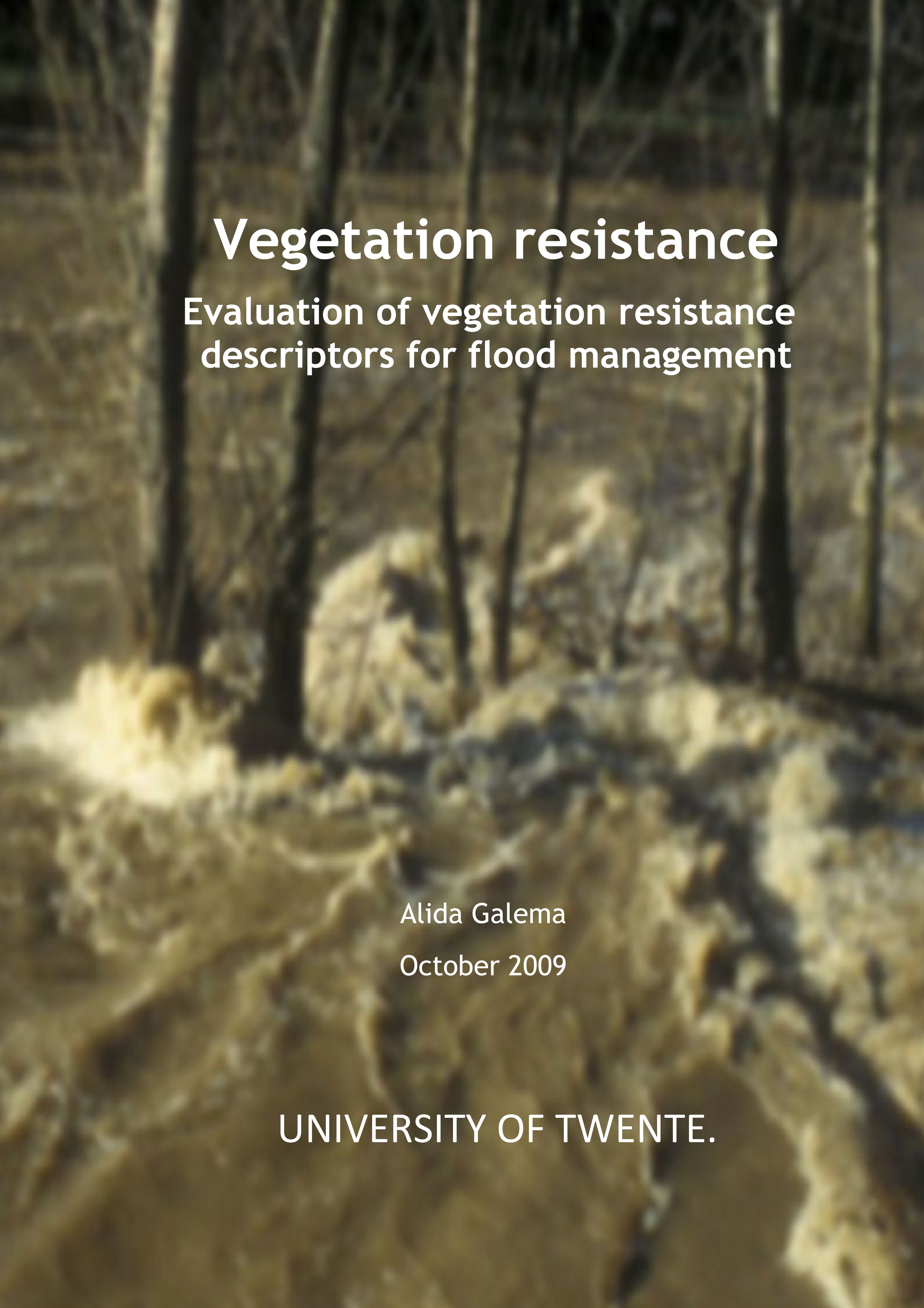

Vegetation resistance

Evaluation of vegetation resistance descriptors for flood management

Alida Galema

October 2009

UNIVERSITY OF TWENTE.

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Front cover: "Vegetation and flow interaction" (photo Bernhard, Leibniz-Institute of Freshwater Ecology and Inland Fisheries, Berlin)

Content

Preface

This report indicates the end of my Master Water Engineering & Management at the University of Twente. After finishing my Bachelor Civil Engineering at the Noordelijke Hogeschool at Leeuwarden, I decided to start my master at Enschede.
After finishing my pre-master course, and all the master courses, the final task is to finish the Master Thesis with good results.
My favourite master course was the course named “Shallow water flows”. Therefore, it was logical to choose as subject for the Master Thesis, the resistance in rivers caused by vegetation.

During this research I was supported by Denie Augustijn and Freek Huthoff. During our meetings they gave me feedback and made me enthusiastic. Even more important, their gave me self-confidence. However, most of all, I want to thank my supervisors for there understanding in times of bad news in family circle.
Moreover, I want to thank my family for there inerasable faith and support during my Master study. Special thank to my mom, for her weekly telephone calls, thanks to my dad for his car rides to the train station and thanks to my sister for her remarks on my English.
I also want to thank my friends, for there sociability and my (ex-) roommates for listening to my nagging and drinking lots of thee with me.

Ali Galema
Enschede, Oktober 2009

Abstract

For the prediction of the behaviour of water levels in rivers, computational river flow models are used. An important parameter of these models is the (hydraulic) flow resistance. The presence of vegetation has a major effect on the flow resistance. Last decades the stimulation of ecological functions around the river became more important, making proper prediction of the resistance caused by vegetation on river flows of vital importance for flood management.
For describing the influence of vegetation resistance on river flows several approaches are available. The aim of this research is to identify the practical suitability of different vegetation resistance descriptions, by compiling a data set of flow experiments and to use this data set to evaluate the ranges of applicability of different (existing) vegetation resistance descriptions.

Three descriptions were found for emergent rigid vegetation and seven useful descriptions were selected for submerged vegetation. An important description for emergent vegetation is the equation of Petryk and Bosmaijan (1975). The two other descriptions for emergent vegetation and the descriptions for submerged vegetation show resemblance with the equation of Petryk and Bosmaijan (for describing the velocity in the vegetation layer). Therefore, it was concluded that further investigation of descriptions for emergent vegetation were not necessary.
For submerged vegetation, most descriptions are based on the two layer theory, which makes a distinction between the velocity in the vegetation layer and in the surface layer. For defining the velocity in the vegetation layer, two different approaches are used. Two descriptors, Klopstra et al. (1997) with three definitions for the turbulent length scale and Huthoff (2007) define the velocity in the vegetation layer by taking the influence of the higher velocities in the surface layer into account. Three other descriptors, Stone and Shen (2002), Van Velzen et al. (2003) and Baptist et al. (2006) assume a constant velocity over the depth in the vegetation layer. Most of these descriptors define the velocity in the surface layer by a logarithmic profile, except the description of Stone and Shen (2002).
A theoretical description for flexible vegetation (even in the simplified form without side-branches and foliage) with input parameters which can be easily measured in the field is still lacking. However, the above mentioned descriptions for rigid vegetation are also used to predict the behavior of flexible vegetation. Therefore, these descriptions are also compared with data of flexible vegetation.

An existing data set from 10 different authors was used and extended with 6 new data sets from other literature. One of the main difficulties in deriving a data set from literature is the fact that authors uses different ways to determine the drag coefficient and slope, which makes comparison of different data sets hard. Therefore, a scheme is developed which can be used to correct existing data and to function as a manual for determining the drag coefficient and slope in deriving data from flume experiments with submerged rigid vegetation. The main assumption of the scheme is that the equation of Petryk and Bosmaijan (1975) is reliable enough to use for calculating the velocity, drag coefficient and/or slope in the vegetation layer. Because the new derived data sets performed well in comparison to the calculated velocities (R^2 = 95%) no big corrections were needed. Only when values for the drag coefficient were not given, a drag coefficient of 1 was assumed. However, assuming a drag coefficient of 1 for all the data showed no improvement.

The total data set consisted of 173 runs from 5 different authors for rigid vegetation and 133 runs from 11 different authors for flexible vegetation. Based on the comparison of the predicted and measured values for both rigid and flexible vegetation, it is concluded that

most theoretical descriptions defined for rigid vegetation can also be used for flexible vegetation (without side branches and leaves). However the predictions are less accurate for flexible vegetation. The description of Klopstra et al. (1997) with the turbulent length scale defined by Meijer (1998) and Van Velzen et al. (2003) and the descriptions of and Van Velzen et al. (2003) and Baptist et al. (2006) show good performance for rigid as well as for flexible vegetation. For water levels beneath 1 m these descriptions show an error of the water level smaller than 25 cm. For water levels above 1 m only one dataset was present, which was also used by four descriptors to define a parameter or a relation. Therefore, conclusions for higher water levels are lacking.
Besides the performance of the descriptions in predicting the resistance of rigid and flexible vegetation, other criteria are investigated like, easiness to use, theoretical soundness and adaptability to take side branches and leaves into account. Based on this study, the description of Klopstra et al. (1997) with the turbulent length scale defined by Meijer (1998) or Van Velzen (2003) performs best (and equally well) and could be used with the same confidence, although it is not a very simple expression. Care should be taken with all descriptions since none are perfect. Uncertainty in resistance predictions remains an issue to deal with in river modeling.

Notations & symbols

Roman

a	blockage area [m^2]
A	area of cross-section [m^2]
A_p	solidity (fraction of horizontal area taken by the cylinder)
A'	help variable
B'	help variable
C	Chézy roughness coefficient [$m^{1/2}/s$]
C_D	drag coefficient [-]
C'	help variable
D	diameter of cylindrical resistance elements [m]
E	modulus of elasticity resistance elements
E'	help variable
f	Weisbach roughness coefficient
F_D	drag force [N/m^3]
F'	help variable
g	gravitational acceleration [m/s^2]
h	water depth [m]
I	stem area's second moment of inertia
i_b	channel slope
k	height of resistance elements [m]
k_d	deflected height of resistance elements [m]
k_N	Nikuradse roughness height [m]
k_s	Stricklers roughness height [m]
l	wetted stem length [m]
l^*	submergence ratio
m	number of cylinders per m^2 horizontal area [m^{-2}]
n	Manning roughness coefficient
P	wetted perimeter [m]
R	hydraulic radius [m]
Re	Reynolds number
S	water level slope
s	separation individual resistance elements [m]
U	depth averaged velocity [m/s]
U_v	depth averaged velocity in vegetation layer [m/s]
U_{v0}	depth averaged velocity in vegetation layer for emergent vegetation [m/s]
U_s	depth averaged velocity in surface layer [m/s]
u'	turbulent velocity fluctuations in stream wise direction [m/s]
u_*	shear velocity [m/s]
u_k	velocity at the top of the resistance layer [m/s]
v'	turbulent velocity fluctuations in lateral direction [m/s]
w'	turbulent velocity fluctuations in vertical direction [m/s]
x	streamwise coordinate [m]
y	lateral coordinate [m]
z	vertical coordinate [m]
z_o	reference level near the bottom where the flow velocity is zero [m]

Greek

α	turbulent length scale
γ	Bos and Bijkerk coefficient
κ	Von Kármán's constant
ν	kinematic viscosity [m^2/s]
ρ	density of water [kg/m^3]
μ	dynamic viscosity [Pa·s]
τ	shear stress [N/m^2]
τ_b	bed shear stress [N/m^2]
τ_v	vegetation resistance force per unit horizontal area [N/m^2]
τ_w	streamwise component of the weight of the water mass [N/m^2]

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1. Project framework

Rivers all over the World have a high impact on the life in surrounding areas. In some cases because water is scarce, in other situations rivers are life threatening due to high peak discharges causing flooding.
In case of flood events it is very important to be able to predict associated water levels, and to predict the impact of possible measures to protect the surrounding area against flooding. Tools to predict the behaviour of rivers are computational river flow models. An important part of these models are the included (hydraulic) resistance. A proper description of the flow resistance is essential, because it largely determines local flow velocities and water levels.

The presence of vegetation has a major effect on the flow resistance. In floodplains, resistance to flow may be entirely determined by vegetation properties. In recent years, it became a trend in water policy to combine measures to prevent the hinterland from flooding and stimulating ecological functions at the same time. Therefore, current environmental river engineers prefer to preserve natural riverbank and floodplain vegetation (Järvelä, 2002). Thus, in order to cope with new management objectives, the influence of vegetation (which obstructs the flow) becomes important.

Many research initiatives have already been undertaken in order to describe the relationship between flow resistance and the presence and spatial distribution of vegetation. Analytical and experimental studies of vegetation-related resistance to flow have shown that the resistance coefficients are water depth dependent (Baptist et al., 2006). Also detailed plant characteristics (leafs, bending) may have an important influences on flow resistance (Freeman et al., 2000 and Järvelä, 2002). As a result of these studies, many resistance descriptions have been proposed. However there is no agreement on a most suitable approach for general application.

1.1. Problem description

Predicting the vegetation resistance is very complex since there are many different species with their own unique characteristics changing during the season. These plant characteristics are influencing the hydraulic resistance, which may vary significantly from place to place, and may also change in time. Therefore, an important aspect is the inhomogeneous character of the vegetation in the field, that is hard to take into account in modelling. Another important aspect of describing vegetation is the difference between flexible and rigid vegetation. The bending of vegetation decreases the height of the vegetation influencing the resistance. Moreover, the difference of submerged and non-submerged vegetation must be taken into account. These aspects are further explained in chapter 2.

There are many formulas available for describing vegetation resistance, ranging from simple wall roughness approximations to (semi-) empirical or theoretically derived resistance descriptions that are a function of flow and plant characteristics.
Empirical relations are suitable when modelling the hydraulic response to exactly those vegetation types, distribution of the vegetation, and flow conditions that were studied. However, extrapolations of these empirical relations to higher discharges are very unreliable, such extrapolations are often necessary because flow models are calibrated with field data of lower discharges (Augustijn et al., 2008). Alternatively, theoretical descriptions give generally more reliable results over a wide range of discharges. When the background of the different processes is understood, important relations and dependencies

between parameters can be derived. The first step in deriving theoretical descriptions is to use a simplified representation of vegetation. Understanding the background of a simplified representation is a useful basis for more complicated situations that include foliage and side-branching etcetera, even though, theoretical descriptions use sometimes empirical relations. However, either type of description have been tested in limited ranges of flow conditions, usually in relatively shallow waters, and give reasonable results in such conditions. Based on the different predictions of vegetation roughness descriptors, there remains a large uncertainty in flow response to the presence of vegetation at peak discharges, even though for flood management it is important to know the effects of peak discharges (Augustijn et al., 2008). According to Augustijn et al. (2008) the uncertainty can be considered too large for designing safety measures. Therefore, more data is required, in particular for large submergence ratios to establish, which description performs best under flood of flow conditions (Augustijn et al., 2008).
In conclusion, there is a need for a wide data set of flow experiments to evaluate the ranges of applicability of vegetation resistance descriptions and to improve reliability of predictions during floods.

1.2. Objective and research question

Based on the problem description, the objective of this research and research questions are formulated. *The aim of this research is to identify the practical suitability of different vegetation resistance descriptions, by compiling a wide data set of flow experiments and to use this data set to evaluate the ranges of applicability of different (existing) vegetation resistance descriptions, for predicting water levels for river management purposes.*

To reach the goal, the following research questions are identified:

1. *What descriptions can be found in literature that can be used to predict vegetation resistance and how are they derived?*

2. *What data can be found to use for comparison of these descriptions?*

3. *How accurate are the predictions of vegetation resistance by the different descriptions in comparison with field/experimental data?*

4. *Which description(s) is (are) most suitable for using in river management models?*

1.3. Layout of the report

In the following chapter, background information is given about the terminology that is often used in resistance descriptions. Firstly, the difference between the terms 'roughness' and 'resistance' is explained. Secondly, the difference between submerged and emergent vegetation is treated. Finally, the importance of plant characteristics like stiff and flexible vegetation is discussed. In chapter 3 the first research question will be answered, by giving an overview of different vegetation descriptions. Chapter 4 will answer the second research question, by describing the background of the collected data. Chapter 5 compares the descriptions from chapter 3 with the data described in chapter 4 and will answer research questions 3 and 4. The last chapter contains the conclusions and recommendations.

2. Vegetation resistance

As mentioned before, in describing the vegetation resistance, differences have been made between submerged, emergent, flexible and rigid vegetation. First the definitions of the terms ‘roughness’ and ‘resistance’ will be explained, because there is ambiguity about these terms. They are not defined quantities so its properties are related to the authors choice of definition. To make clear what is meant (in this study) by hydraulic roughness, and resistance to the flow, the definitions are given in the next section.

2.1. Roughness and resistance

Resistance accounts for the (boundary) turbulence caused by surface properties, geometrical boundaries, obstructions and other factors causing energy losses. Therefore, a resistance coefficient reflects the dynamic behaviour in terms of momentum or energy losses in resisting the flow of the fluid. Here, flow resistance is considered to be made up of four parts: skin drag, shape drag, form drag and some other factors, shown in Figure 1.

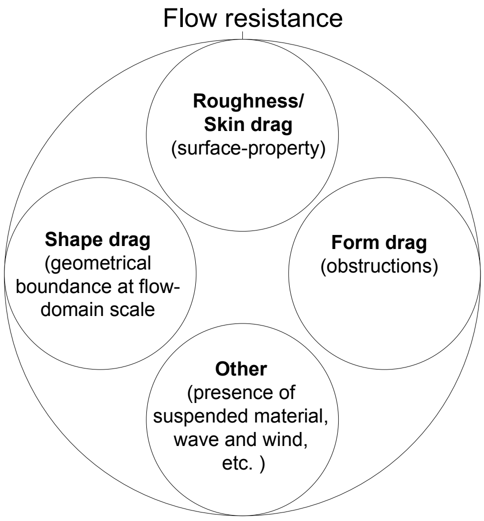

Figure 1: Flow resistance versus roughness

Roughness reflects the influence of the surface on the momentum and energy dissipation in resisting the flow of the fluid. Therefore, with a roughness factor the actual or effective unevenness of the boundary surface is meant.
Shape drag occurs as a result of the geometry of the channel (e.g. resistance due to overall channel shape, meanders, bends). The flow has a tendency to form vortices.
Form drag arises because of the form of the object (e.g. resistance due to surface geometry, bed forms, vegetation, structures).
Other factors, which can influence the resistance of the flow are the presence of suspended material in the flow, wave and wind resistance from free surface distortion etc.
Regarding the impact of vegetation on the flow field, “resistance” is used as it incorporates form drag and skin friction.

2.2. Submerged/ emergent vegetation

In describing vegetation resistance the height of the vegetation with respect to the water level is important because it influences the flow velocity profile. The flow velocity profile for submerged and emergent vegetation is very different so these are treated separately.

By means of figures of simplified rigid cylindrical vegetation without side branches and foliage, the difference between submerged and emergent vegetation is explained.
The following three different situations can be distinguished (Kleinhans, 2008):

1. Flow over well-submerged vegetation $h >> 5 \cdot k$
   With h water depth, and vegetation height k. As shown in Figure 2, the velocity in the deeper part of the river is delayed by the vegetation, however, the vegetation does not block the velocity at the upper part of the water column. When the water level is high enough, after a certain depth, the velocity becomes a logarithmic profile. At such large submergence ratios vegetation can be expressed as a rough surface and therefore can be approximated by a constant Manning coefficient (Augustijn et al., 2008).

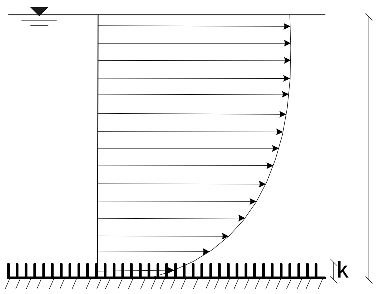

Figure 2: Flow velocity profile for well submerged vegetation

2. Flow through and over submerged vegetation $5 \cdot k > h > k$
   For submerged conditions the vegetation is relatively high in relation to the flow depth, as a consequence the velocity profile changes a lot over depth (shown in Figure 3). At the bed of the river, the velocity is influenced by the bottom roughness. Inside the vegetation sufficiently away from the bed and sufficiently away from the top of the vegetation, the velocity is uniform (Baptist et al. 2006). Near the top of the vegetation there is a transitional profile between the velocity inside the vegetation and the higher velocities above the vegetation.

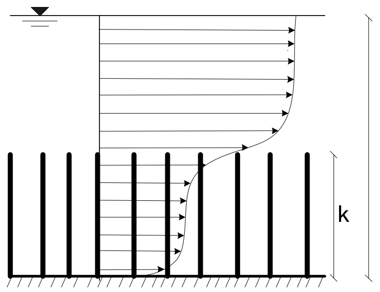

Figure 3: Flow velocity profile for submerged vegetation

3. Flow through emergent vegetation: $h < k$
   As shown in Figure 4 the velocity sufficiently far away from the bed is uniform. Near the bed, the velocity is lower, due to bottom roughness. With rigid cylindrical plants, the velocity becomes constant over depth (neglecting the bottom roughness).

