	.08	.08	.08
14.00	.08	.08	.08	.08	.08	.08
15.00	.08	.08	.08	.08	.08	.08
16.00	.00	.00	.00	.00	.00	.00
17.00	.00	.00				
18.00	.20	.04				
19.00	.25	.15	.00	.00		
20.00	.24	.17	.01	.00	.00	
21.00	.20	.15	.04	.00	.00	.00
22.00	.16	.13	.05	.00	.00	.00
23.00	.12	.10	.04	.00	.00	.00
24.00	.09	.07	.03	.00	.00	.00
25.00	.06	.05	.02	.00	.00	.00
26.00	.04	.03	.00	.21	.00	.00
27.00	.02	.01	.00	.00	.00	.00
28.00	.00	.00	.00	.00	.00	.00
29.00	.00	.00	.00	.00	.00	.00
30.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N3 with a boat speed of 0.5 m/s in canal C14 (depth 1.2 m, width 12 m and slope 1:2)

	Y-distance from boat centerline [m]							
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
0.00	.00	.00	.00	.00	.00	.00	.00	.00
1.00	.13	.13	.13	.06	.06	.06	.06	.06
2.00	.13	.13	.13	.06	.06	.06	.06	.06
3.00	.13	.13	.13	.06	.06	.06	.06	.06
4.00	.06	.06	.06	.06	.06	.06	.06	.06
5.00	.06	.06	.06	.06	.06	.06	.06	.06
6.00	.06	.06	.06	.06	.06	.06	.06	.06

7.00	.06	.06	.06	.06	.06	.06	.06	.06
8.00	.06	.06	.06	.06	.06	.06	.06	.06
9.00	.06	.06	.06	.06	.06	.06	.06	.06
10.00	.06	.06	.06	.06	.06	.06	.06	.06
11.00	.06	.06	.06	.06	.06	.06	.06	.06
12.00	.06	.06	.06	.06	.06	.06	.06	.06
13.00	.06	.06	.06	.06	.06	.06	.06	.06
14.00	.06	.06	.06	.06	.06	.06	.06	.06
15.00	.06	.06	.06	.06	.06	.06	.06	.06
16.00	.00	.00	.00	.00	.00	.00	.00	.00
17.00	.00	.00						
18.00	.20	.04						
19.00	.25	.15	.00	.00				
20.00	.24	.17	.01	.00	.00			
21.00	.20	.15	.04	.00	.00	.00		
22.00	.16	.13	.05	.00	.00	.00	.00	
23.00	.12	.10	.04	.00	.00	.00	.00	.00
24.00	.09	.07	.03	.00	.00	.00	.00	.00
25.00	.06	.05	.02	.00	.00	.00	.00	.00
26.00	.04	.03	.00	.21	.00	.00	.00	.00
27.00	.02	.01	.00	.00	.00	.00	.00	.00
28.00	.00	.00	.00	.00	.00	.00	.00	.00
29.00	.00	.00	.00	.00	.00	.00	.00	.00
30.00	.00	.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N3 with a boat speed of 1.0 m/s in canal C10 (depth 1.0 m, width 10 m and slope 1:2)

	Y-distance from boat centerline [m]					
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50
0.00	.00	.00	.00	.00	.00	.00
1.00	.51	.51	.51	.26	.26	.26
2.00	.51	.51	.51	.26	.26	.26
3.00	.51	.51	.51	.26	.26	.26
4.00	.26	.26	.26	.26	.26	.26
5.00	.26	.26	.26	.26	.26	.26
6.00	.26	.26	.26	.26	.26	.26
7.00	.26	.26	.26	.26	.26	.26
8.00	.26	.26	.26	.26	.26	.26
9.00	.26	.26	.26	.26	.26	.26
10.00	.26	.26	.26	.26	.26	.26
11.00	.26	.26	.26	.26	.26	.26
12.00	.26	.26	.26	.26	.26	.26
13.00	.26	.26	.26	.26	.26	.26
14.00	.26	.26	.26	.26	.26	.26
15.00	.26	.26	.26	.26	.26	.26
16.00	.00					
17.00	.09	.00				
18.00	.21	.00	.00			
19.00	.15	.01	.00	.00		
20.00	.07	.00	.00	.00	.00	
21.00	.00	.00	.00	.00	.00	.00