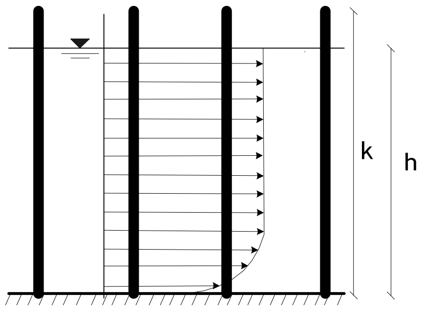

Figure 4: Flow velocity profile for emergent vegetation

2.3. *Rigid/ flexible vegetation*

In both submerged and emergent vegetation flexible elements are distinguished from that of rigid elements because the drag coefficient of flexible vegetation decreases when the vegetation is bending (shown in Figure 5). In Figure 5, k is the erected vegetation height and k_d is the deflected plant height.

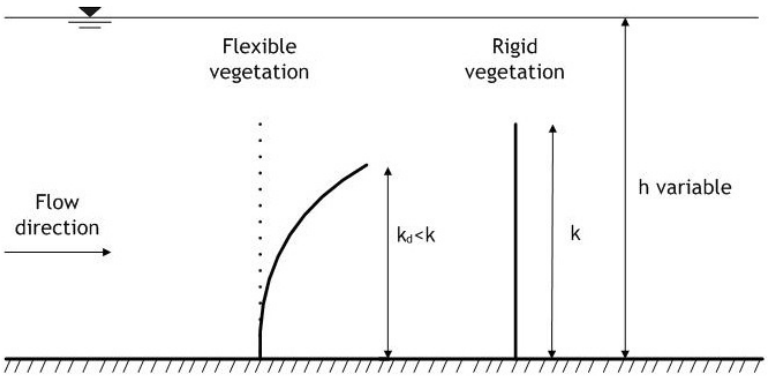

Figure 5: Flexible vegetation compared to rigid vegetation (Adapted from Carollo et al. 2005)

It is less complex to describe a theoretical equation for the resistance of rigid vegetation than for the resistance caused by flexible vegetation. The behaviour of flexible vegetation depends on the flow conditions making it more complex than rigid vegetation. For submerged vegetation, bending of the vegetation influences the mean velocity.

For submerged flexible vegetation, three different configurations can be distinguished depending on the flow velocity and the plant characteristics. These three configurations are shown in Figure 6 (Kouwen et al., 1969; Gourlay,1970 cited in Carollo et al., 2005).

1. Vegetation that is erected and do not change their position in time;
2. Vegetation that is subjected to a waving motion and, thus, change their position in time;
3. Vegetation that assumes a permanently prone position (bended forward).

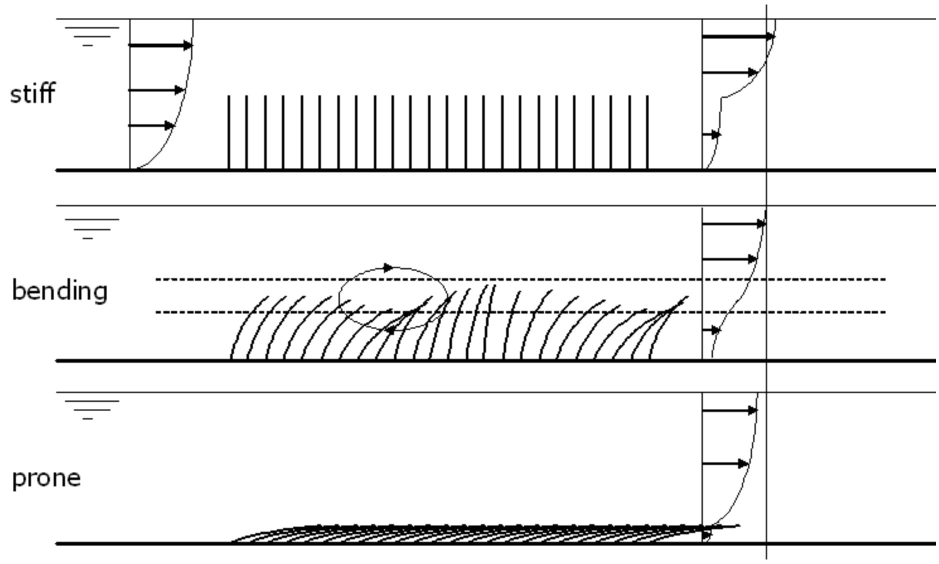

Figure 6: Configurations flexible vegetation (adapted from Dijkstra and Uittenbogaard, 2006)

At low flow velocities the flexible vegetation shows a rigid behaviour. In situation 2 and 3 the behaviour of the vegetation depends not only on the flow velocity but also on the bending stiffness of the vegetation. The difficulties of flexible vegetation are to determine the deflected vegetation height for each hydraulic condition and to take into account the vegetation concentration. For bending vegetation the vegetation height changes in time, leading to increases and decreases of resistance.

2.4. Foliage and side-branching

In the preceding sections, the vegetation is schematized as cylindrical stems without side-branches and leaves. In reality, most vegetation types have foliage and side-branches, which makes describing the vegetation resistance even more complicated. These branches and leafs move from side to side in the channels as a result of physical contact and flow interaction (Green, 2005). However, according to Meursing (1995) cited in Van Velzen et al. (2003), physical contact and interaction between plants are negligible when the distance between the vegetation is over 30 times the vegetation diameter.
At higher velocities the leaf mass shape changes and forms a streamlined, almost teardrop-shaped profile (Freeman et al., 2000). Due to streamlining, a decrease in the drag coefficient occurs and therefore a decrease in flow resistance. However, in case of streamlining, the flexibility of the vegetation plays a major role. Wilson et al. (2008) and also Freeman et al. (2000) concluded that the flow resistance of a plant may be significantly less for a flexible plant with considerable foliage compared to a less flexible plant with minimal foliage. It becomes clear that the resistance coefficient changes with changing velocity.

Due to natural variability, the position and amount of side branches and leaves may be different even for the same type of vegetation. Moreover, the flexibility of vegetation and the amount of leaves changes per season which makes describing the influence on the flow resistance very complex.

3. Vegetation resistance descriptions

In this chapter, several descriptions are introduced to describe the resistance of vegetation, ranging from general roughness descriptions, to descriptions that account for various vegetation characteristics. First traditional descriptions, which were originally derived to describe the roughness of the bottom and side-walls are mentioned. Next, newly developed resistance equations for describing the resistance caused by vegetation are explained and discussed.

3.1. *Traditional descriptions*

In history different formulas have been developed to describe the channel roughness. These formulas were first derived for pipes, however, they are now also used for describing resistance caused by vegetation.

3.1.1. Roughness descriptions with constant roughness coefficient

<u>Chézy (1769)</u>

A conventional approach for describing the roughness of the bottom and side walls is the uniform-flow formula established by the French engineer Antoine Chézy (1769):

$$U = C\sqrt{R \cdot i} \tag{1}$$

Where U is the velocity, i is the channel slope, C is the Chézy coefficient, which expresses the roughness of the bottom and walls and R stands for the hydraulic radius:

$$R = \frac{A}{P} \tag{2}$$

Where A is the cross section area and P the wetted perimeter.
In case of the Chézy coefficient, a higher value of the Chézy coefficient stands for a smoother bottom and wall.

The Chézy formula can be derived mathematically from two assumptions (Chow, 1959):

- The force resisting the flow per unit area of the stream bed is proportional to the square of the velocity
- In steady flow, the effective component of the gravity force causing the flow must be equal to the total force of resistance.

<u>Darcy-Weisbach (1845)</u>

A combination of the equation of Julius Weisbach (derived in 1845) and the formula of Henry Darcy (derived in 1858) resulted in the well known Darcy-Weisbach equation:

$$u = \sqrt{\frac{8g}{f}}\sqrt{Ri} \tag{3}$$

Where g is the gravitational acceleration and f is the Weisbach roughness coefficient, which can be derived from the Moody diagram. The above mentioned equation predicts the losses due to roughness of the flume wall and does not include shape drag caused by inlets, elbows and other fittings (Brown, 2002).

<u>Manning (1889)</u>

A roughness description commonly used is the uniform-flow formula for open-channel flow, derived by the Irish engineer Manning:

$$U = \frac{1}{n} R^{2/3} i^{1/2} \tag{4}$$

Where n is Manning's roughness coefficient.
This equation is developed from seven different formulas, based on Bazin's experimental data, and further verified by 170 observations (Chow, 1959). The equation is limited for water in rough channels at moderate velocities and large hydraulic radii (Fathi-Maghadam and Kouwen, 1997).
To determine the total channel resistance, values for the Manning coefficient are often determined by using tables such as Chow (1959).

Strickler (1923) derived an equation for the Manning coefficient with a dependence on the roughness height, which reflects the size of irregularities at the channel wall:

$$n = 0.04 k_s^{1/6} \tag{5}$$

Where k_s is the roughness height of Strickler.

For the three roughness equations mentioned above, the hydraulic radius R can be replaced by the water depth in case of wide channels (width >> depth). These equations are related in the following way:

$$\frac{U}{\sqrt{hi}} = C = \sqrt{\frac{8g}{f}} = \frac{1}{n} h^{1/6} \tag{6}$$

The Chézy equation and the Darcy-Weisbach equation show the same dependency on the slope and the water level. Manning's equation shows another dependency on the water level.

The above mentioned roughness descriptors are all empirical in character. In case of vegetated channels, these roughness descriptions can be used for vegetation with high submergence ratios h>>k. In that situation the vegetation can be approximated by a constant roughness coefficient (Augustijn et al. 2008).

3.1.2. Roughness coefficients dependent on flow characteristics

Instead of using a constant roughness coefficient, several equations are derived with a dependence of the roughness coefficient on flow characteristics.

Strickler (1923)

To determine the value of the Chézy coefficient with a dependence on the water level, the equation of Strickler can be used and requires an estimate of the Strickler roughness height:

$$C = 25(R / k_s)^{1/6} \tag{7}$$

The Strickler method is appropriate for uniform flow calculations where the R/k_s ratio is greater than 1 (HEC-RAS User's Manual, 2008). The stickler relationship gives reasonably estimates of the velocity profile for 4-<C<70 $m^{1/2}$/s.

Keulegan (1938)

Keulegan derived an equation for the Chézy coefficient which is applicable for rigid boundary channels and requires, just like the Strickler equation, an estimate of the roughness height:

$$C = 18 \cdot {}^{10}\log(12R / k_N) \tag{8}$$

Where k_N is the Nikuradse sand grain roughness. The Nikuradse sand gain roughness is similar to the roughness height of Strickler in the sense that they both reflect the size of irregularities on the channel bed.

In the Netherlands, the above mentioned equation is often referred to as the White-Colebrook equation.

<u>Manning's coefficient used in software</u>
In software (like MIKE-SHE or Sobek) the roughness equation of Manning is often used. Sometimes it is useful to define Manning's roughness in terms of predescribed functions:

$$n = a\ln(uR)^{b} \tag{9}$$

Or:

$$n = ah^{b} \tag{10}$$

Where a and b are empirical constants.

De Bos and Bijkerk (1963) derived an equation of the form of equation (10). With γ^{-1} for a, and 1/3 for b:

$$n = h^{1/3} / \gamma \tag{11}$$

Where γ is the De Bos and Bijkerk coefficient. For winter conditions a value of γ= 33.79 is recommended and γ= 22.53 for the summer (De Bos and Bijkerk, 1963).

Software packages like HEC-RAS and SOBEK allows roughness to be computed by five different methods. These methods are the Strickler equation, Keulegan equation, Limerinos equation, Brownlie equation, and the Soil Conservation Service equations for grass-lined channels (HEC-RAS User's Manual, 2008 and SOBEK-RE Flow Technical Reference, 2005). The last three methods are also used in MIKE-SHE.

3.2. *New approaches*

In this section, more recent attempts (last 50 years) to describe vegetation resistance, are presented. These descriptions are not directly based on the above mentioned roughness equations, however, sometimes they can be approached by these historical equations.
In this research theoretical descriptions are investigated. Most descriptions are derived for rigid vegetation. For all these theoretical descriptions the hydraulic response of vegetation is studied in an idealized form. Due to the complexity of flexible vegetation, theoretical descriptions for flexible vegetations are rare. Therefore a distinction between descriptions of rigid and flexible vegetation has been made.
First descriptions of the resistance of rigid vegetation are described containing a distinction between emergent vegetation and submerged vegetation. Finally, a section has been dedicated to flexible vegetation.

3.2.1. Rigid vegetation

For stiff cylindrical vegetation without foliage and side-branching, several theoretical descriptions for determining the resistance for emergent and/or submerged vegetation can be found in literature. For simplicity, a fixed and identical plant height and plant diameter for all individual plants is assumed, the vegetation is assumed to be a homogeneous field of identical stems, and the flow is considered steady and uniform.
Moreover, the channel is considered to be sufficiently wide, such that sidewall effects can be neglected. The bottom roughness is also neglected, because the influence of bottom roughness is very small in vegetated channels and accounts for less than 3% of the total resistance caused by vegetation (Stone and Shen, 2002). Other factors influencing the flow resistance like non-vegetative obstructions, channel form etcetera (shown in Figure 1) are neglected.

3.2.1.1. Emergent vegetation

The mean velocity of emergent vegetation is easier to calculate than the mean velocity of submerged vegetation, because the velocity is not influenced by a higher velocity above (and partly inside) the vegetation.

Petryk and Bosmaijan (1975)

Petryk and Bosmaijan (1975) derived an equation using the forces acting on the flow balanced with the drag force.

The forces acting on the flow are; gravity, shear forces on the boundary caused by viscosity and wall roughness and drag forces on the plants. For steady uniform flow, the sum of these forces in the streamwise direction are equal to zero. Because the bed shear stress is neglected the following equation is derived:

$$\rho \cdot g \cdot i - F_D = 0 \tag{12}$$

Where ρ is the density of water, and F_D is the drag force, which can be expressed as:

$$F_D = \frac{1}{2} C_D \cdot \rho \cdot U^2 \cdot a \tag{13}$$

Where a is the projected area of the vegetation and C_D is the drag coefficient. The projected area can be calculated multiplying the stem diameter of the cylindrical vegetation (D) with the number of cylinders per m^2 horizontal area (m).

Substitution of equation (13) in equation (12) and solving it for U gives the velocity inside the vegetation for emergent conditions:

$$U_{v0} = \sqrt{\frac{2g}{C_D \cdot m \cdot D}} \cdot \sqrt{i} \tag{14}$$

The equations are derived for a steady uniform flow. However, Petryk and Bosmaijan (1975) mention that equation (14) is also applicable to gradually varied flow conditions.

Stone and Shen (2002)

Stone and Shen derived an equation to determine the vegetation resistance validated by their laboratory study for submerged and emergent rigid vegetation with stems of various sizes and densities.

Stone and Shen (2002), started with the momentum balance in streamwise direction:

$$\tau_w = \tau_v + \tau_b \tag{15}$$

Where τ_w is the streamwise component of the weight of the water mass, τ_v is the resistance due to the drag around the cylinders and τ_b is the bed shear stress (which is neglected). The streamwise weight component of the water mass per unit bed area is:

$$\tau_w = \rho g h i (1 - A_p l^*) \tag{16}$$

Where A_p is the solidity, which is defined as the fraction of horizontal area taken by the cylinder:

$$A_p = \frac{1}{4} \pi D^2 m \tag{17}$$

The submergence ratio l* is expressed as:

$$l^* = \frac{l}{h} \tag{18}$$

Where l is the wetted stem length, which is the same as the water height for emergent vegetation. Therefore for emergent vegetation the submergence ratio is 1. Because this equation can also be used for submerged vegetation (explained in the next paragraph) the submergence ratio is shown in the following equations.

The stem drag force per unit bed area is:

$$\tau_v = \frac{1}{2} C_D \cdot \rho \cdot U_c^2 \cdot m \cdot D \cdot l \tag{19}$$

Where U_C is the maximum velocity in the vegetation layer, instead of the often-used apparent vegetation layer velocity U_v. The apparent vegetation layer velocity is defined as the discharge in the vegetation layer over the gross cross-sectional are, Bl (B is the channel width). The relationship between these two velocity's is obtained by Stone and Shen (2002) from continuity of flow in the stem layer, $U_vB=U_cB_c$ in which B_c is the minimum channel flow width at a constricted cross section:

$$B_c = B\left(1 - D\sqrt{m}\right) \tag{20}$$

Therefore:

$$U_v = U_c\left(1 - D\sqrt{m}\right) = U_c\left[1 - \sqrt{\frac{4A_p}{\pi}}\right] \tag{21}$$

Substituting equation (16) and (19) in equation (15), using equation (21) and neglecting the bed shear stress gives:

$$\rho ghi(1 - \frac{1}{4}\pi \cdot D^2 \cdot m \cdot l^*) = \frac{1}{2} C_D \cdot \rho \cdot U_v^2 \cdot \left(1 - D\sqrt{m}\right)^2 \cdot m \cdot D \cdot l \tag{22}$$

From the above shown equation and using the fact that l=h and l*=1 for emergent vegetation the velocity for emergent vegetation can be expressed as:

$$U_{v0} = \sqrt{\frac{2g}{C_D \cdot m \cdot D}}\sqrt{i}\sqrt{\left(1 - D\sqrt{m}\right)\cdot\left(1 - \frac{1}{4}\pi \cdot m \cdot D^2\right)} \tag{23}$$

In contrast to the description of Petryk and Bosmaijan (1975), Stone and Shen (2002) take the solidity (the fraction of horizontal area taken by the cylinders) into account. Without the solidity, the description of Stone and Shen (2002) reduces to the equation of Petryk & Bosmaijan (1975) equation (14).

<u>Hoffmann (2004)</u>

Hoffmann (2004) developed a space-time averaged form of the Navier-Stokes equation treating the vegetation as a porous media. Reynolds averaging is used for the turbulent flow and volume averaging is used in order to take the vegetation into account. The obstacle density is modeled by a porosity term and structural parameters of the vegetation are taken into account.

Hoffmann (2004) averaged the Navier-Stokes equation in time and volume. Next he defined the closure term needed in the time and volume averaged Navier-Stokes equation. This closure term describes the interaction of the flow with the porous media and takes into account the extra drag exerted on the fluid due to the presence of the plant stems, based on the macroscopic variables.
Hoffman (2004) choose to express the combined influence of viscous drag and the pressure drag in a combined drag force approach to define the closure term.

To determine the drag coefficient Hoffmann (2004) used the correlation by Taylor et al. (1985) (cited in Hoffmann, 2004) who used a discrete element approach to derive:

$$\log C_D = -0.125 \log \mathrm{Re} + 0.275 \tag{24}$$

With the Reynolds number (Re) defined as:

$$\mathrm{Re} = \frac{\rho \cdot \mu \cdot h}{\nu} \tag{25}$$

Where v is the kinematic viscosity and μ is the dynamic viscosity.

Assuming steady, hydrostatic pressure distribution, flows driven by the bed slope i and using the relation between the porosity and the representative unit cell (RUC) gives:

$$U_{v0} = \sqrt{\frac{2g}{C_D \cdot D}}\sqrt{i} \cdot \sqrt{sh - \frac{1}{2}\pi D^2} \tag{26}$$

Where the separation between cylinders s is defined as:

$$s = \frac{1}{\sqrt{m}} \tag{27}$$

Equation (27) shows the distance between the center of two cylinders instead of the distance between the cylinders. It is not always clear which distance is used. Therefore, special attention should be given to this parameter when it is used by an author of a method to determine the resistance of vegetation.

The description of Hoffmann (2004) differs from the other two models because the porosity (area taken by the cylinders in m^3/m^3) is taken into account.
The description is restricted for vegetation with a stem geometry like reed with high porosities (values between 0.8 and 0.99). When the porosity is 1 (volume of the flume/volume of the RUC), equation (26) reduces to the equation of Petryk and Bosmaijan (1975), equation (14).

3.2.1.2 Submerged vegetation

In contrast to the constant velocity over depth for emergent vegetation (neglecting the bed shear stress), the velocity in the vegetation layer for submerged conditions increases as the water surface is approached (shown in chapter 2). Due to higher velocities in the surface layer above the vegetation, a shearing effect in the vegetation layer occurs. Because of the difference in velocity in these two layers, vegetation descriptions for submerged vegetation are often based on a two-layer approach as shown in Figure 7. The two-layer approach describes the velocity inside the vegetation layer separately from the velocity inside the layer above the vegetation, the so called surface layer. The mean velocity inside the vegetation (U_v) is often assumed to be constant (except by Klopstra et al., 1997 and Huthoff, 2007). Above the vegetation often a logarithmic profile is assumed for the velocity distribution in the surface layer (U_s).

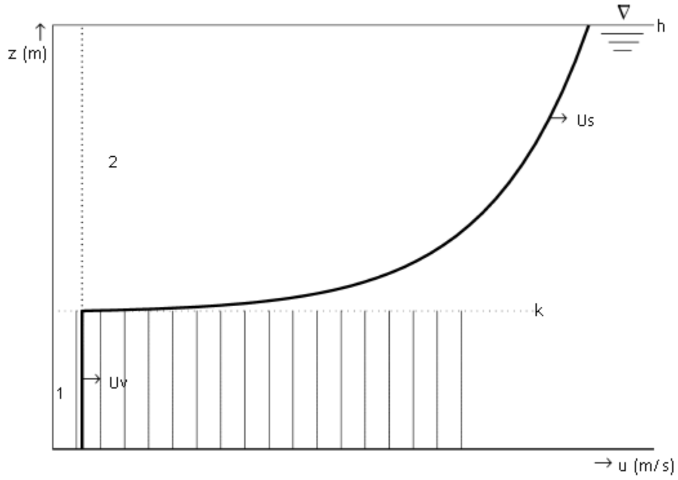

Figure 7: Two layer approach (adapted from: Baptist et al. 2006)

Borovkov and Yurchuk (1994)
Borovkov and Yurchuk derived an equation for the resistance of submerged vegetation based on flume experiments. They formulated a functional dependence of the main factors which influence the resistance. Using the theory and laboratory investigations from Tai (1973), Kouwen et al. (1969), Chow (1959 Besserbrennikov (1958) and Ludov (1976), Borovkov and Yurchuk (1994) derived an equation.

The velocity is based on the Darcy-Weisbach formula and is defined as:

$$U = \sqrt{\frac{8g \cdot h \cdot i}{f}} \tag{28}$$

Where f is the Darcy-Weisbach's friction factor. Using the experimental data, Borovkov and Yurchuk (1994) defined the friction factor as:

$$\frac{1}{\sqrt{f}} = K\left(\frac{h}{k}\right)^{\sqrt{f}} \cdot \sqrt{\frac{s}{k \cdot D \cdot C_D}} \tag{29}$$

With:

$$s = \frac{1}{\sqrt{m}}$$

Where K is an unknown factor of proportionality. However, from a figure presented in the paper of Borovkov and Yurchuk (1994) the value of K can be determined;

$$K = 0.4 \tag{30}$$

The value of K is the same as the Von Karman constant which is used in describing the logarithmic velocity profile of a turbulent steady and uniform flow near a boundary.

The description of Borovkov and Yurchuk (1994) is implicit and derived from data. Therefore, this description will not be used to compare with the data.

Klopstra et al. (1997)
The method of Klopstra et al. (1997) is incorporated in the two-dimensional WAQUA models, which is used in the Netherlands for modeling.
In this method average flow velocities inside and above the vegetation are combined to yield the average velocity over the total depth:

$$U = \frac{k}{h}U_v + \frac{h-k}{h}U_s \tag{31}$$

U_v is defined as:

$$U_v = \frac{2}{k\sqrt{2A'}}\left(\sqrt{C'\cdot e^{k\sqrt{2A'}} + U_{v0}} - \sqrt{C' + U_{v0}}\right) + \frac{u_{so}}{k\sqrt{2A'}}\cdot \ln\left[\frac{\left(\sqrt{C'\cdot e^{k\sqrt{2A'}} + U_{v0}^2} - U_{v0}\right)\left(\sqrt{C' + U_{v0}^2} + U_{s0}\right)}{\left(\sqrt{C'\cdot e^{k\sqrt{2A'}} + U_{v0}^2} + U_{s0}\right)\left(\sqrt{C' + U_{v0}^2} - U_{v0}\right)}\right] \tag{32}$$

And U_s follows from:

$$U_s = \frac{u_*}{\kappa(h-k)}\left((h-(k-a))\ln\left(\frac{h-(k-a)}{z_o}\right) - a\cdot\ln\left(\frac{a}{z_o}\right) - (h-k)\right) \tag{33}$$

Where A' is a is help variable:

$$A' = \frac{C_d \cdot a}{2\alpha} \tag{34}$$

With turbulent length scale α derived by Van Velzen et al. (2003) from experimental data:

$$\alpha = 0.0227k^{0.7} \tag{35}$$

The flow velocity through the vegetation U_{v0} equation (14) derived by Petryk and Bosmaijan (1975) is used.

Help variable C' is expressed as:

$$C' = \frac{-2B'(h-k)}{\sqrt{2A'}\cdot\left(e^{k\sqrt{2A'}} + e^{-k\sqrt{2A'}}\right)} \tag{36}$$

The help variable B is defined as:

$$B' = -\frac{gi}{\alpha} \tag{37}$$

One of the parameters, which is necessary to determine U_s is the shear velocity for the surface layer u_*:

$$u_* = \sqrt{g(h-(k-a))\cdot i} \tag{38}$$

The penetration depth a is defined as:

$$a = \frac{1 + \sqrt{1 + \frac{4\cdot E'^2\cdot\kappa^2\cdot(h-k)}{g\cdot i}}}{\frac{2\cdot E'^2\cdot\kappa^2}{g\cdot i}} \tag{39}$$

Where help variable E' is defined as:

$$E' = \frac{\sqrt{2A'}\left(C'\cdot e^{-k\sqrt{2A'}} + C'\cdot e^{k\sqrt{2A'}}\right)}{2\sqrt{-C'e^{-k\sqrt{2A}} + C'e^{k\sqrt{2A}} + U_{v0}^2}} \tag{40}$$

For determining the roughness height of the surface layer the following formula can be used:

$$z_o = a \cdot e^{-F'} \tag{41}$$

Where help variable F' can be defined as:

$$F' = \frac{\kappa \cdot \left(\sqrt{-C' \cdot e^{-k\sqrt{2A'}} + C' \cdot e^{k\sqrt{2A'}} + U_{v0}^2} \right)}{\sqrt{g(h-(k-a)) \cdot i}} \tag{42}$$

Alternative turbulent length scales

The turbulent length scale α of Van Velzen et al. (2003) is empirically determined. There are also other authors who derived an equation for this parameter. Meijer (1998b) used the results of 56 flume tests and derived empirically the following relation:

$$\alpha = 0.0144\sqrt{hk} \qquad \text{(Meijer, 1998b)} \tag{43}$$

Another formula for the turbulent length scale is defined by Huthoff (2007). Base on the same experiments as used by Meijer (1998b) He found the highest coefficient of correlation (R^2) for the relation:

$$\alpha = (0.39)\frac{sh}{2b(h-k)} \qquad \text{(Huthoff, 2007)} \tag{44}$$

With drag length b defined as:

$$b = \frac{1}{C_D mD} \tag{45}$$

All the above mentioned turbulent length scales will be used in combination with the method of Klopstra et al. (1997). To avoid long names in tables, the different descriptions of the turbulent length scale are called a, b and c:

- Klopstra (a) = turbulent length scale derived by Meijer (1998b) equation (43).
- Klopstra (b) = turbulent length scale derived by Van Velzen et al. (2003) equation (35).
- Klopstra (c) = turbulent length scale derived by Huthoff (2007) equation (44).

Van Velzen et al. (2003)

Van Velzen et al. assumed a flow velocity in the vegetation layer that is unaffected by surface layer flow and used the equation (14) of Petryk and Bosmaijan (1975):

$$U_v = U_{v0} = \sqrt{\frac{2g}{C_D \cdot m \cdot D}}\sqrt{i} \tag{46}$$

The flow in the surface layer is described by a logarithmic term (based on the Keulegan equation), superimposed on the velocity in the resistance layer:

$$U_s = U_{v0} + 18\sqrt{(h-k)i} \cdot \log\frac{12(h-k)}{k_N} \tag{47}$$

The roughness height is given by an empirical function, obtained from regression analysis using the data of Meijer (1998b):

$$k_N = 1,6k^{0.7} \tag{48}$$

The average flow velocity over the entire flow depth used by Van Velzen et al. (2003) is the same as equation (31).

The description for surface layer and resistance layer together yield:

$$U = \sqrt{\frac{2g}{C_D \cdot m \cdot D}}\sqrt{i} + 18(h-k)^{3/2}\frac{\sqrt{i}}{h}\cdot\log\frac{12(h-k)}{k_N} \tag{49}$$

Stone and Shen (2002)

Equation (22) given by Stone and Shen is used to describe the mean velocity inside the vegetation layer using the following submergence fraction:

$$l^* = \frac{k}{h} \tag{50}$$

To calculate the apparent channel velocity the following relationship is given between the velocity in the vegetation layer and the apparent channel velocity:

$$U = \frac{U_v}{\sqrt{l*}} \tag{51}$$

Using equation (22), (50) and (51) the mean velocity can be predicted with the following relationship:

$$U = \sqrt{\frac{2g}{C_D \cdot m \cdot D}}\sqrt{i}\cdot\left(1 - D\sqrt{m}\right)\cdot\sqrt{\left(\frac{h}{k} - \frac{1}{4}\pi \cdot D^2 \cdot m\right)\cdot\frac{h}{k}} \tag{52}$$

Baptist et al. (2006)

From the momentum balance for flow through submerged vegetation Baptist et al. (2006) used the following equation to represent the velocity inside the vegetation layer:

$$U_v = \sqrt{\frac{2g}{C_D \cdot m \cdot D}}\sqrt{i}\cdot\sqrt{\frac{h}{k}} \tag{53}$$

With genetic programming Baptist et al. (2006) derived a formula for the velocity inside the surface layer. Genetic programming is a technique that can be used to find the symbolic form of an equation, including a set of coefficients. Baptist et al. (2006) used a set of 990 model simulation results of a more detailed flow model of a wide variety of cylinders and water depths.

The equation for the mean velocity found by Baptist et al. (2006) is:

$$U = \left(\sqrt{\frac{2g}{C_D m D k}} + \frac{\sqrt{g}}{\kappa}\ln\left(\frac{h}{k}\right)\right)\sqrt{hi} \tag{54}$$

The first term in the above mentioned formula is the same formula derived by Petryk & Bosmaijan (1975) for emergent vegetation. The second term is the same as the Keulegan equation (8) with k_N = 12*k.

Huthoff (2007)

Using scaling assumptions, Huthoff (2007) derived an analytical expression for bulk flow through and over vegetation.

Huthoff (2007) defined the velocity in the vegetation layer as equation (53).

The velocity in the surface layer is defined as:

$$U_s = \sqrt{\frac{2gi}{C_D mD}} \cdot \left(\frac{h-k}{s}\right)^{2/3\left(1-\left(\frac{h}{k}\right)^{-5}\right)} \tag{55}$$

With s defined as:

$$s = \frac{1}{\sqrt{m}} - D \tag{56}$$

The term $\left(1-\left(\frac{h}{k}\right)^{-5}\right)$ in equation (55) can be neglected if h>k.

Using equation (31) to determine the average flow velocity over the entire flow depth and using equation (53) and (55) results in:

$$U = \sqrt{\frac{2gi}{C_D mD}} \left(\sqrt{\frac{k}{h}} + \frac{h-k}{h}\left(\frac{h-k}{s}\right)^{2/3}\right) \tag{57}$$

When h becomes large the above mentioned formula approaches:

$$U = \sqrt{\frac{2g}{C_D \cdot m \cdot D \cdot s^{4/3}}} h^{2/3} \sqrt{i} \tag{58}$$

Equation (58) show the same dependency on the water level and the slope as the Manning equation (4).

3.2.2. Flexible vegetation

In the sections before, descriptions of vegetation resistance are introduced, for rigid submerged and emergent vegetation. For flexible vegetation most descriptions are empirically determined, due to its complexity a theoretical based description is lacking. However, knowledge of flow resistance in channels with rigid vegetation provides the basis for analyzing flow resistance with flexible stems (Stone and Shen, 2002).

Kutija and Hong (1996) demonstrated that formulas developed for rigid vegetation could be extended to include the effects of plant flexibility by an iterative method using a simple cantilever beam theory. Similar methods have been proposed by Thompson and Roberson (1976) and Manz and Westhoff (1998) as cited in Stone and Shen (2002). However, defining the flexibility of the stem and the associated deflected vegetation height is very complicated. Most descriptions use the elasticity of the vegetation to calculate the deflected vegetation height. For example, Kouwen and Unny (1973) suggested to establish values of mEI (stem density · elasticity · stem area's second moment of inertia) empirically to define the deflected vegetation height. However, there are a lot of arguments against such methods:

- Fischenich (2000) mentioned that the mEI value has been proven to be difficult to measure in the field, and has no direct physical meaning.
- The flexibility changes during season and depends whether the vegetation is in dormant or in growth.
- Wilson (2007) argued that the flexibility of an individual grass blade is difficult to determine and highly variable; variations in modulus of elasticity of up to 100% can occur between samples. Moreover, densely packed groups of blades will have different bending properties compared to a single blade, hence correlating

deflected height as a function of bending stiffness may be inappropriate (Wilson, 2007).

Even in a simplified form, neglecting waving of the vegetation and side branches and foliage, it is very complicated to take the flexibility into account and to determine deflected vegetation height.

3.3. *Conclusions*

From literature it is known that constant roughness parameters are not useful for describing vegetation resistance. Except for very large submergence ratios (h>>k), vegetation could be calculated with a constant roughness coefficient (Augustijn et al. 2008).
Petryk and Bosmaijan (1975) derived an equation for flow through emergent vegetation. Two other descriptors for emergent rigid vegetation also resemble the equation of Petryk and Bosmaijan (1975) taking the solidity or porosity into account. However, from literature it is known that the effects of the solidity and porosity are small (Baptist et al., 2006). Most of the descriptions found in literature for submerged vegetation also use the equation of Petryk and Bosmaijan (1975). Moreover, results from many studies comparing the equation of Petryk and Bosmaijan (1975) with flume experiments show that this method predicts the velocity for rigid cylindrical emergent vegetation well. Because of these arguments, no further investigation of resistance descriptions for emergent vegetation is carried out in this research. In addition, the processes for submerged conditions are less clear. Therefore, theoretical descriptions for cylindrical rigid submerged vegetation are compared with data. The method of Borovkov and Yurchuk (1994) is implicit and empirical, so that method is discarded.

For flexible vegetation, no theoretical descriptions have yet been found. All descriptions use empirical parts, depending on the vegetation specie. Because of the lack of a theoretical description, descriptions defined for rigid vegetation are often used to determine the resistance of flexible vegetation neglecting parameters which are difficult to determine (for example swaying or vibrating vegetation). For submerged vegetation, bending of the vegetation results in a reduction of the drag coefficient and results in a smaller resistance layer, and a thicker surface layer (Fathi-Maghadam and Kouwen, 1997). The velocity for flexible vegetation will be higher with respect to the same plant characteristics and flow conditions for rigid vegetation. Therefore, it is interesting to investigate how well simplified theoretical equations can predict the behavior of the more complex flexible vegetation. In the next chapter, not only data of rigid vegetation, but also data of flexible vegetation will be collected. In chapter 5 the descriptors for rigid vegetation will also be compared with data of flexible vegetation.

In conclusion, the descriptors which will be compared with the data are listed in Table 1.

AUTHOR	EQUATION
Klopstra et al. (1997)	$U = \frac{k \cdot U_v + (h-k) \cdot U_s}{h}$ With sub-descriptions for U_v and U_s and three different definitions for the turbulent length scale.
Stone and Shen (2002)	$U = \sqrt{\frac{2g}{C_D \cdot m \cdot D}} \sqrt{i} \cdot \left(1 - D\sqrt{m}\right) \cdot \sqrt{\left(\frac{h}{k} - \frac{1}{4}\pi m D^2\right) \cdot \frac{h}{k}}$
Van Velzen et al. (2003)	$U = \sqrt{\frac{2g}{C_D \cdot m \cdot D}} \sqrt{i} + 18(h-k)^{3/2} \frac{\sqrt{i}}{k} \cdot \log \frac{12(h-k)}{1.6 \cdot k^{0.7}}$
Baptist et al. (2006)	$U = \left(\sqrt{\frac{2g}{C_D \cdot m \cdot D}} \sqrt{i} \cdot \sqrt{k} + \frac{\sqrt{g}}{\kappa} \ln\left(\frac{h}{k}\right) \cdot \sqrt{i} \right) \sqrt{h}$
Huthoff (2007)	$U = \sqrt{\frac{2g}{C_D \cdot m \cdot D}} \sqrt{i} \cdot \left(\sqrt{\frac{k}{h}} + \frac{h-k}{h} \left(\frac{h-k}{s} \right)^{2/3} \right)$

Table 1: Overview of vegetation resistance descriptors for submerged vegetation

Every equation needs the following parameters: acceleration due to gravity, channel slope, water depth, vegetation height, drag coefficient, bed surface density of the vegetation and the stem diameter of the vegetation.

4. Inventory data

In this chapter flume data of different authors have been collected and compared. A data set for submerged vegetation used in the article of Augustijn et al. (2008) was available including results from 10 studies. To extend the present data set new data from other literature has been added.

In the present data set only one experimental field study has been included. The others have been performed in a laboratory. The large number of meaningful parameters and other influences which occur with field measurements, makes a laboratory environment preferable above field tests.
Another remark is the fact that in most flume experiments “resistance elements” are used to simulate the vegetation instead of real vegetation.

4.1. Available data set

The data used in the article of Augustijn et al. (2008) was available for this research and is also used by other authors. To check the reliability of this dataset, as far as possible, the background information about these data is researched, explained and discussed in this section.
The data used in the above mentioned article can be divided in flexible and rigid vegetation, all for submerged conditions.
Data for rigid vegetation:

- Tsujimoto and Kitamura (1990)
- Dunn et al. (1996)
- Meijer (1998b)

Data for flexible vegetation:

- Kouwen et al. (1969)
- Ree and Crow (1977)
- Murota et al. (1984)
- Tsujimoto et al. (1993a)
- Ikeda and Kanazawa (1996)
- Meijer (1998a)
- Järvelä (2003)

The data of the above mentioned authors is added in appendix A.

For each flume experiment, the following aspects are treated: first the aim of the experiment is mentioned, second the way of determining the slope is described and finally some information is given about the drag force. For flexible vegetation the used plant height is also mentioned; the normal plant height, or the deflected plant height, because it is a point of discussion which plant height should be used.
At the end of this section an overview of the technical properties and vegetation types is summarized in Table 2. Unfortunately, the article Tsujimoto and Kitamura (1990) and the article of Kouwen et al. (1969) were not available, therefore, these data sets are not described below.

<u>Dunn et al. (1996)</u>
In a report of Dunn et al. (1996) 18 experiments are described. The first twelve experiments are with rigid vegetation (also described in López & García (2001)), the last six experiments are conducted with flexible vegetation.

- The intent of the investigation of Dunn et al. (1996) was to measure the flow and turbulence structure in and above vegetation.

- Channel slopes of the used channel could be set from 0 to 10 percent because the flume was equipped with a mechanism which allowed it to be tilted, to adjust the bed slope.
- Dunn et al. (1996) found that the value of the drag coefficient rigid cylindrical vegetation in open channels is not constant in the vertical; the value reaches a maximum at a distance close to one third of the height with a mean value close to 1.13. This value for the drag coefficient is used in the dataset.
- The deflected plant heights (for the six experiments with flexible vegetation) given in the report of Dunn et al. (1996) did not agree with the values in the dataset. Therefore the values in the data set are adapted.

<u>Meijer (1998b)</u>

- The goal of the experimental setup of Meijer (1998b) was to validate the analytical model of Klopstra et al. (1996), which predicts the velocity profiles and the hydraulic roughness for submerged vegetation.
- The slope is determined by measuring the water levels at the beginning and the end of the flume.
- The drag coefficient is calculated using the equation of Petryk and Bosmaijan (1975), using the measured velocity in the vegetation layer.

Remark: an interesting feature of these experiments are the high water levels (1 to 2.50 m) with large vegetation heights (0.45 to 1.50 m).

<u>Ree and Crow (1977)</u>

- Ree and Crow (1977) conducted experiments in the field over a 4-year period to determine the friction factors for vegetated waterways with small slope. The cross section of the channel was trapezoidal. Very steep side banks of 1:1¼ were used to approximate a rectangular cross section.
- The slope was calculated by dividing the difference of the water level by the length of the reach (46 m).
- No information about the drag coefficient is given by the author. However, in the available data values were given for the drag coefficient.
- Ree and Crow (1977) did not measure the deflected plant height. Therefore, the erected plant height is used.

Ree and Crow used living plants (wheat).

<u>Murota et al. (1984)</u>

- The objective of the study of Murota et al. (1984) was to investigate the effects of sway of flexible standing resistance elements on the profiles of mean velocity, turbulence intensities and Reynolds stress.
- The author did not mention how the slope was determined.
- The drag coefficient is not measured in this experimental study with swaying vegetation. However, in the data set, a value of 2,75 is given. It is unknown how this value was determined.
- The deflected plant height was given by the author, and is used in the dataset.