22.00	.00	.00	.00	.00	.00	.00
23.00	.00	.00	.00	.00	.00	.00
24.00	.00	.00	.00	.00	.00	.00
25.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N3 with a boat speed of 1.0 m/s in canal C13 (depth 1.2 m, width 10 m and slope 1:2)

	Y-distance from boat centerline [m]					
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50
0.00	.00	.00	.00	.00	.00	.00
1.00	.40	.40	.40	.20	.20	.20
2.00	.40	.40	.40	.20	.20	.20
3.00	.40	.40	.40	.20	.20	.20
4.00	.20	.20	.20	.20	.20	.20
5.00	.20	.20	.20	.20	.20	.20
6.00	.20	.20	.20	.20	.20	.20
7.00	.20	.20	.20	.20	.20	.20
8.00	.20	.20	.20	.20	.20	.20
9.00	.20	.20	.20	.20	.20	.20
10.00	.20	.20	.20	.20	.20	.20
11.00	.20	.20	.20	.20	.20	.20
12.00	.20	.20	.20	.20	.20	.20
13.00	.20	.20	.20	.20	.20	.20
14.00	.20	.20	.20	.20	.20	.20
15.00	.20	.20	.20	.20	.20	.20
16.00	.00					
17.00	.00	.00				
18.00	.00	.00	.00			
19.00	.00	.00	.00	.00		
20.00	.00	.00	.00	.00	.00	
21.00	.00	.00	.00	.00	.00	.00
22.00	.00	.00	.00	.00	.00	.00
23.00	.00	.00	.00	.00	.00	.00
24.00	.00	.00	.00	.00	.00	.00
25.00	.00	.00	.00	.00	.00	.00

Distribution flow velocities over the canal width for boat N3 with a boat speed of 1.0 m/s in canal C14 (depth 1.2 m, width 12 m and slope 1:2)

	Y-distance from boat centerline [m]							
X-distance[m] from the bow	.00	.50	1.00	1.50	2.00	2.50	3.00	3.50
0.00	.00	.00	.00	.00	.00	.00	.00	.00
1.00	.30	.30	.30	.15	.15	.15	.15	.15
2.00	.30	.30	.30	.15	.15	.15	.15	.15
3.00	.30	.30	.30	.15	.15	.15	.15	.15
4.00	.15	.15	.15	.15	.15	.15	.15	.15
5.00	.15	.15	.15	.15	.15	.15	.15	.15
6.00	.15	.15	.15	.15	.15	.15	.15	.15
7.00	.15	.15	.15	.15	.15	.15	.15	.15

8.00	.15	.15	.15	.15	.15	.15	.15	.15
9.00	.15	.15	.15	.15	.15	.15	.15	.15
10.00	.15	.15	.15	.15	.15	.15	.15	.15
11.00	.15	.15	.15	.15	.15	.15	.15	.15
12.00	.15	.15	.15	.15	.15	.15	.15	.15
13.00	.15	.15	.15	.15	.15	.15	.15	.15
14.00	.15	.15	.15	.15	.15	.15	.15	.15
15.00	.15	.15	.15	.15	.15	.15	.15	.15
16.00	.00							
17.00	.00	.00						
18.00	.00	.00	.00					
19.00	.00	.00	.00	.00				
20.00	.00	.00	.00	.00	.00			
21.00	.00	.00	.00	.00	.00	.00		
22.00	.00	.00	.00	.00	.00	.00		
23.00	.00	.00	.00	.00	.00	.00		
24.00	.00	.00	.00	.00	.00	.00		
25.00	.00	.00	.00	.00	.00	.00		