<u>Tsujimoto et al. (1993)</u>

- Tsujimoto et al. (1993) investigated the turbulent characteristics of flow over flexible vegetation which is simulated by flexible nylon cylinders with beads at their heads.
- It is not mentioned how the slope is measured.
  In the dataset, the Chézy coefficient is given (probably calculated from the slope, because Tsujimoto et al. (1993) did not mention the Chézy coefficient). Using the Chézy coefficient the slope can be calculated. Using that equation to compare the

given slope by the calculated slope, it becomes clear that for run BZ 3 the value in table 1 of the article of Tsujimoto et al. (1993) is 0.00005 and the calculated value is 0.0005. It is probably a fault in the table because otherwise a Chézy coefficient around 30 would be used, which is very smooth in comparison to the other Chézy values in these data set. Therefore, the slope for run BZ 3 is adapted in the available dataset.

- Tsujimoto et al. (1993) mention that the drag force can be calculated using the equation of Petryk and Bosmaijan (1975) and the measured velocity in the vegetation layer. However, the velocity in the vegetation is not given, only the mean velocity. Therefore it is unknown which value was used to determine the drag coefficient. In the data set a value of 2 is used for the drag coefficient.
- The deflected vegetation height is used.

Ikeda and Kanazawa (1996)

- Ikeda and Kanazawa (1996) studied open channel flow over flexible bottom vegetation.
- Ikeda and Kanazawa (1996) did not mention how they determined the channel slope.
- The drag coefficient is not measured during the experimental study of Ikeda and Kanazawa. However, in the data set a value of 1 is mentioned for the drag coefficient. From literature it is known that a drag coefficient of 1 for rigid vegetation is acceptable. However, it is questionable if this yields also for flexible vegetation, because bending of the vegetation decreases the drag coefficient. However, it is assumed that a drag coefficient of 1 can also be used for flexible emergent vegetation.
- The deflected plant height is used.

Meijer (1998a)

These data are derived under the same experimental setup as explained for Meijer (1998b). The only difference is the fact that instead of using vertical steal bars, natural reed is used. The deflected plant height was not measured.

Järvelä (2003)

- Järvelä (2003) carried out a flume study to investigate flow structures for relatively low velocities and vegetation typical for floodplains and wetlands, such as grasses and bushes.
- The author did not mention how the slope was determined.
- Järvelä (2003) did not mention the drag coefficient. Therefore a value of 1 is assumed.
- Järvelä (2003) gave the deflected plant height.

Järvelä (2003) used living plants in the experimental study (wheat and sedges).

Author(s)	Number of experiments	Dimensions flume (LxWxH)	Vegetation type	Measured velocity
Dunn et al. (1996)	5	L = 19,50 m W = 0,91 m H = 0,61 m	Cylindrical wooden dowels	Acousic Doppler velocimeter
Meijer (1998b)	48	L = 100 m W = 3 m H = 3 m	Vertical steel bars	Acoustic Doppler Velocimeter
Ree and Crow (1977)	14	L = 183 m W = 6,1 m H = 0,91 m & 1,30 m	Natural flexible vegetation	2-foot Parshal flume and with the weir
Murota et al. (1984)	8	L = 20 m W = 0,5 m H = 0,35 m	Flexible standing elements of synthetic resin	Constant-temperature anemometer with a dual censor hot film probe
Tsujimoto et al. (1993)	12	Not mentioned	Flexible nylon cylinders	Electromagnetic currentmeter
Ikeda & Kanazawa (1996)	7	L = 15 m W = 0,4 m	Nylon filaments	Two-component laser Doppler velocimeter
Meijer (1998a)	7	L = 100 m W = 3 m H = 3 m	Natural reed	
Järvelä (2003)	12	L = 50 m W = 1,1 m H = 1,3 m	Wheat and sedges	3D acoustic Doppler velocimeter

Table 2: Technical details of the existing dataset

The associated parameters of the above described experiments fall in the following range:

$$0.00024 < D < 0.008 \text{ [m]}$$
$$42 < m < 20000 \text{ [m}^{-2}\text{]}$$
$$0.04 < k < 1.65 \text{ [m]}$$
$$0.96 < C_D < 3$$
$$0.05 < h < 2.5 \text{ [m]}$$
$$0.03 < U < 1.24 \text{[m/s]}$$
$$0.0002 < i < 0.0161$$

4.2. *More additional data for submerged vegetation*

Data is extracted from literature to extend the already available data set for submerged rigid and flexible vegetation.
To get insight in which parameters are needed to calculate the flow resistance, and to inventory which parameters are given by the authors and which data is lacking in the newly collected data, Table 3 is derived.

	Given parameters by author								
Author	D	m	k	C_D	h	U_v	U_s	U	i
Submerged rigid vegetation									
Einstein & Banks (1950)	0	0	0	0	0	X	X	0	0
Shimizu & Tsujimoto (1994)	0	0	0	0	0	X	X	0	0
Stone & Shen (2002)	0	0	0	0	0	0	C	0	0
Poggi et al. (2004)	0	0	0	0	0	E	E	C	0
Murphy et al. (2007)	0	0	0	0	0	0	0	C	0
Submerged flexible vegetation									
Fenzl (1962)	0	0	0	0	0	X	X	0	0
Starosolsky (1983)	0	0	0	0	0	X	X	X	0
Nallari & Judy (1989)	0	0	0	0	0	X	X	X	0
Tsumimoto et al. (1991)	0	0	0	0	0	0	C	0	0
Freeman et al. (2002)	0	0	0	X	0	X	X	0	0
Rowinski et al. (2002)	0	0	0	0	0	0	X	0	0
Carollo et al. (2005)	0	0	0	A	0	X	X	0	0

0 = given
C = not given by the author, therefore calculated
E = not given but the author extracted from figures in the paper
X = not given nor calculated or extracted
A= a value is assumed

Table 3: Overview of the collected data with the needed parameters

Poggi et al. (2004) did not mention the measured velocities. However, they showed the velocities in a graph. From that graph, the velocities are extracted and used. The slope was given in another article published by the same author (Poggi and Katul, 2008).
The data of Starosolsky (1983) and Nallari and Judy (1989) were mentioned by other authors. Unfortunately, the articles of these authors were not available. Therefore, the velocities could not be retrieved and the data could not be used in this study.
Freeman et al. (2002) used natural plants with side-branches and foliage, however, they neither give the drag coefficient, nor the deflected plant height. This point of attention is discussed further in this section.
The article of Fenzl (1962) was not available.

A short description of the experiments mentioned in Table 3 is given below. First the aim of the experiment (and some specialties) is given. Second a table with some technical details is given. Finally, special attention is given to the way the drag coefficient and slope are determined.

<u>Einstein and Banks (1950)</u>
Einstein and Banks (1950) conducted flume experiments to determine the resistance of different types of obstacles opposing the flow of water through an open channel.

<u>Shimizu and Tsjujimoto (1994)</u>
These authors derived flume experiments to validate their numerically analyzed k-ε turbulence model.

Stone and Shen (2002)
Stone and Shen (2002) conducted experiments under emergent and submerged conditions to determine the hydraulic resistance characteristics of a channel with vegetation.

Poggi et al. (2004)
Poggi et al. (2004) conducted flume experiments to examine the inter-connection between vegetation density and key flow statics within and just above the vegetation, as needed for quantifying momentum and scalar transport.

Murphy et al. (2007)
Murphy et al. (2007) described flume experiments with rigid model vegetation to study the structure of coherent vortices and vertical transport in shallow vegetated shear flows.
Information is also extracted from the following related articles; Ghisalberti and Nepf (2004) and Ghisalberti and Nepf (2006).

Tsujimoto et al. (1991)
Tsjumimoto et al. (1991) measured the turbulence characteristics of flexible vegetation under emergent and submerged conditions in a laboratory flume.
The deflected plant height was measured under uniform flow conditions by eyes and by means of video-film analysis for a special case.

Freeman et al. (2002):
Freeman et al. (2002) investigated the effect of natural vegetation, particularly ground cover plants, small trees, and shrubs, on flow resistance under emergent and submerged conditions. Thirteen different plant types in groups of uniform sized plants and groups of mixed plants with varying plant density, sizes and shapes were used to measure in situ flow resistance and drag force.

Freeman et al. (2002) measured the drag force instead of the drag coefficient. Therefore it is investigated if the drag coefficient can be calculated from the given drag force. Equation (13) can be used to calculate the drag coefficient. To do so, the blockage area of the plants and the velocity need to be known. Freeman et al. (2002) gave values of the drag force for certain velocities for four different plant species. So it was not possible to calculate the drag coefficient for the other species.
The blockage area was given for 27 plant species. For two of the four plant species used to measure the drag force, information about the blockage area was lacking. However, information about the width of the plant and the erected plant height was given. Assuming uniform width of the plant over the height and multiplying with the height, results in the blockage area. Unfortunately, the deflected plant height was not given by Freeman et al. (2002). Because they used flexible plants with side-branches and foliage, that parameter became important. Due to bending of the vegetation the blockage area becomes smaller with increasing velocity, and therefore the drag coefficient decreases.
Due to lack of information, the data of Freeman et al. (2002) is not useful for the purpose of this research.

Rowinski et al. (2002)
Submerged vegetation was simulated in a flume, with small cylindrical little stems of elliptical cross-sections to study the problem of the proper evolution of the vertical velocity distributions in vegetated channels.

Carollo et al. (2005)

Carollo et al. (2005) collected experimental data from a bed covered by grasslike vegetation to analyze flow resistance.

Carollo et al. (2005) used very flexible vegetation with deflected plant heights of half the erected plant heights. The flexible vegetation changes with velocity so the drag force is very important. However, Carollo et al. (2005) did not mention a drag coefficient at all. As mentioned before, drag coefficient of 1 are used for rigid vegetation. For very flexible vegetation it is questioned if a drag coefficient of 1 is realistic. Nevertheless, a drag coefficient of 1 is assumed.

Author(s)	Number of experiments	Dimension flume (LxWxH)	Vegetation type	Measured velocity
Rigid vegetation				
Einstein & Banks (1950)	19	L = 5.18 m W = 0.30 m H = 0.46 m	Pins	Calculated from the measured discharge and water level.
Shimizu & Tsjujimoto (1994)	12	Not mentioned	Plastic cylinders	Micro-propeller currentmeter
Stone & Shen (2002)	136	L = 12 m W = 0.45 m H = 0.61 m	Wooden, circular dowels of uniform size	Marsh Mc Birney model
Poggi et al. (2004)	5	L = 18 m W = 0.90 m H = 1.0 m	Stainless steel cylinders	A two-component laser Doppler anemometry (LDA)
Murphy et al. (2007)	27	L = 24 m W = 0.38 m H > 0.47 m	Wooden cylinders	(3-D) acoustic Doppler velocity meters (ADV)
Flexible vegetation				
Tsujimoto et al. (1991)	6	L = 12m W = 0.40 m	Plastic strips	Micro-propeller currentmeter
Freeman et al. (2002)	77	Large flume: L = 152.4 m W = 2.44 m H = 1.82 m	Real (flexible) plants of 21 different species	Marsh McBirney Model 201b portable water current meter.
Rowinski et al. (2002)	8	L = 16 m W = 0,58 m H = 0.60 m	Flexible elements	Electromagnetic liquid velocity meter
Carollo et al. (2005)	80	L = 14.4 m W = 0.60 m H = 0.60 m	Grass	Calculated from the measured discharge and water level.

Table 4: Technical details for the newly collected data

The associated parameters of the above described experiments are very divers, and fall in the following range:

$0.0008 < D < 0.0127$ [m]
$2.70 < m < 44000$ [m^{-2}]
$0.014 < k < 0.165$ [m]
$0.61 < C_D < 3.14$
$0.600 < h < 0.014$ [m]
$0.013 < U < 1.200$ [m/s]
$0.000003 < i < 0.050000$

One of the main difficulties of deriving a dataset from flume experiments of different authors, is the fact that there are many different ways of determining the slope and the drag coefficient. Because these two parameters are very important in predicting flow resistance, an overview is made which shows for each article how the author(s) derived the slope and the water level (Table 5).

Author	Determining C_D	Determining slope
Submerged rigid vegetation		
Shimizu & Tsujimoto (1944)	Measured using a hot-film anemometer	u* is measured. Slope calculated by: $i = \frac{u_*^2}{gh}$
Einstein & Banks (1950)	Not mentioned	Determined using the measured water levels
Stone & Shen (2002)	Calculated by: $\tau_v = \frac{1}{2} C_D \cdot U_v \cdot m \cdot D$	Calculated by: $i = \frac{2C_D A_p (l/h) U_v^{\ 2}}{\pi \left(1 - \sqrt{\frac{4A_p}{\pi}}\right)^2 gD(1 - A_p \frac{l}{h})}$
Poggi et al. (2004)	$C_D = -8.5 \times 10^{-4} \mathrm{Re}_d + 1.5$ Where Re_d is the (measured) Reynolds number inside the vegetation.	u* is measured. Slope calculated by: $i = \frac{u_*^2}{g(h-k)}$
Murphy et al. (2007)	$C_D = \frac{\frac{\partial u'w'}{\partial z}\Big\vert h > z > z2 - \frac{\partial u'w'}{\partial z}(z)}{(1/2) m U^2(z)}$ Mean value in 'exchange' zone (zone between vegetation layer and surface layer at top of vegetation)	Estimated by: $i = \frac{1}{g}\left[\frac{\partial u'w'}{\partial z}\right]$, $h<z<z_2$
Submerged flexible vegetation		
Tsumimoto et al. (1991)	Assumed a constant value of 3.14	Changing bed slope flume
Freeman et al. (2002)	Not given	Not mentioned
Rowinski et al. (2002)	$C_D = 3.07 \mathrm{Re}_p^{-0.168}$ for $\mathrm{Re}_p<800$ Where $\mathrm{Re}_p = \frac{UD}{\nu}$ denotes the Reynolds number computed for trees. (According to the Wieselberger monogram)	Changing bed slope flume
Carollo et al. (2005)	Not given	Changing flume bed slope

Table 5: Used method for determining the drag coefficient and slope

It becomes clear that the method used to determine the drag coefficient and the slope depends on the author's preference. In the next sections more attention is given to these two important parameters.

4.3. *Synchronization collected data*

Before the collected data can be used to compare with resistance descriptors, it is important to investigate the reliability of the newly collected data and to correct data where necessary. Using the equation of Petryk and Bosmaijan (1975) the measured velocities in the vegetation layer will be compared with the predicted velocities. When there are large deviations between predicted values and measured values, it could be helpful to adjust the data to make it useful. The procedure of checking the data and synchronisation of the data is discussed in the next subsections.
Unfortunately, as shown in Table 3 not all authors mentioned the velocity inside the vegetation layer or inside the surface layer, they only gave the mean velocity. These datasets can not be checked. It is assumed that these data can be used, however, if they show very large deviations with the calculated values of the different descriptors in chapter 5, the data will be removed from the data set.

4.3.1. Measured values versus calculated values

From literature it is known that the equation of Petryk and Bosmaijan (1975) can be used to predict the velocity for rigid emergent vegetation and for predicting the velocity in the vegetation layer for rigid submerged vegetation. Because the equation of Petryk and Bosmaijan (1975) does not take the influence of the higher velocities in the surface layer into account in predicting the mean velocity in the vegetation layer, it is expected that the measured velocities will be higher than the predicted ones. Moreover, due to bending of the vegetation, the equation of Petryk and Bosmaijan (1975) will be less accurate for flexible vegetation, however, it is assumed that the equation will still give a good estimation.

Two papers describe experiments for emergent vegetation. Because the equation of Petryk and Bosmaijan (1975) is especially derived for emergent vegetation, it is expected that the predicted values compared with the measured values for emergent conditions show better performance, than for the velocity in the vegetation layer for submerged conditions. Therefore, also graphs of predicted values and measured values for emergent vegetation are shown (Figure 8).

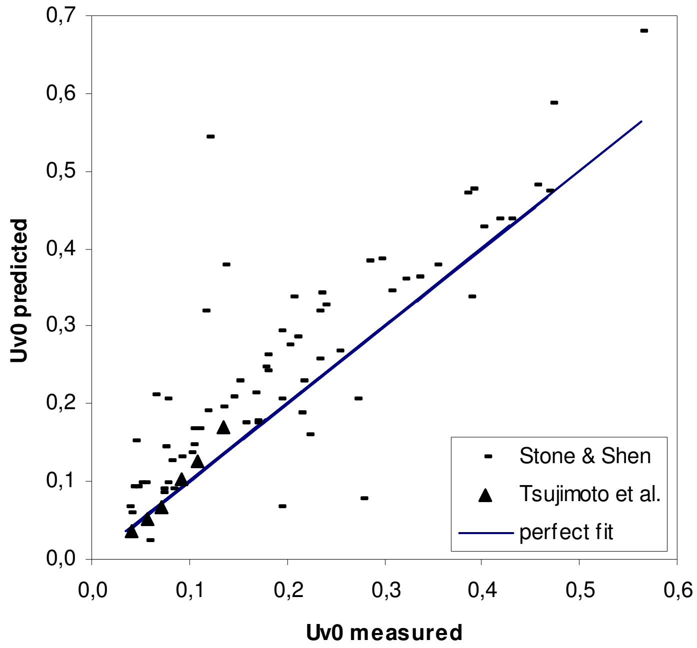

Figure 8: Comparison of the measured velocity with the predicted velocity for emergent vegetation

The predicted velocities of Stone and Shen (2002) are systematic lower than the predicted velocities for the rigid vegetation. The R^2 of the data of Stone et al. is 0.915. Also half of the points of the data of Tsujimoto et al. (1991) are over estimated by the equation of Petryk and Bosmaijan (1975). Because Tsujimoto et al. (1991) used flexible data, the overestimation of the equation of Petryk and Bosmaijan (1975) could be explained due to bending of the vegetation (which increases with higher velocities) which are not taken into account in the equation of Petryk and Bosmaijan (1975) but results locally in more compact vegetation.

For submerged vegetation, Petryk and Bosmaijan (1975) predicts the measured average velocities in the vegetation layer better than for emergent vegetation (Figure 9). The R^2 of the predicted velocity inside the vegetation layer and the measured velocity inside the vegetation layer is 0.971.

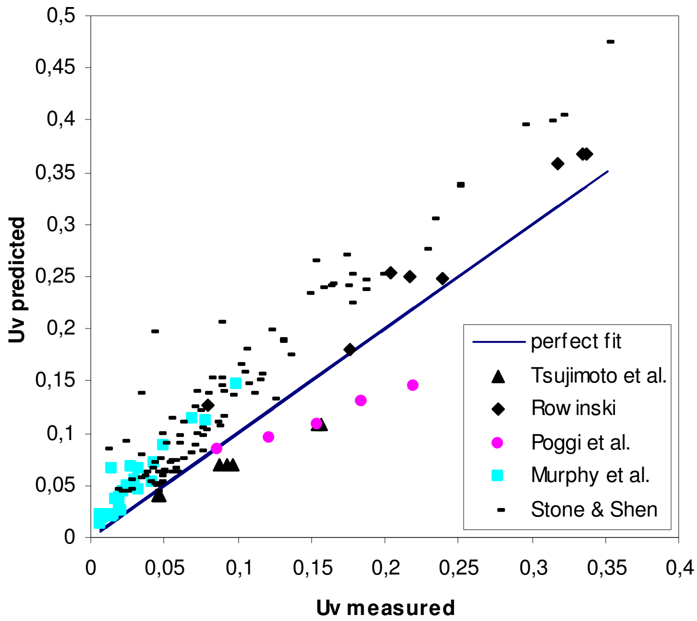

Figure 9: Comparison of the measured velocity (inside the vegetation) with the predicted velocity for submerged vegetation

It was expected that the predicted values for emergent vegetation would be more accurate than the predicted values for submerged vegetation inside the vegetation layer, due to the fact that the influence of the surface layer on the vegetation layer is not taken into account in the equation of Petryk and Bosmaijan (1975). Therefore, the measured values of the average velocity in the vegetation layer for submerged vegetation should be higher than the predicted values. That is exactly what happened with the data of Tsujimoto et al. (1991). Therefore, it is unexpected that the data of Stone and Shen (2002) show better performance for the velocity in the vegetation layer for submerged vegetation than for emergent vegetation.

For three data sets (shown in Figure 9), the equation of Petryk and Bosmaijan (1975) is again over estimating the mean velocity in the vegetation layer. Therefore, it could be suggested that the equation of Petryk and Bosmaijan (1975) is not accurate enough. However, two of the parameters used in the equation of Petryk and Bosmaijan (1975) (drag coefficient and slope) are difficult to determine with flume experiments. It is expected that the over-estimation is caused by the uncertainties of these parameters. It is questioned if this data for submerged vegetation is accurate enough, or if it should be corrected. Therefore, it is investigated how data for submerged vegetation could be corrected.

The parameters needed to calculate the velocity in the vegetation layer with the equation of Petryk and Bosmaijan (1975) are the gravitational acceleration, the blockage area, the drag coefficient and the slope. There is no doubt about the value of the gravitational acceleration and the blockage area is neither difficult to determine for vegetation without side branches and foliage. There is more ambiguity about the slope and the drag force. As shown in Table 5, different authors use different ways to determine the drag coefficient and the slope. Therefore, it is most plausible that the drag coefficient and/or the slope are the weakest link in calculating the vegetation velocity with the equation of Petryk and Bosmaijan (1975).

Corrections can be applied for data which shows large deviations between measured and predicted values. To correct data, a scheme (Figure 10) is devised which can be used.

The first step presented in the scheme is already discussed. The next steps will be discussed in the following sections.

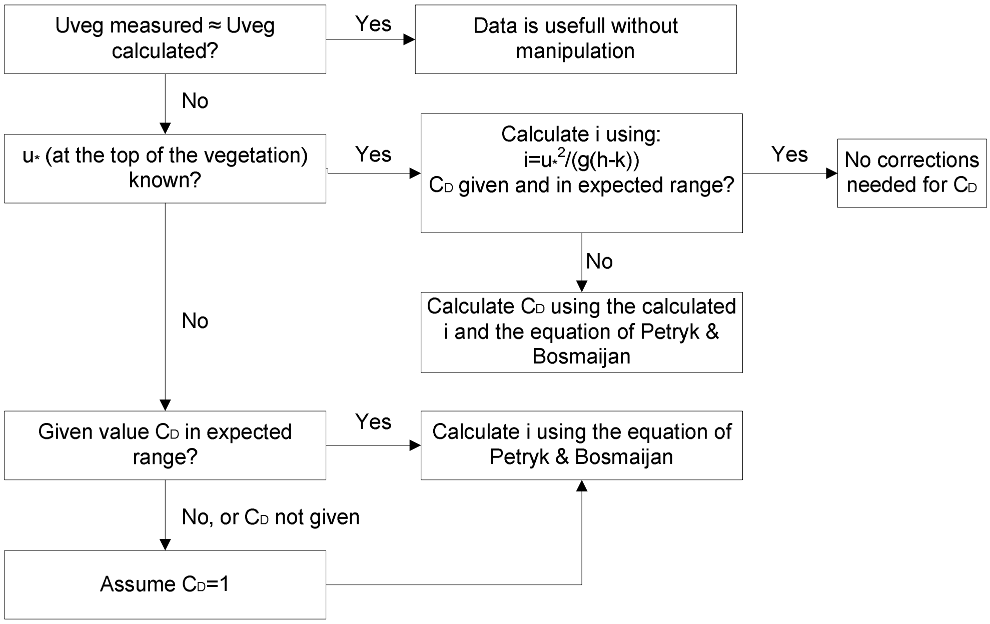

Figure 10: Scheme to correct data of submerged vegetation

4.3.2. Correction scheme

Several ways are used to determine the slope (shown in Table 5). In some flumes it is possible to change the slope of the entire flume, so the bed itself can change (Rowinski et al., 2002). This method is rare because most flumes have a horizontal bed without a slope and are not movable. A more often used method is to measure the difference in water level at the beginning and the end of the flume (at the points where the water level is steady) and divide it over the length between these points (Einstein and Banks, 1950). However, very flat slopes are used, therefore the difference between these points is about millimeters until centimeters (depending on the length of the flume) and hard to read accurately from the used instruments.

Another way to determine the slope for submerged conditions is to calculate the shear stress at the top of the vegetation using the density of the water and the measured turbulent velocity fluctuations in streamwise direction (u') and in vertical direction (v'). Using that shear stress the slope can be calculated within two steps. First the friction velocity (u_*) at the top of the vegetation can be calculated by using the following equation:

$$\tau = \rho(u' \cdot v') = \rho \cdot u_*^2 \tag{59}$$

Finally, the slope can be calculated using the measured water level:

$$i = \frac{u_*^2}{g(h-k)} \tag{60}$$

The next step in the scheme (in horizontal direction) questions if de drag coefficient is given and if it is in the expected range. If the drag coefficient is not given, or not in the expected range, the drag coefficient can be calculated using the equation of Petryk and Bosmaijan (1975) using the calculated slope from equation (60):

$$C_D = \frac{2 \cdot g \cdot i}{m \cdot D \cdot U_v^2} \tag{61}$$

When u_* is not given, the next step (in vertical direction) in Figure 10 can be taken.

From literature it is known that the drag coefficient for rigid vegetation is about 1. Using that knowledge, a given drag coefficient can be checked, whether the drag coefficient falls in a reliable range or not (0.2-5). When the value of the drag coefficient seems reliable the slope can be calculated using the equation of Petryk and Bosmaijan (1975), assuming that the given drag coefficient is correct:

$$i = U_v^2 \frac{C_D \cdot m \cdot D}{2g} \tag{62}$$

When the given drag coefficient is extremely high or extremely low (or not given at all), the fourth step must be taken in Figure 10. A drag coefficient of 1 for rigid vegetation as well as for flexible vegetation (without foliage and side branches) can be assumed. Assuming a value of 1 for the drag coefficient, the slope can be calculated using the equation of Petryk and Bosmaijan (1975) equation (62).

As mentioned before, the data of Stone and Shen (2002) show some deviations between the predicted and measured velocity inside the vegetation layer. The question is, when is data accurate enough to use, or when should it be corrected? Because the R^2 for submerged vegetation is above 0.95 it is decided to use the original data of Stone and Shen (2002).

4.3.3. Drag coefficient

As mentioned before, several ways are used to determine the drag coefficient. Two authors used an equation depending on the Reynolds number for calculating the drag coefficient. Other authors did not mentioned how they derived a value for the drag coefficient, and some authors did not even give a value for the drag coefficient.
Another point of interest is the fact that most of the authors use a constant value for the drag coefficient. Rowinski et al. (2002), Poggi et al (2004) and Murphy et al. (2007) use drag coefficients which change with changing depth. For rigid emergent vegetation a constant value is expected, however, for submerged vegetation, the average drag coefficient will change over water depth.
For flexible vegetation it is even more complicated, because the drag coefficient in the vegetation layer is not constant due to bending of vegetation, and the depth of the vegetation layer changes with changing velocity. For example, Tsujimoto et al. (1991), used a mean value for the drag coefficient of 3.14. At the lower velocities the calculated slope (using equation Petryk and Bosmaijan, 1975) corresponds well to the given slope, however, for higher velocities the calculated slope differs from the given slope. Due to increasing velocities, the deflected plant height decreases, therefore the drag coefficient should also decrease at higher velocities.

Because a standard way to determine the drag coefficient is lacking, it is hard to make values comparable. Therefore, it is investigated if a standard value for the drag coefficient would be preferable, especially for rigid vegetation.
The values of the drag coefficient given by the author are shown in Table 6. The drag coefficient for flexible vegetation (without side-branches and foliage) is > 1 and the drag coefficient for rigid vegetation is <1.

Author	Given C_D	Vegetation type
Tsujimoto et al. (1991)	3.14	Flexible
Rowinski et al. (2002)	1.22-1.35	Flexible
Poggi et al. (2004)	0.69-1.02	Rigid
Murphy et al. (2007)	0.66-1	Rigid
Stone and Shen (2002)	0.98-1.11	Rigid

Table 6: Values for the drag coefficient as given by different studies

The above described data for rigid and flexible vegetation are shown in Figure 11 with a standard drag coefficient of 1.

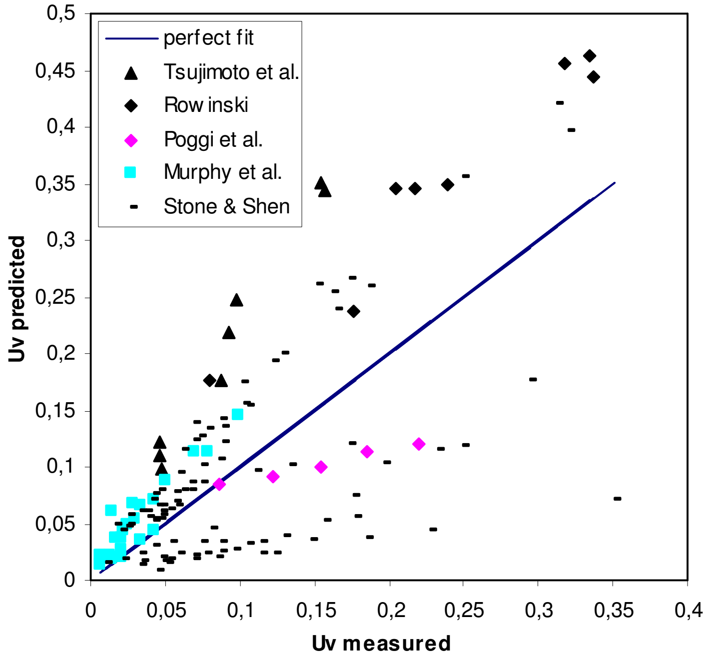

Figure 11: Data submerged rigid and flexible vegetation with drag coefficient all to1

Figure 11 makes clear that using a chosen drag coefficient of 1 for this data, does not improve the results. Data with an original drag coefficient > 1, show higher predicted velocities than measured velocities, while data with an original drag coefficient < 1 performs the other way around, except for the data of Murphy et al. (2007) because a part of that data already had a drag coefficient of 1 (assumed). Moreover, in Figure 9 (with the original drag coefficient) Murphy et al. (2007) already showed higher predicted velocities than the measured velocities.
Using a drag coefficient of 1 does not result in a smaller difference between the predicted and measured velocities. Therefore, it is decided to use the drag coefficients given by the author.

4.4. Conclusion and discussion

Because authors of flume experiments uses different ways of determining the slope and drag coefficients, comparison of these data is difficult. The developed scheme helps to get consistency in the ways of determining the slope and the drag coefficient. This scheme can be used as manual to determine the drag coefficient and slope in deriving data from flume experiments. The scheme was originally derived to correct data, however it is not used to correct the data, only for data without a given drag coefficient the data is 'corrected' by

assuming a drag coefficient of 1. Using a standard drag coefficient of 1 for all data did not improve the results.
The main assumption of the scheme is that the equation of Petryk and Bosmaijan (1975) is reliable enough to use for determining the depth averaged velocity in the vegetation layer, the slope and/or the drag coefficient. The equation of Petryk and Bosmaijan (1975) is derived for rigid vegetation, therefore the scheme yields especially for rigid vegetation. Because a resistance description is lacking for flexible vegetation, the scheme is also used for flexible vegetation taking the deflected plant height into account. However, using the deflected plant height or erected plant height in resistance descriptors for rigid vegetation is a point of discussion. In the data set for flexible vegetations the erected plant height is used when the deflected plant height was not given by the extractors of data. It is out of the scope of this study to investigate which plant height fits best comparing the measured and predicted values.

Another point of interest is the fact that most data sets use low water levels (<1 m). For flood management higher water levels are more realistic. For small vegetation species (grass etc.) the difference in resistance between low or high water levels is small for submerged conditions. The combination of high water levels with high vegetation is interesting for flood management.

Unless the above mentioned difficulties a data set from 5 different authors with a total amount of 173 runs for rigid vegetation, and a data set from 11 different experimental studies with 133 runs for flexible vegetation is available.

5. Comparison resistance descriptors with data

In this chapter, the seven resistance descriptors mentioned in section 3 are used to calculate the velocity, water level, Manning and Chézy coefficient which are compared with data for rigid and flexible vegetation.

The data described in chapter 4 are used. As mentioned before, the velocity inside the vegetation layer and/or the surface layer was not always known. Therefore, the data is only computed for the depth averaged velocity. In a quick comparison of the data with the description of Baptist et al. (2006) resulted that Einstein and Banks (1950), Fenzl (1962) and Carollo et al. (2002) show large deviations (shown in Figure 12).
Einstein and Banks (1950) used very sparse vegetation (2.7-108 m^{-2}), however, for sparse vegetation coverage, bed roughness becomes more important. It may be expected that the measured velocities are lower than the predicted velocities. Lower numbers of cylinders per m^2, resulted in large deviations between the predicted an measured velocities.
For the data of Carollo et al. (2002) a drag coefficient of 1 was assumed, because the author did not mention the drag coefficient. However, it is questioned if a drag coefficient of 1 is reliable for very flexible vegetation. That could explain the deviations between the predicted and calculated velocities.
Since background on the data of Fenzl (1962) is missing, it is hard to explain the results shown in Figure 12.
These data is removed from the dataset.

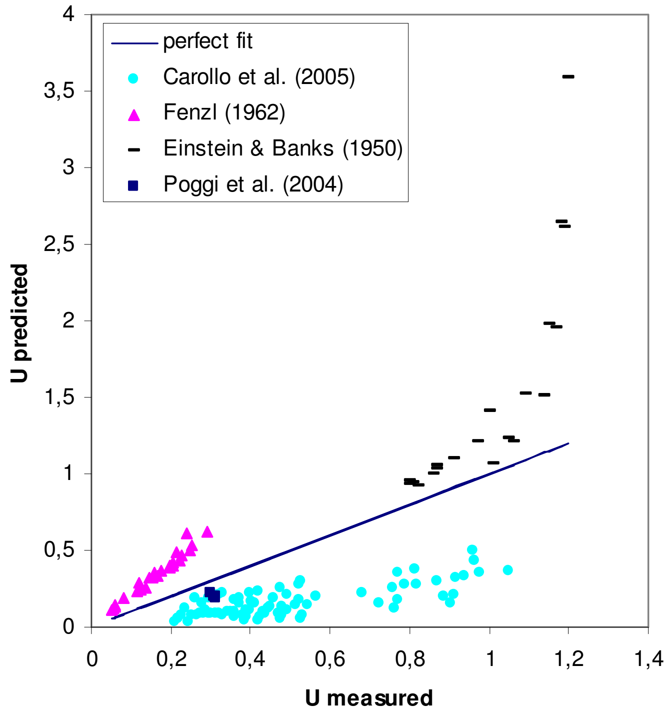

Figure 12: Data of flexible vegetation compared with predicted values method Baptist et al. (2006)

Besides the above mentioned data, also the data of Poggi et al. (2004) was out of range compared to the predicted values especially for the Chézy coefficient. In the comparison of the measured velocity in the vegetation layer with the predicted velocity in chapter 4 Poggi et al. (2004) showed reasonable agreement between the predicted and measured values (shown in Figure 9). However, from the comparison of the measured and predicted Chézy coefficient it was clear that the measured value was much higher than the predicted Chézy coefficient, independent of the used description (Figure 13). Not only for the Chézy coefficient but also for the velocity, water level and Manning coefficients large deviations between the predicted and measured values are present.

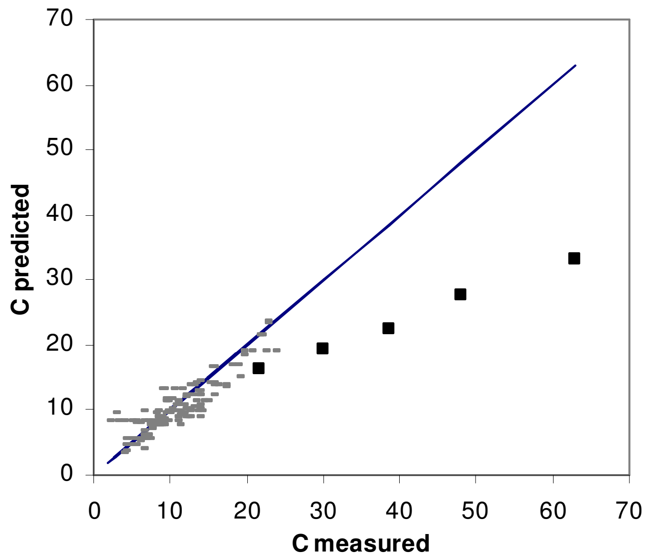

Figure 13: Data set and data of Poggi et al. (2004) (squares) compared with predicted values of the description of Huthoff (2007)

Notable of the data of Poggi et al. (2004) is the fact that the water level was constant for all runs. Poggi et al. (2004) varied the number of cylinders per square meter. Higher numbers of cylinders per m^2 resulted in lower velocities in the vegetation layer and higher velocities in the surface layer. The difference in the mean velocity for the five runs was small with 0.004 m/s difference between the highest and lowest value.
The reason for the strange behavior was not found and could not be corrected, therefore, the data of Poggi et al. (2004) was removed from the data set.

In the following section, the calculated values from the different resistance descriptors are first compared with data of rigid vegetation. Secondly, it is investigated how well the resistance descriptors for rigid vegetation can predict the resistance of flexible vegetation. Thirdly, a qualitative comparison of some of the properties of the resistance descriptors is made. Finally, a conclusion and discussion are given.

5.1. *Descriptions compared with data of rigid vegetation*

Graphs of the comparison between the measured and predicted values for the depth averaged velocity, water level, Chezy coefficient and Manning coefficient for the seven vegetation resistance descriptions are shown in appendix C. The coefficient of determination (R^2), the mean error (μ) and the standard deviation of the mean error (σ) are shown in Table 7. The equations of these parameters are shown in appendix D. High values of R^2 and low values of μ and σ indicating good performance.
For flood management the water level is the most important parameter, however, the velocity is also of interest, especially for purposes like sediment transport in a river. Therefore, not only the R^2, μ and σ are calculated for the water level, but also for the velocity. For the Chézy and Manning coefficient only the R^2 is given.

Descriptor	Velocity			Water level			Chézy	Man-ning
	R^2	μ (m/s)	σ (m/s)	R^2	μ (cm)	σ (cm)	R^2	R^2
Klopstra et al. (1997) (a)	0.985	-0.031	0.042	0.998	2.3	4.0	0.958	0.885
Klopstra et al. (1997) (b)	0.990	-0.014	0.037	0.994	1.2	9.7	0.964	0.983
Klopstra et al. (1997) (c)	0.990	-0.018	0.036	0.995	1.1	8.2	0.970	0.896
Stone et al. (2002)	0.910	0.046	0.116	0.918	-37.6	82.2	0.902	0.818
Van Velzen et al. (2003)	0.988	0.019	0.045	0.997	-3.3	7.7	0.964	0.894
Baptist et al. (2006)	0.974	-0.047	0.055	0.992	3.6	8.9	0.949	0.884
Huthoff (2007)	0.988	0.007	0.043	0.997	-0.5	5.5	0.971	0.902

Table 7: Performance of different descriptors in describing experimental data for rigid vegetation n=173 from 5 different authors)

Most descriptors show good performance. However, Stone and Shen (2002) performs less well, especially for higher water levels (shown in Figure 14). Because river models are used to set safety standards, it is very important that a method can predict higher water levels as accurate as possible.

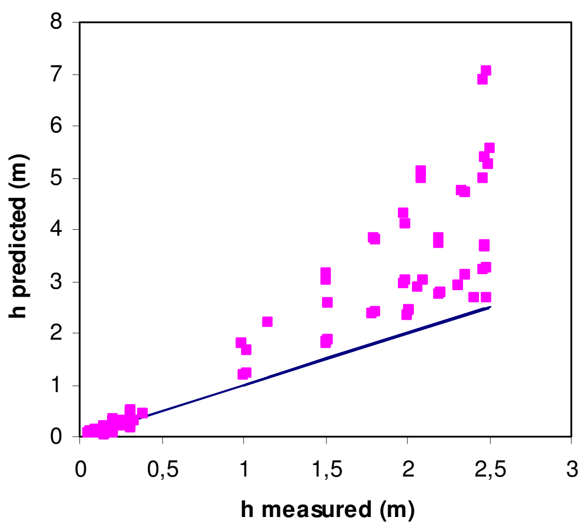

Figure 14: Performance of the description by Stone & Shen (2002) for water levels and rigid vegetation

The remaining six descriptors show good performance in case of predicting the velocity and the water level (also the higher water levels). The differences between the R^2 of the seven predictors are higher for predicting the Chézy coefficient and the Manning coefficient. An explanation for that fact is not found. As mentioned before, for flood management the water level and velocities are more important.

To get more insight in the deviation of the velocity and the water level, μ and σ are calculated. When μ > 0 (positive value) the value of the measured average velocity or water level is higher than the predicted values. In such cases, the description is under estimating. When μ < 0 (negative value) the measured velocity/water level is lower than the predicted values. Therefore, de descriptor is over estimating. For safety reasons it is better that a description is overestimating the water levels than under estimating.

In general the differences between the performances of the six remaining descriptors are small. Therefore, it is interesting to investigate under which circumstances the descriptors show the largest/smallest errors. Because the water level is very important for flood management, graphs are made with the mean error between the predicted and measured water level, against the water level (an example is shown in Figure 15). Also graphs are made which take the submergence ratio's into account. These graphs are shown in appendix F.

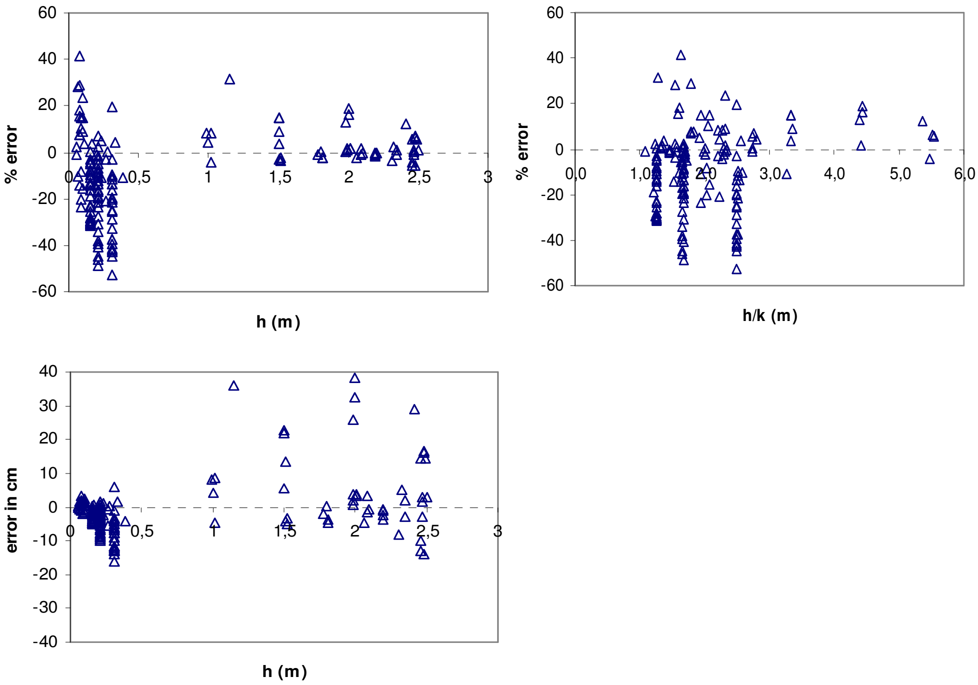

Figure 15: Error in predicted water levels for the description of Klopstra et al. (1997) with turbulent length scale defined by Huthoff (2007)

The method of Klopstra et al. (1997) with the turbulent length scale defined by Van Velzen et al. (2003) and by Meijer (1998b), show the smallest errors for water depths higher than 1.0 m. That is not really surprising, because for water depths higher than 1 m only the data of Meijer (1998b) was available for this research. The same data of Meijer (1998b) are used to define the turbulent length scales and also to determine the roughness height given by the description of Van Velzen et al. (2003). Unfortunately, only one data set with high water levels could be used to compare with the descriptors, therefore, it is hard to draw conclusions from this result. The other descriptors show errors smaller than 40 cm for water levels above 1 m.

For smaller water levels, more data sets were available. However, the difference in performance of the six descriptors is small. The maximum percentage error for the smaller water levels was 60 % which falls in a range smaller than 20 cm error. The graphs of the percentage error against the submergence ratio show more or less the same results as for the error against the water level. The method of Klopstra et al. (1997) with the turbulent length scale given by Meijer (1998b) and the method of Huthoff (2007) show the smallest error in cm (for water levels <1m), namely within a range < 15 cm.

The difference in vegetation height and water levels varies between the data sets, made it interesting to investigate the influence of the submergence ratio's on the mean error. However, a relation between the mean error and submergence ratio's is lacking.

5.2. *Descriptions compared with data of flexible vegetation*

Often theoretical vegetation resistance descriptions derived for rigid vegetation, are also used for describing the resistance of flexible vegetation. Because it is questioned how reliable it is to use resistance descriptions for rigid vegetation in calculating the behavior of flexible vegetation, the seven resistance descriptors, are also compared with data of flexible vegetation.

The graphs, with the measured values for flexible vegetation compared to the predicted values are shown in appendix E. Some remarks on the data are the facts that the calculated velocities for the data of Rowinski et al. (2002) are higher than the measured values for all descriptions. It occurs systematic and is not dependent on the used method. Another systematic deviation which occurs for all descriptors, is the fact that the measured Manning coefficient of Ree and Crow (1977) is much higher than the calculated Manning coefficient. In spite of these irregularities, the data of Rowinski et al. (2002) and Ree and Crow (1977) are taken into account in calculating the R^2.
The performance of the different descriptions is summarized in Table 8.

	Velocity			Water level			Chézy	Man-ning
Descriptor	R^2	μ (m/s)	σ (m/s)	R^2	μ (cm)	σ (cm)	R^2	R^2
Klopstra et al. (1997) (a)	0.953	-0.045	0.073	0.993	2.4	4.3	0.959	0.914
Klopstra et al. (1997) (b)	0.945	-0.010	0.068	0.992	0.8	4.4	0.951	0.915
Klopstra et al. (1997) (c)	0.943	-0.026	0.074	0.980	1.2	8.5	0.940	0.908
Stone et al. (2002)	0.740	0.061	0.130	0.787	-48.8	76.2	0.766	0.647
Van Velzen et al. (2003)	0.937	0.020	0.068	0.994	-2.2	6.1	0.943	0.900
Baptist et al. (2006)	0.957	-0.045	0.069	0.990	3.5	5.7	0.959	0.915
Huthoff (2007)	0.847	0,019	0,123	0.980	-4,2	9,4	0.855	0.867

Table 8: Peformance of different descriptors in describing experimental data for flexible vegetation (n=133 from 11 different authors)

Observing the graphs in Appendix E and Table 8, it becomes clear that the prediction of flexible vegetation is less accurate than the prediction of rigid vegetation. The description of Stone and Shen (2002) performs again the least in comparison to the other descriptors.
For all descriptors yields that the performance is most accurate for the water level. The maximum difference between the R^2 of the water level between rigid and flexible vegetation is only 1.7 % (neglecting the performance of Stone and Shen, 2002).
The method of Huthoff (2007) shows large deviations between the measured and calculated values for the velocity, Chézy and Manning coefficient. However, the water levels are predicted quite well except for the data of Tsujimoto et al. (1991) and the data of Kouwen et al. (1969). In the graphs of the error against the water level and the submergence ratio, shown in appendix G, the error of the description of Huthoff (2007) is very high (Figure 16). Also the method of Klopstra et al. (1997) with the turbulent length scale defined by Huthoff (2007) show large errors (both shown in Figure 16). Especially for

the data of Tsujimoto et al. (1991) very high errors occur for these two descriptions. It is clear that these two descriptions perform less than the four remaining descriptions.

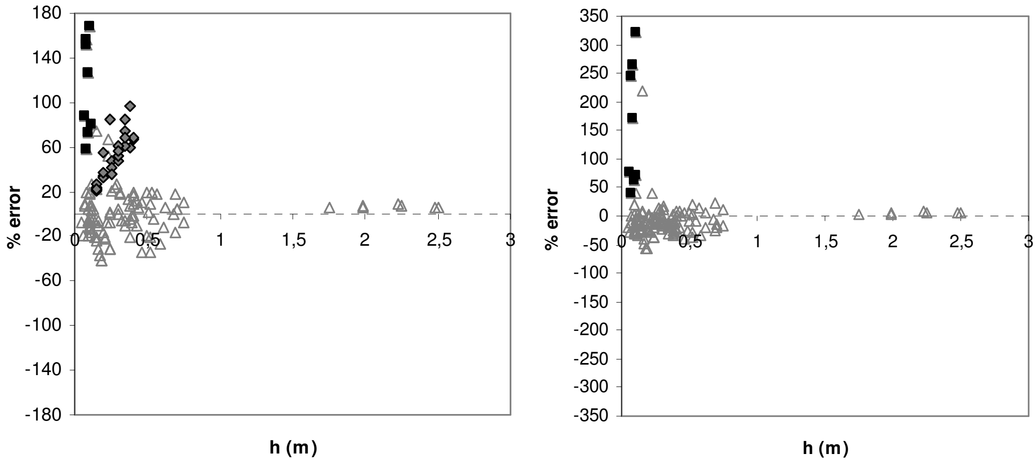

Figure 16: Method of Huthoff (2008) (left figure) and Klopstra et al. (1997) with α given by Huthoff (2008) (right figure) circles are the data of Kouwen et al. (only at the left figure) and the squares represent the data of Tsujimoto, et al. (1991)

All descriptions show a large error for one point of the data of Tsujimoto et al. (1993). As example that point is shown in Figure 17 with the description of Baptist et al. (2006). Neglecting that point, the four remaining descriptions show errors smaller than 50 % which results in errors in water level lower than 25 cm.

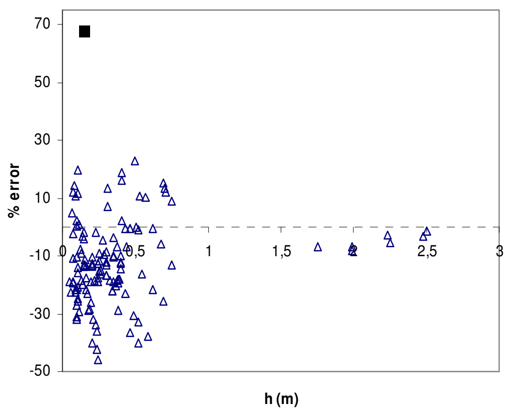

Figure 17: Deviation of one point (square in the left upper corner) of the data of Tsujimoto et al. (1993) shown with the description of Baptist et al. (2006)

Also in the data sets with flexible vegetation, most water levels are smaller than 1 meter. Only the data of Meijer (1998a and 1998b) used water levels between 1,5 and 2,5 meter. As discussed before it is unreliable to draw conclusions from one data set which is also used to derive some of the descriptors. However, some data sets used very small vegetation which results in high submergence ratio’s. A relation between errors and submergence ratio’s again is lacking.

It was questioned whether descriptors for rigid vegetation could be used to predict the velocity and water levels for flexible vegetation. It is shown that the descriptions perform less for flexible vegetation than for rigid vegetation, however, the predicted values for four descriptors are still quite accurate. The descriptions of Klopstra et al. (1997) with the turbulent length scale defined by Meijer (1998b) and Van Velzen et al. (2003) perform very well in predicting hydraulic effects of flexible vegetation and also the method of Van Velzen et al. (2003) and the method of Baptist et al. (2006) show good performance.

5.3. *Analysis of descriptions*

The main result of the analysis of the performance of the above described descriptions is the fact that the method of Stone and Shen (2002) performs poorly for rigid as well as for flexible vegetation. The other six descriptors perform all quite well for rigid vegetation, and there are no significant differences which make one method preferable above another. For flexible vegetation four resistance descriptors performed equally well. To determine which method is most appropriate for application, some other aspects are taken into account. These aspects are:

- Easiness to use
- Theoretical soundness
- Adaptability to take side branches and leaves into account

Easiness to use

The method of Klopstra et al. (1997) with the three definitions of the turbulent length scale consists of multiple equations to calculate the mean velocity. It could be rewritten in one giant formula, however, that does not make it less complex. The other descriptors use one or two equations to calculate the velocity, which works a lot easier. However, when this method is inserted in a computer model, easiness to use is less important.

Some descriptors cannot be used when the submergence ratio is smaller than 1 ($h \leq k$), i.e. emergent conditions (Klopstra et al., 1997). However, the description of Stone and Shen (2002), Van Velzen et al. (2003), Baptist et al. (2006) and Huthoff (2007) can also be used for emergent vegetation without adaptations. The last three descriptions reduce to the equation of Petryk and Bosmaijan (1975) when $h=k$.

Theoretical soundness

All used descriptions describe the processes around the resistance caused by the vegetation in more or inferior degree. It is important that these processes are known, because it is essential that flow behavior and the hydraulic impact of the surrounding flow domain is well-understood and realistically represented. However, it is not always necessary to describe the processes precisely to derive good predictions (Huthoff, 2007). Therefore, it is briefly explained (using Figure 18) to what extend the descriptions are theoretical based, and if they consist of empirical parts.

The the main difference between the models depends on the transition of the velocity in the vegetation layer and the surface layer (shown in Figure 18). Baptist et al. (2006), Van Velzen et al. (2003) and Stone and Shen (2002) assume a constant velocity over the depth in the vegetation layer neglecting the influence of the higher velocities in the vegetation layer.

The descriptions of Klopstra et al. (1997) and Huthoff (2007) describe the velocity in the vegetation layer and surface layer more realistic by taking the interaction between these two layers into account. Between the vegetation layer and the surface layer, the turbulence is the highest, due to the difference in velocity between these two layers. Due to that turbulence the velocity inside (the upper part) of the vegetation is dragged by the surface layer. The velocity profile at the top of the vegetation is needed to define the velocity profile in the surface layer. Klopstra et al. (1997) used the turbulent length-scales to define the energy exchange between the two layers. These turbulent length-scales are determined empirically with the data of Meijer (1998b).

Huthoff (2007) used scaling considerations of the bulk flow field to avoid complications associated with smaller scale flow processes and that still the behavior of depth-averaged flow over vegetation is described accurately. Huthoff (2007) used the data of Meijer

(1998b) to define the scaling length (ℓ) and the transition exponent (ß, needed to describe the transition as the depth of the surface layer decreases).

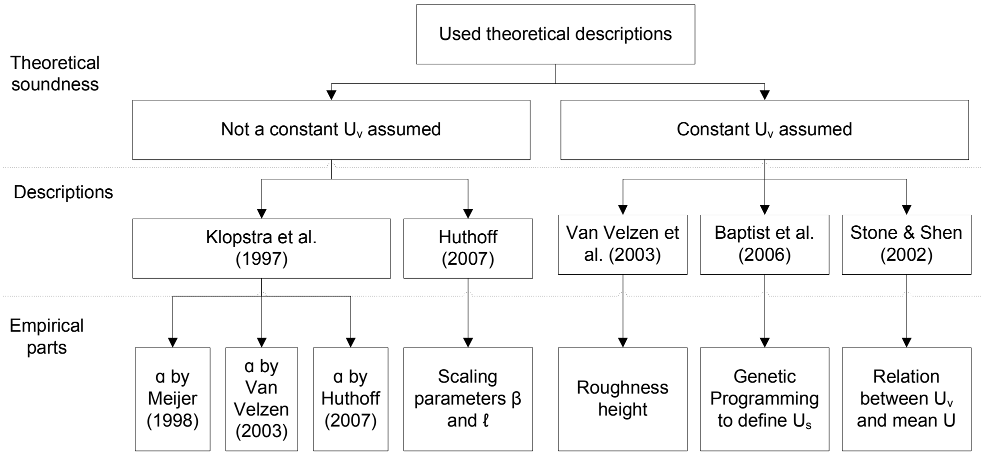

Figure 18: Theoretical soundness and empirical parts used by the different descriptors

The descriptions which assumed a constant velocity in the vegetation layer used also empirical parts. Van Velzen et al. (2003) also used the data of Meijer (1998b) to obtain an empirical roughness height used in the Keulegan equation to define the velocity in the surface layer.
Baptist et al. (2006) used simulated data to find an equation for the surface layer, by genetic programming. The equation for the surface layer is the same as the Keulegan equation when the a roughness height of 12k is used.
The description of Stone and Shen (2002) differs from the method of Baptist et al. (2006) and Van Velzen (2003) due to the fact that the solidity is taken into account. Stone and Shen (2002) used data to define the relation between the velocity in the vegetation layer, and the mean velocity over the entire depth.

The theoretical background of the descriptions of Klopstra et al. (1997) and Huthoff (2007) is most realistic, because they describe the mean velocity taking the interaction between the vegetation layer and surface layer into account. Therefore, the theoretical soundness of these descriptions is better than the other (more simplified) descriptions.

Adaptability to take side branches and foliage into account
According to Van Velzen et al. (2003) the description of Klopstra et al. (1997) can also be used for natural vegetation with side branches and foliage. The representative blockage area of the vegetation can be used, and the drag force could be adapted to take the interaction of the stem/branches of different plants into account. However, the blockage areas of different vegetation species given in that report do not take branches and foliages into account. Moreover, the flexibility of the vegetation is not even taken into account. It was shown that the descriptions for rigid vegetation can be used to predict the behavior of flexible vegetation without side branches and leaves. It is expected that for vegetation with side branches and leaves, the flexibility of the plant will play a major role.
Huthoff (2007) used the data of Meijer (1998b) to define two parameters. These parameters should be adapted for flexible vegetation with side branches and foliage. Also the part of the descriptions of Huthoff (2007) which exist of the equation of Petryk and Bosmaijan (1975) should be adapted. The real blockage area including the leaves and branches should be used instead of the diameter of the stem.
For the descriptions of Van Velzen et al. (2003) and Baptist et al. (2006), which use the Keulegan equation to define the velocity profile above the vegetation, the definition of the roughness height should be adapted, as well as the first term of the equation (velocity

in vegetation layer defined by Petryk and Bosmaijan (1975)). Next, it should be investigated if it is reliable enough to assume an uniform flow velocity inside the vegetation layer for flexible vegetation with side branches and leaves.
For the description of Stone and Shen (2002) a new relationship should be found between the velocity in the vegetation layer (which should be adapted, as described above) and the mean velocity. However, the description of Stone and Shen (2002) performs in general less accurate. Therefore, this method is not very useful in taking side branches and foliage into account.
However, adapting the descriptions to take vegetation with foliage and side branches into account is probably not the only problem. More difficult are the input parameters needed for these kind of vegetation, which are difficult to determine in the field (e.g. blockage area). Especially the combination and interaction of flexibility and side branches and leaves. Different authors (e.g. Dunn et al. (1996), Wilson (2008) and Freeman et al. (2000)) concluded that the flow resistance of a plant may be significantly less for a flexible plant with considerable foliage compared to a less flexible plant with minimal foliage. Another characteristic of flexible vegetation is waving of the vegetation, which is very difficult to take into account.

The above mentioned aspects with the evaluation for the different descriptors is summarized in Table 9. The numbers and the characters in the table stand for:
1 = very poor
2 = poor
3 = sufficient
4 = good
5 = very good

Description criteria	**Klopstra et al. (a)**	**Klopstra et al. (b)**	**Klopstra et al. (c)**	**Stone & Shen**	**Van Velzen et al.**	**Baptist et al.**	**Huthoff**
Predicting capacity rigid vegetation	4	4	4	2	4	4	4
Predicting capacity flexible vegetation	3	3	2	1	3	3	2
Easiness to use	3	3	3	4	4	4	4
Theoretical soundness	4	4	4	2	3	3	4
Adaptability to take foliage into account	3	3	3	1	2	2	3

Table 9: Performance of the descriptors on different criteria

Taking the scores of the descriptions at the different criteria into account, one description performs better than another. In the first place the performance of the descriptions in predicting the water levels for rigid and flexible vegetation is the most important. Secondly, the theoretical soundness and the adaptability to take foliage into account, are important criteria. The least important (due to the fact that computers make the use of the descriptions easy) is the criteria ‘easiness to use’. Using that degrees of importance, the descriptions of Klopstra et al. (1997) with the turbulent length scale given by Meijer (1998) and Van Velzen (2003) performs best.

5.4. Discussion and conclusions

Six descriptions show reasonable agreement with data of rigid vegetation. However, the method of Klopstra et al. (1996) with the turbulent length scale given by Meijer (1998) show smaller errors than the other descriptors for all water depths. For smaller water depths (< 1m) the description of Huthoff (2007) performs equally well.
In case of predicting the resistance of flexible vegetation, the description of Klopstra et al. (1997) with the turbulent length scale given by Meijer (1998b) and Van Velzen et al. (2003) perform the best, also the descriptions of Van Velzen et al. (2003) and Baptist et al. (2006) show good performance.
From a theoretical point of view it is surprising that the descriptions show reasonable agreement with data of flexible vegetation. In most datasets the deflected plant height (which changes with changing velocity) is used, and for three data sets the erected plant height was used. Apparently, the opinions about using the deflected plant height or erected height in the descriptions for rigid vegetation are divided. Moreover, it is hard to determine the deflected plant height, especially when the vegetation is waving. These points of discussion are out of the scope of this research. The errors of the four best performing descriptors fall between a range of 50 % error, independent which plant height is used.

Taking other criteria into account besides the performance of the descriptions in predicting the resistance for rigid and flexible vegetation, the descriptions of Klopstra et al. (1997) with the turbulent length scale of Meijer (1998b) or Van Velzen (2003) performs well at the different criteria.

Related to flood conditions, predicting the resistance in case of high water levels is very important. Unfortunately, due to lack of data for high water levels, it is hard to conclude which description is most suitable for river management models related to flood conditions. Especially high water levels with high vegetation is important to investigate. Such submergence ratio's for lower water levels and vegetation could be scaled to get an estimate of uncertainty in predicting higher water levels. However, data for higher water levels with high vegetation would be more reliable.

Most plants are flexible with side-branches and foliage. Therefore, the performance of the descriptors for flexible vegetation is very important. In the Netherlands, the method of Klopstra et al. (1996) with the turbulent length scale of Van Velzen et al. (2003) is used in the 2D model, WAQUA. As described above, that description performs very well at different criteria. Therefore, it is concluded that the method of Klopstra et al. (1996) is useful for that purpose. The method of Baptist et al. (2006) is also used often by water managers, and performs quite well. However, that descriptions is less theoretical sounded and performs less accurate than the method of Klopstra et al. (1996).
Neglecting the other criteria and only taking the performance of predicting the water levels into account, the used method (Klopstra et al., 1996 (a), Klopstra et al., 1996 (b), Van Velzen et al., 2003 or Baptist et al., 2006), does not make a big difference. More important is to take the shortcoming and assumptions of the model into account. Using common sense and safety factors remains very important in modeling the resistance of vegetation and using the results for flood management decisions.

Even though, four descriptions performs well in predicting the water levels for flexible vegetation, further investigation is necessary, especially to get a better insight in the effect of side branches and foliage. In my opinion, more information is needed about the effect of flexible vegetation, because most of the vegetation with side branches and foliage is flexible and is most common in natural floodplains.

6. Conclusions and recommendations

6.1. Answers to the research questions

The aim of this research was to identify the practical suitability of different vegetation resistance descriptions, by compiling a wide data set of flow experiments and to use this data set to evaluate the ranges of applicability of different (existing) vegetation resistance descriptions, for predicting water levels for river management purposes.

The aim is achieved by answering the following research questions:

1: What descriptions can be found in the literature that can be used to predict vegetation resistance and how are they derived?

Several descriptions for rigid cylindrical vegetation under emergent and submerged conditions were found in literature. Three descriptions were found for emergent vegetation and eight descriptions were selected for submerged vegetation.
All descriptions uses vegetation in a simplified form with fixed and identical plant height and diameter. Also the vegetation is assumed to be a homogeneous equally distributed field. The flow is assumed to be steady and uniform. The channel is considered to be sufficiently wide, so that sidewall effects can be neglected. Most descriptions take the bottom roughness into account. However, from literature it is known that the influence of bottom roughness is small in vegetated channels (Stone and Shen, 2002). Therefore, the influence of the bottom roughness is removed from the descriptions.

An important description for emergent vegetation is the equation of Petryk and Bosmaijan (1975). The other two descriptions for emergent vegetation show resemblance with the equation of Petryk and Bosmaijan (1975). The description of Stone and Shen (2002) takes the solidity of the vegetation into account. Hoffmann (2004) uses the porosity of the vegetation. However, from literature it is known that the effects of the solidity and porosity are very small (Baptist et al, 2006).
Seven of the eight selected descriptors for submerged vegetation show resemblance with the equation of Petryk and Bosmaijan (1975) for describing the velocity in the vegetation layer. It was concluded that further investigation for a description describing the resistance for emergent vegetation was not necessary in this research, in addition, the influence of the solidity and porosity is negligible. Therefore, the descriptions for emergent vegetation were not used for further analysis in this study.
The description for submerged vegetation of Borovkov and Yurchuk (1994) was implicit and empirically based, therefore, that method is neglected.

Most descriptions for submerged vegetation are based on the two layer theory, which makes a distinction between the velocity in the vegetation layer and in the surface layer. For defining the velocity in the vegetation layer, two different trends are present. Two descriptors, Klopstra et al. (1997) with three different descriptions for the turbulent length scale and the description of Huthoff (2007) define the velocity in the vegetation layer by taking the influence of the higher velocities in the surface layer into account. Three descriptors (Stone and Shen, 2002; Van Velzen et al., 2003 and Baptist et al., 2006) assume a constant velocity over the depth in the vegetation layer. Most descriptors define the velocity in the surface layer by a logarithmic profile, except Stone and Shen, 2002 which assumed a relation between the velocity in the vegetation layer and the mean velocity.

A theoretical description for flexible vegetation (even in the simplified form without side-branches and foliage) with input parameters which can be easily measured in the field is still lacking. Descriptions derived to predict the behavior of rigid vegetation are also used to predict the behavior of flexible vegetation.

2: *What data can be found to use for comparison of these descriptions?*

A data set for submerged rigid and flexible vegetation used in the article of Augustijn et al. (2008) was available including results from 10 studies. To extend the present data set new data from other literature has been added. In totality 173 runs from 5 different authors for rigid vegetation are used and 133 runs from 11 different authors for flexible vegetation were present.

The main difficulty in deriving a data set from literature is the fact these authors uses different ways to determine the drag coefficient and slope, which make a comparison of different data sets hard. Due to uncertainties in the drag coefficient and the slope, it was wondered if the data was reliable enough. To investigate the reliability of the data and in order to correct the data, a scheme based on the equation of Petryk and Bosmaijan (1975) was developed using the measured velocity in the vegetation layer. The scheme is used for rigid and for flexible vegetation. The main assumption of the scheme is that the equation of Petryk and Bosmaijan (1975) is reliable enough to use for calculating the velocity, drag coefficient and/or slope in the vegetation layer. However, the equation of Petryk and Bosmaijan (1975) (and therefore the scheme) is less accurate for flexible vegetation because the flexibility is not taken into account. The new derived data sets performed well in comparison to the calculated velocities (R^2 = 95%), therefore no big corrections were needed. Only when values for the drag coefficient were not given, a drag coefficient of 1 was assumed. Moreover, it was investigated if a standard drag coefficient (of 1) for all vegetation could be used. It can be concluded that a standard drag coefficient does not improve the results and the drag coefficients given by the extractors of data were used.

Another purpose of the above mentioned scheme is the fact that it can also be used as manual for determining the drag coefficient and slope in deriving data from flume experiments with submerged rigid vegetation. Consistency in determining the drag coefficient and the slope, makes data sets from different authors easier to compare with each other.

Most data are limited to relatively low water levels. Due to practical reasons (small experimental flumes) most authors used water levels beneath 1 meter. Only one data sets for water levels above 1 m and high vegetation heights was present. However for flood management high water levels with high vegetation are most important. Such submergence ratios for lower water levels and vegetation could be scaled to get an estimate of uncertainty in predicting higher water levels.

3: **How accurate are the predictions of vegetation resistance by the different descriptions in comparison with field/experimental data?**

The descriptors predicts the water levels for rigid vegetation very well with R^2 above 0.99 for the water level shows good performance. Only, the method of Stone and Shen (2002) performs less well, especially for higher water levels (>1 m). The difference in performance between the different descriptors is small for rigid vegetation. For the six remaining descriptions the error in the water level prediction is within a range

smaller than 40 cm. Unfortunately, only one data set with higher water levels (>1 m) were present (Meijer, 1998) which was also used by four different authors of descriptions to define parameters or relations. Therefore, it is unreliable to draw conclusions about the performance of the descriptions for higher water levels.
For water levels < 1 m the description of Klopstra at al. (1997) with the turbulent length scale of Meijer (1998) or the turbulent length scale defined by Huthoff (2007) show the smallest error for the water level in cm, namely <15 cm.

The performance of the seven descriptors in predicting the water levels for flexible vegetation is more divers. The description of Klopstra et al. (1997) with the turbulent length scale given by Meijer (1998) and Van Velzen et al. (2003) perform very well in predicting hydraulic effects of flexible vegetation, also the method of Van Velzen et al. (2003) and the method of Baptist et al. (2006) show good performance. All these descriptors show errors smaller than 25 cm for water levels < 1 m.

It is concluded that most theoretical descriptions defined for rigid vegetation can also be used for flexible vegetation (without side branches and leaves), even though the predictions are less accurate. However, it is not investigated if the descriptions can be used for all types of flexible vegetation. Highly flexible vegetation, were not present in the data set and it is unknown if these descriptions defined for rigid vegetation can predict the behavior of that kind of flexible vegetation.

4: **Which description(s) is (are) most suitable for using in river management models?**
As mentioned before, conclusions about the predictions of higher water levels which are very important for flood management, are lacking.

For the lower water levels, the descriptions by Klopstra et al. (1997) with the turbulent length scale given by Meijer (1998) and Van Velzen et al. (2003), Van Velzen et al. (2003) and Baptist et al. (2006) perform equally well in predicting the resistance and could also be used with the same confidence.
Besides the performance of the descriptions in predicting the resistance of rigid and flexible vegetation (described at research question 3) also other criteria are investigated like; easiness to use, theoretical soundness and adaptability to take side branches and leaves into account. Taking the performance and the other criteria into account, the description of Klopstra et al. (1997) with the turbulent length scale defined by Meijer (1998) or Van Velzen (2003) performs best (and equally well).

In the Netherlands, the method of Klopstra et al. (1996) with the turbulent length scale defined by Van Velzen et al. (2003) is incorporated in the 2D model WAQUA which is used for flood management. Based on this study this seems a right choice, although it is not a very simple description.

The input parameters used in the descriptions, are sometimes hard to determine (e.g. slope and drag force, flexibility etc.). Moreover, all descriptions use simplified representation of the reality. Care should be taken with all descriptions since none are perfect. Uncertainty in resistance predictions remains an issue to deal with in river modeling.

6.2. *Recommendations*

Based on this research a few recommendations are made. One of the most important aspects which needs improvement is determining the drag coefficient and slope. An uniform method to determine the drag coefficient and the slope are needed so that results from different experiments are comparable, for that purpose the developed scheme can be used. Moreover, a standard approach in using deflected or erected plant height in theoretical descriptions for rigid vegetation is needed.

Recommendations for further laboratory experiments are:

- experiments with higher water levels and high vegetation
- experiments to investigate the difference in resistance of rigid and flexible vegetation (with and without side branches and leaves)
- experiments to get better insight in the drag coefficient, especially for vegetation with side-branches and leaves

Using the results of the above mentioned laboratory experiments the theoretical descriptions could be adapted for more realistic vegetation, taking the flexibility, foliage and side branches into account.

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Content Appendix

Appendix A. Available dataset

In this appendix the data set which was already available is shown.

Rigid vegetation										
Author(s)	run	D (m)	m (m^{-2})	k (m)	Cd	h (m)	U (m/s)	i	h/k	C
Tsujimoto & Kitamura (1990)	A11	0,0015	2500	0,046	1,46	0,095	0,133	0,00101	2,07	13,59
	A12	0,0015	2500	0,046	1,46	0,075	0,117	0,00100	1,63	13,54
	A31	0,0015	2500	0,046	1,46	0,094	0,196	0,00300	2,04	11,69
	A32	0,0015	2500	0,046	1,46	0,074	0,179	0,00299	1,60	12,08
	A71	0,0015	2500	0,046	1,46	0,090	0,331	0,00703	1,95	13,20
	A72	0,0015	2500	0,046	1,46	0,073	0,267	0,00701	1,58	11,83
Meijer (1998b)	1	0,008	256	1,500	0,99	1,980	0,175	0,00109	1,32	3,76
	2	0,008	256	1,500	0,98	1,990	0,233	0,00180	1,33	3,89
	3	0,008	256	1,500	0,99	2,190	0,212	0,00095	1,46	4,65
	4	0,008	256	1,500	0,99	2,190	0,238	0,00125	1,46	4,55
	5	0,008	256	1,500	0,99	2,350	0,242	0,00081	1,57	5,56
	6	0,008	256	1,500	0,98	2,330	0,337	0,00154	1,55	5,62
	7	0,008	256	1,500	1,00	2,500	0,255	0,00065	1,67	6,33
	8	0,008	256	1,500	0,99	2,470	0,368	0,00143	1,65	6,19
	9	0,008	64	1,500	0,97	2,010	0,309	0,00106	1,34	6,70
	10	0,008	64	1,500	0,97	2,010	0,419	0,00193	1,34	6,73
	11	0,008	64	1,500	0,97	2,200	0,347	0,00101	1,47	7,36
	12	0,008	64	1,500	0,96	2,190	0,468	0,00188	1,46	7,29
	13	0,008	64	1,500	0,97	2,350	0,372	0,00093	1,57	7,97
	14	0,008	64	1,500	0,96	2,310	0,499	0,00187	1,54	7,59
	15	0,008	64	1,500	0,97	2,480	0,391	0,00094	1,65	8,10
	16	0,008	64	1,500	0,96	2,460	0,535	0,00178	1,64	8,08
	17	0,008	256	0,900	0,99	1,510	0,248	0,00107	1,68	6,17
	18	0,008	256	0,900	0,97	1,520	0,355	0,00204	1,69	6,38
	19	0,008	256	0,900	0,99	1,810	0,331	0,00085	2,01	8,46
	20	0,008	256	0,900	0,97	1,800	0,473	0,00165	2,00	8,69
	21	0,008	256	0,900	0,98	2,090	0,403	0,00071	2,32	10,46
	22	0,008	256	0,900	0,97	2,090	0,577	0,00138	2,32	10,75
	23	0,008	256	0,900	0,98	2,480	0,500	0,00055	2,76	13,53
	24	0,008	256	0,900	0,97	2,460	0,808	0,00149	2,73	13,35
	25	0,008	64	0,900	0,97	1,510	0,386	0,00103	1,68	9,78
	26	0,008	64	0,900	0,97	1,520	0,554	0,00205	1,69	9,92
	27	0,008	64	0,900	0,97	1,810	0,461	0,00085	2,01	11,76
	28	0,008	64	0,900	0,97	1,780	0,661	0,00180	1,98	11,68
	29	0,008	64	0,900	0,97	2,100	0,537	0,00075	2,33	13,54
	30	0,008	64	0,900	0,97	2,060	0,764	0,00164	2,29	13,14
	31	0,008	64	0,900	0,96	2,470	0,645	0,00071	2,74	15,40
	32	0,008	64	0,900	0,97	2,470	0,902	0,00143	2,74	15,18

	33	0,008	256	0,450	0,98	1,020	0,283	0,00078	2,27	10,04
	34	0,008	256	0,450	0,97	0,990	0,441	0,00164	2,20	10,95
	35	0,008	256	0,450	0,98	1,510	0,461	0,00059	3,36	15,45
	36	0,008	256	0,450	0,97	1,500	0,680	0,00138	3,33	14,94
	37	0,008	256	0,450	0,98	1,980	0,630	0,00058	4,40	18,58
	38	0,008	256	0,450	0,97	1,990	0,942	0,00142	4,42	17,72
	39	0,008	256	0,450	0,97	2,460	0,802	0,00070	5,47	19,33
	40	0,008	256	0,450	0,97	2,490	0,961	0,00090	5,53	20,33
	41	0,008	64	0,450	0,97	1,020	0,438	0,00075	2,27	15,83
	42	0,008	64	0,450	0,97	1,000	0,661	0,00187	2,22	15,29
	43	0,008	64	0,450	0,96	1,500	0,624	0,00069	3,33	19,44
	44	0,008	64	0,450	0,97	1,500	1,061	0,00199	3,33	19,40
	45	0,008	64	0,450	0,97	2,000	0,955	0,00099	4,44	21,47
	46	0,008	64	0,450	0,97	2,000	1,219	0,00159	4,44	21,63
	47	0,008	64	0,450	0,97	2,480	0,883	0,00063	5,51	22,35
	48	0,008	64	0,450	0,97	2,410	1,242	0,00127	5,36	22,45
Dunn et al. (1997)	1	0,0064	170	0,120	1,13	0,335	0,587	0,00360	2,79	16,91
	2	0,0064	170	0,120	1,13	0,229	0,422	0,00359	1,91	14,71
	3	0,0064	170	0,120	1,13	0,164	0,308	0,00359	1,37	12,69
	4	0,0064	170	0,120	1,13	0,276	0,709	0,00761	2,30	15,47
	5	0,0064	170	0,120	1,13	0,203	0,531	0,00761	1,69	13,51
	6	0,0064	42	0,120	1,13	0,267	0,733	0,00360	2,23	23,63
	7	0,0064	42	0,120	1,13	0,183	0,570	0,00359	1,53	22,23
	8	0,0064	384	0,120	1,13	0,391	0,506	0,00360	3,26	13,48
	9	0,0064	384	0,120	1,13	0,214	0,398	0,00643	1,78	10,73
	10	0,0064	384	0,120	1,13	0,265	0,746	0,01607	2,21	11,43
	11	0,0064	97	0,120	1,13	0,311	0,625	0,00360	2,59	18,69
	12	0,0064	97	0,120	1,13	0,233	0,854	0,01101	1,94	16,86
Flexible vegetation										
Author(s)	**run**	**D (m)**	**m (m^{-2})**	**k (m)**	**Cd**	**h (m)**	**u (m/s)**	**i**	**h/k**	**C**
Kouwen et al. (1969)	1	0,005	5000	0,100	3,00	0,151	0,030	0,00051	1,51	3,41
	2	0,005	5000	0,100	3,00	0,253	0,110	0,00100	2,53	6,91
	3	0,005	5000	0,085	3,00	0,382	0,367	0,00300	4,49	10,85
	4	0,005	5000	0,100	3,00	0,152	0,098	0,00502	1,52	3,55
	7	0,005	5000	0,100	3,00	0,151	0,143	0,01001	1,51	3,68
	8	0,005	5000	0,050	3,00	0,242	0,560	0,00939	4,84	11,74
	9	0,005	5000	0,100	3,00	0,350	0,205	0,00100	3,50	10,93
	10	0,005	5000	0,100	3,00	0,250	0,268	0,00491	2,50	7,65
	11	0,005	5000	0,100	3,00	0,400	0,156	0,00050	4,00	11,05
	12	0,005	5000	0,100	3,00	0,300	0,106	0,00050	3,00	8,64
	13	0,005	5000	0,100	3,00	0,150	0,071	0,00297	1,50	3,37
	14	0,005	5000	0,100	3,00	0,200	0,055	0,00050	2,00	5,48
	15	0,005	5000	0,095	3,00	0,300	0,271	0,00300	3,16	9,03
	16	0,005	5000	0,100	3,00	0,200	0,079	0,00099	2,00	5,60
	17	0,005	5000	0,060	3,00	0,199	0,395	0,01001	3,32	8,85

	18	0,005	5000	0,100	3,00	0,350	0,133	0,00050	3,50	10,06
	19	0,005	5000	0,075	3,00	0,300	0,400	0,00500	4,00	10,33
	20	0,005	5000	0,100	3,00	0,300	0,158	0,00101	3,00	9,09
	21	0,005	5000	0,100	3,00	0,200	0,135	0,00298	2,00	5,53
	22	0,005	5000	0,100	3,00	0,200	0,185	0,00502	2,00	5,84
	24	0,005	5000	0,060	3,00	0,349	0,536	0,00501	5,81	12,83
	25	0,005	5000	0,090	3,00	0,399	0,229	0,00100	4,43	11,49
	26	0,005	5000	0,100	3,00	0,253	0,082	0,00050	2,53	7,31
	27	0,005	5000	0,090	3,00	0,351	0,352	0,00299	3,90	10,86
	28	0,005	5000	0,100	3,00	0,259	0,196	0,00300	2,59	7,03
	29	0,005	5000	0,055	3,00	0,383	0,609	0,00491	6,96	14,05
	30	0,005	5000	0,100	3,00	0,149	0,041	0,00098	1,49	3,39
Ree and Crow (1977)	k4	0,005	1464	0,203	1,00	0,242	0,070	0,00147	1,19	3,71
	k5	0,005	1464	0,203	1,00	0,247	0,068	0,00128	1,22	3,83
	k6	0,005	1464	0,203	1,00	0,302	0,054	0,00042	1,49	4,82
	k7	0,005	1464	0,203	1,00	0,302	0,109	0,00143	1,49	5,25
	k8	0,005	1464	0,203	1,00	0,345	0,106	0,00123	1,70	5,15
	k9	0,005	1464	0,203	1,00	0,375	0,086	0,00052	1,85	6,15
	k10	0,005	1464	0,203	1,00	0,428	0,174	0,00167	2,11	6,51
	k11	0,005	1464	0,203	1,00	0,379	0,161	0,00116	1,87	7,67
	k12	0,005	1464	0,203	1,00	0,438	0,133	0,00052	2,16	8,78
	k13	0,005	1464	0,203	1,00	0,431	0,268	0,00187	2,12	9,44
	k14	0,005	1464	0,203	1,00	0,465	0,246	0,00129	2,29	10,05
	k15	0,005	1464	0,203	1,00	0,521	0,208	0,00070	2,56	10,88
	k16	0,005	1464	0,203	1,00	0,528	0,412	0,00205	2,60	12,53
	k17	0,005	1464	0,203	1,00	0,570	0,376	0,00145	2,81	13,08
	L2	0,005	1076	0,305	1,00	0,324	0,055	0,00210	1,06	2,11
	L3	0,005	1076	0,305	1,00	0,342	0,052	0,00176	1,12	2,12
	L4	0,005	1076	0,305	1,00	0,382	0,046	0,00121	1,25	2,14
	L6	0,005	1076	0,305	1,00	0,463	0,058	0,00108	1,52	2,59
	L7	0,005	1076	0,305	1,00	0,520	0,049	0,00061	1,71	2,75
	L8	0,005	1076	0,305	1,00	0,493	0,101	0,00157	1,62	3,63
	L9	0,005	1076	0,305	1,00	0,520	0,094	0,00124	1,71	3,70
	L10	0,005	1076	0,305	1,00	0,585	0,081	0,00076	1,92	3,84
	L11	0,005	1076	0,305	1,00	0,547	0,187	0,00174	1,79	6,07
	L12	0,005	1076	0,305	1,00	0,617	0,154	0,00099	2,02	6,24
	L13	0,005	1076	0,305	1,00	0,690	0,131	0,00059	2,26	6,51
	L14	0,005	1076	0,305	1,00	0,619	0,298	0,00180	2,03	8,94
	L15	0,005	1076	0,305	1,00	0,680	0,262	0,00125	2,23	9,00
	L16	0,005	1076	0,305	1,00	0,751	0,227	0,00089	2,46	8,78
	L17	0,005	1076	0,305	1,00	0,692	0,427	0,00189	2,27	11,81
	L18	0,005	1076	0,305	1,00	0,749	0,377	0,00140	2,46	11,65
Murota et al. (1984)	A1	0,00024	4000	0,058	2,75	0,116	0,127	0,00100	2,00	11,77
	A3	0,00024	4000	0,052	2,75	0,106	0,191	0,00201	2,04	13,09

	A6	0,00024	4000	0,052	2,75	0,103	0,229	0,00297	1,98	13,09
	A7	0,00024	4000	0,060	2,75	0,110	0,099	0,00050	1,83	13,33
	A14	0,00024	4000	0,055	2,75	0,102	0,167	0,00191	1,86	12,00
	A20	0,00024	4000	0,053	2,75	0,106	0,173	0,00148	2,00	13,82
	A21	0,00024	4000	0,048	2,75	0,092	0,258	0,00383	1,93	13,78
	A22	0,00024	4000	0,058	2,75	0,097	0,085	0,00073	1,68	10,12
Tsujimoto et al. (1993)	BZ1	0,00062	10000	0,065	2,00	0,100	0,078	0,00122	1,54	7,07
	BZ2	0,00062	10000	0,065	2,00	0,140	0,092	0,00089	2,15	8,26
	BZ3	0,00062	10000	0,065	2,00	0,160	0,086	0,00051	2,46	9,51
	BZ4	0,00062	10000	0,065	2,00	0,110	0,132	0,00298	1,69	7,29
	BZ5	0,00062	10000	0,065	2,00	0,130	0,161	0,00320	2,00	7,89
	BZ6	0,00062	10000	0,065	2,00	0,160	0,164	0,00212	2,46	8,91
	BZ7	0,00062	10000	0,064	2,00	0,100	0,192	0,00505	1,56	8,54
	BZ8	0,00062	10000	0,064	2,00	0,120	0,245	0,00633	1,88	8,89
	BZ9	0,00062	10000	0,064	2,00	0,150	0,273	0,00120	2,34	20,32
	BZ10	0,00062	10000	0,063	2,00	0,100	0,275	0,00999	1,59	8,70
	BZ11	0,00062	10000	0,062	2,00	0,130	0,333	0,00922	2,10	9,62
	BZ12	0,00062	10000	0,061	2,00	0,110	0,385	0,01076	1,80	11,19
Ikeda and Kanazawa (1996)	1	0,00024	20000	0,040	1,00	0,148	0,503	0,00446	3,70	19,57
	2	0,00024	20000	0,042	1,00	0,142	0,444	0,00392	3,38	18,83
	3	0,00024	20000	0,045	1,00	0,146	0,349	0,00247	3,24	18,39
	4	0,00024	20000	0,042	1,00	0,190	0,493	0,00491	4,52	16,14
	5	0,00024	20000	0,040	1,00	0,165	0,606	0,00641	4,13	18,64
	6	0,00024	20000	0,042	1,00	0,171	0,360	0,00278	4,07	16,50
	7	0,00024	20000	0,040	1,00	0,180	0,444	0,00420	4,50	16,15
Meijer (1998a)	R2	0,0057	254	1,640	1,81	1,990	0,142	0,00113	1,21	2,99
	R3	0,0057	254	1,650	1,81	2,250	0,201	0,00111	1,36	4,02
	R4	0,0057	254	1,650	1,81	2,480	0,258	0,00109	1,50	4,97
	R5	0,0057	254	1,550	1,81	1,750	0,152	0,00208	1,13	2,52
	R6	0,0057	254	1,580	1,81	1,990	0,196	0,00190	1,26	3,19
	R7	0,0057	254	1,580	1,81	2,230	0,279	0,00165	1,41	4,60
	R8	0,0057	254	1,580	1,81	2,500	0,393	0,00195	1,58	5,63
Järvelä (2003)	R4-1	0,0028	12000	0,205	1,00	0,306	0,119	0,00150	1,49	5,55
	R4-2	0,0028	12000	0,155	1,00	0,3084	0,295	0,00360	1,99	8,85
	R4-3	0,0028	12000	0,23	1,00	0,4065	0,09	0,00510	1,77	6,28
	R4-4	0,0028	12000	0,19	1,00	0,4041	0,225	0,00130	2,13	9,82
	R4-5	0,0028	12000	0,16	1,00	0,407	0,319	0,00200	2,54	11,19
	R4-6	0,0028	12000	0,245	1,00	0,5044	0,072	0,00020	2,06	7,18
	R4-7	0,0028	12000	0,22	1,00	0,495	0,184	0,0006	2,25	10,65
	R4-8	0,0028	12000	0,26	1,00	0,7065	0,129	0,00020	2,72	10,83
	R4-9	0,0028	12000	0,215	1,00	0,7037	0,185	0,00030	3,27	12,71
	S3-1	0,003	512	0,295	1,00	0,4003	0,091	0,00040	1,36	7,18
	S3-2	0,003	512	0,2	1,00	0,3961	0,23	0,00100	1,98	11,53
	S3-3	0,003	512	0,17	1,00	0,3942	0,33	0,00180	2,32	12,38

Appendix B. Collected dataset

In this appendix the data collected from literature is shown. The data which was not complete, like the data of Freeman et al. (2002) is not added. The data which did not gave the velocity inside the vegetation layer and/or above the vegetation layer, and gave large deviations in comparison the data with the seven resistance descriptors is marked grey.

Rigid vegetation										
Author(s)	run	D (m)	m (m^{-2})	k (m)	Cd	h (m)	U_v (m/s)	U_s (m/s)	U (m/s)	i
Einstein and Banks (1950)	106	0,0064	3	0,038	1,40	0,073			1,200	0,00774
	107	0,0064	5	0,038	1,40	0,073			1,190	0,00797
	108	0,0064	5	0,038	1,40	0,073			1,180	0,00815
	109	0,0064	11	0,038	1,40	0,074			1,170	0,00858
	110	0,0064	11	0,038	1,40	0,075			1,150	0,00860
	111	0,0064	22	0,038	1,40	0,076			1,140	0,00941
	112	0,0064	22	0,038	1,40	0,079			1,090	0,00906
	113	0,0064	32	0,038	1,40	0,086			1,000	0,00975
	114	0,0064	43	0,038	1,40	0,081			1,060	0,00993
	115	0,0064	43	0,038	1,40	0,082			1,050	0,01019
	116	0,0064	43	0,038	1,40	0,089			0,970	0,00884
	117	0,0064	54	0,038	1,40	0,095			0,910	0,00796
	118	0,0064	65	0,038	1,40	0,085			1,010	0,01024
	119	0,0064	65	0,038	1,40	0,099			0,870	0,00775
	120	0,0064	65	0,038	1,40	0,1			0,870	0,00803
	121	0,0064	86	0,038	1,40	0,101			0,860	0,00880
	122	0,0064	108	0,038	1,40	0,107			0,800	0,00845
	123	0,0064	108	0,038	1,40	0,107			0,810	0,00860
	124	0,0064	108	0,038	1,40	0,106			0,820	0,00833
	125	0,0064	108	0,038	1,40	0,108			0,800	0,00862
Shimizu and Tsujimotot (1994)	R22	0,0010	10000	0,041	1,00	0,073			0,096	0,00108
	R24	0,0010	10000	0,041	1,00	0,0948			0,128	0,00100
	R31	0,0010	10000	0,041	1,00	0,0631			0,112	0,00164
	R32	0,0010	10000	0,041	1,00	0,0747			0,139	0,00213
	R41	0,0010	10000	0,041	1,00	0,0659			0,145	0,00470
	R42	0,0010	10000	0,041	1,00	0,0735			0,172	0,00263
	R44	0,0010	10000	0,041	1,00	0,095			0,221	0,00256
	R53	0,0010	10000	0,041	1,00	0,0841			0,233	0,00435
	R55	0,0010	10000	0,041	1,00	0,1052			0,305	0,00476
	A11	0,0015	2500	0,046	1,00	0,095			0,133	0,00106
	A12	0,0015	2500	0,046	1,00	0,0749			0,117	0,00142
	A31	0,0015	2500	0,046	1,00	0,0936			0,196	0,00260
	A71	0,0015	2500	0,046	1,00	0,0895			0,331	0,00886
Stone & Shen (2002)	S9	0,0127	481	0,124	1,11	0,151	0,059	0,182	0,081	0,00232
	S22	0,0127	481	0,124	1,11	0,155	0,033	0,103	0,047	0,00091
	S23	0,0127	481	0,124	1,11	0,155	0,046	0,141	0,065	0,00159
	S24	0,0127	481	0,124	1,11	0,155	0,073	0,233	0,105	0,00406

S25	0,0127	481	0,124	1,11	0,155	0,101	0,326	0,146	0,00761
S26	0,0127	481	0,124	1,11	0,155	0,186	0,521	0,253	0,01668
S27	0,0127	481	0,124	1,11	0,155	0,250	0,770	0,354	0,03165
S28	0,0127	481	0,124	1,11	0,155	0,024	0,079	0,035	0,00055
S51	0,0127	481	0,124	1,11	0,153	0,026	0,089	0,038	0,00059
S52	0,0127	481	0,124	1,11	0,155	0,042	0,127	0,059	0,00144
S53	0,0127	481	0,124	1,11	0,155	0,062	0,187	0,087	0,00334
S54	0,0127	481	0,124	1,11	0,155	0,312	0,917	0,433	0,04402
S29	0,0127	481	0,124	1,11	0,206	0,017	0,067	0,037	0,00045
S30	0,0127	481	0,124	1,11	0,207	0,026	0,098	0,055	0,00063
S31	0,0127	481	0,124	1,11	0,205	0,041	0,140	0,080	0,00094
S32	0,0127	481	0,124	1,11	0,205	0,074	0,206	0,126	0,00198
S33	0,0127	481	0,124	1,11	0,206	0,106	0,307	0,186	0,00445
S34	0,0127	481	0,124	1,11	0,207	0,162	0,491	0,294	0,01207
S35	0,0127	481	0,124	1,11	0,207	0,129	0,401	0,238	0,00742
S36	0,0127	481	0,124	1,11	0,207	0,048	0,123	0,078	0,00081
S46	0,0127	481	0,124	1,11	0,206	0,039	0,099	0,063	0,00059
S47	0,0127	481	0,124	1,11	0,209	0,046	0,115	0,074	0,00054
S48	0,0127	481	0,124	1,11	0,206	0,056	0,139	0,089	0,00090
S49	0,0127	481	0,124	1,11	0,207	0,062	0,159	0,101	0,00117
S50	0,0127	481	0,124	1,11	0,212	0,067	0,171	0,110	0,00134
S37	0,0127	481	0,124	1,11	0,311	0,042	0,107	0,081	0,00036
S38	0,0127	481	0,124	1,11	0,308	0,045	0,124	0,092	0,00054
S39	0,0127	481	0,124	1,11	0,308	0,056	0,160	0,118	0,00076
S40	0,0127	481	0,124	1,11	0,313	0,074	0,202	0,151	0,00093
S41	0,0127	481	0,124	1,11	0,314	0,047	0,126	0,095	0,00040
S42	0,0127	481	0,124	1,11	0,308	0,089	0,266	0,195	0,00188
S43	0,0127	481	0,124	1,11	0,308	0,043	0,117	0,087	0,00035
S43	0,0127	481	0,124	1,11	0,308	0,047	0,127	0,095	0,00047
S45	0,0127	481	0,124	1,11	0,311	0,058	0,148	0,112	0,00054
S66	0,0127	173	0,124	1,00	0,155	0,053	0,098	0,062	0,00035
S67	0,0127	173	0,124	1,00	0,155	0,067	0,132	0,080	0,00058
S68	0,0127	173	0,124	1,00	0,155	0,086	0,171	0,103	0,00103
S69	0,0127	173	0,124	1,00	0,155	0,110	0,220	0,132	0,00170
S70	0,0127	173	0,124	1,00	0,155	0,134	0,264	0,160	0,00275
S71	0,0127	173	0,124	1,00	0,155	0,174	0,429	0,225	0,00523
S72	0,0127	173	0,124	1,00	0,155	0,294	0,629	0,361	0,01394
S90	0,0127	173	0,124	1,00	0,155	0,197	0,442	0,246	0,00568
S91	0,0127	173	0,124	1,00	0,155	0,233	0,508	0,288	0,00838
S94	0,0127	173	0,124	1,00	0,155	0,250	0,575	0,315	0,01013
S95	0,0127	173	0,124	1,00	0,155	0,176	0,381	0,217	0,00452
S99	0,0127	173	0,124	1,00	0,155	0,074	0,144	0,088	0,00098
S109	0,0127	173	0,124	1,00	0,155	0,081	0,181	0,101	0,00207
S110	0,0127	173	0,124	1,00	0,155	0,054	0,144	0,072	0,00118
S73	0,0127	173	0,124	1,00	0,207	0,035	0,062	0,046	0,00023

	S74	0,0127	173	0,124	1,00	0,207	0,049	0,084	0,063	0,00027
	S75	0,0127	173	0,124	1,00	0,207	0,053	0,098	0,071	0,00036
	S76	0,0127	173	0,124	1,00	0,207	0,059	0,119	0,083	0,00063
	S77	0,0127	173	0,124	1,00	0,207	0,069	0,131	0,094	0,00053
	S78	0,0127	173	0,124	1,00	0,207	0,077	0,152	0,107	0,00071
	S79	0,0127	173	0,124	1,00	0,207	0,114	0,219	0,156	0,00153
	S80	0,0127	173	0,124	1,00	0,207	0,177	0,409	0,270	0,00428
	S92	0,0127	173	0,124	1,00	0,207	0,157	0,344	0,232	0,00382
	S93	0,0127	173	0,124	1,00	0,207	0,130	0,270	0,186	0,00234
	S97	0,0127	173	0,124	1,00	0,207	0,052	0,102	0,072	0,00035
	S98	0,0127	173	0,124	1,00	0,207	0,096	0,193	0,135	0,00123
	S108	0,0127	173	0,124	1,00	0,207	0,022	0,069	0,041	0,00057
	S81	0,0127	173	0,124	1,00	0,308	0,047	0,091	0,073	0,00045
	S82	0,0127	173	0,124	1,00	0,308	0,045	0,092	0,073	0,00009
	S83	0,0127	173	0,124	1,00	0,308	0,050	0,107	0,084	0,00036
	S84	0,0127	173	0,124	1,00	0,308	0,070	0,139	0,111	0,00045
	S85	0,0127	173	0,124	1,00	0,308	0,085	0,165	0,133	0,00054
	S86	0,0127	173	0,124	1,00	0,308	0,124	0,240	0,193	0,00079
	S101	0,0127	173	0,124	1,00	0,308	0,105	0,221	0,174	0,00147
	E143	0,00318	696	0,124	0,98	0,155	0,010	0,045	0,017	0,00063
	E144	0,00318	696	0,124	0,98	0,155	0,033	0,103	0,047	0,00170
	E145	0,00318	696	0,124	0,98	0,155	0,088	0,208	0,112	0,00378
	S153	0,00318	696	0,124	0,98	0,155	0,033	0,103	0,047	0,00054
	S154	0,00318	696	0,124	0,98	0,155	0,088	0,208	0,112	0,00205
	S156	0,00318	696	0,124	0,98	0,155	0,228	0,468	0,276	0,00676
	S161	0,00318	696	0,124	0,98	0,206	0,185	0,376	0,261	0,00372
	S170	0,00318	696	0,124	0,98	0,207	0,115	0,245	0,167	0,00162
	S171	0,00318	696	0,124	0,98	0,205	0,042	0,093	0,062	0,00260
	S172	0,00318	696	0,124	0,98	0,205	0,148	0,323	0,217	0,00365
	S173	0,00318	696	0,124	0,98	0,205	0,351	0,733	0,502	0,01509
	S174	0,00318	696	0,124	0,98	0,308	0,020	0,065	0,047	0,00009
	S175	0,00318	696	0,124	0,98	0,308	0,037	0,112	0,082	0,00017
	S176	0,00318	696	0,124	0,98	0,308	0,070	0,189	0,141	0,00088
	S177	0,00318	696	0,124	0,98	0,311	0,152	0,421	0,314	0,00308
	S207	0,00635	173	0,124	0,96	0,155	0,103	0,178	0,118	0,00108
	S208	0,00635	173	0,124	0,96	0,155	0,320	0,490	0,354	0,00703
	S211	0,00635	173	0,124	0,96	0,155	0,164	0,289	0,189	0,00255
	S212	0,00635	173	0,124	0,96	0,155	0,089	0,164	0,104	0,00083
	S213	0,00635	173	0,124	0,96	0,205	0,078	0,139	0,102	0,00061
	S214	0,00635	173	0,124	0,96	0,205	0,122	0,208	0,156	0,00127
	S215	0,00635	173	0,124	0,96	0,205	0,173	0,297	0,222	0,00239
	S218	0,00635	173	0,124	0,96	0,31	0,069	0,166	0,127	0,00034
	S219	0,00635	173	0,124	0,96	0,31	0,088	0,191	0,150	0,00045
Poggi et al. (2004)	D1	0,00400	67	0,120	1,50	0,600	0,220	0,331	0,309	4,00E-05
	D2	0,00400	134	0,120	1,50	0,600	0,185	0,344	0,312	7,00E-05

	D3	0,00400	268	0,120	1,50	0,600	0,154	0,353	0,313	1,10E-04
	D4	0,00400	536	0,120	1,50	0,600	0,122	0,361	0,313	1,80E-04
	D5	0,00400	1072	0,120	1,50	0,600	0,087	0,353	0,30	3,20E-04
Murhpy et al. (2007)	A	0,0064	250	0,139	0,81	0,467	0,016	0,037	0,031	5,03E-06
	C	0,0064	340	0,139	0,77	0,467	0,020	0,055	0,045	1,02E-05
	D	0,0064	340	0,0139	0,85	0,467	0,014	0,038	0,037	5,50E-07
	E	0,0064	400	0,138	0,67	0,467	0,042	0,106	0,087	4,56E-05
	G	0,0064	400	0,138	0,82	0,467	0,014	0,037	0,030	6,20E-06
	H	0,0064	800	0,138	0,61	0,467	0,033	0,111	0,088	5,12E-05
	I	0,0064	800	0,138	0,66	0,467	0,021	0,072	0,057	2,24E-05
	A6	0,006	250	0,07	1,00	0,298	0,006	0,016	0,014	6,47E-07
	B6	0,006	250	0,07	1,00	0,298	0,033	0,084	0,072	1,96E-05
	C6	0,006	250	0,07	1,00	0,298	0,017	0,044	0,038	5,79E-06
	A1	0,006	250	0,07	1,00	0,236	0,007	0,016	0,013	1,11E-06
	B1	0,006	250	0,07	1,00	0,236	0,043	0,102	0,085	4,19E-05
	C1	0,006	250	0,07	1,00	0,236	0,022	0,051	0,042	1,10E-05
	A2	0,006	250	0,07	1,00	0,14	0,013	0,029	0,021	6,46E-06
	B2	0,006	250	0,07	1,00	0,14	0,078	0,155	0,117	2,33E-04
	C2	0,006	250	0,07	1,00	0,14	0,050	0,106	0,078	9,56E-05
	A3	0,006	250	0,07	1,00	0,105	0,025	0,540	0,197	3,19E-05
	C3	0,006	250	0,07	1,00	0,105	0,069	0,147	0,095	2,43E-04
	A5	0,006	250	0,07	1,00	0,088	0,028	0,053	0,033	4,77E-05
	C5	0,006	250	0,07	1,00	0,088	0,099	0,187	0,117	5,96E-04
	C6D	0,006	800	0,07	1,00	0,298	0,008	0,046	0,037	3,68E-06
	C2D	0,006	800	0,07	1,00	0,14	0,030	0,093	0,062	1,10E-04
	A2D	0,006	800	0,07	1,00	0,14	0,010	0,034	0,022	1,22E-05
	A3D	0,006	800	0,07	1,00	0,105	0,020	0,052	0,031	6,52E-05
Flexible vegetation										
Author	**run**	**D (m)**	**m (m^{-2})**	**k (m)**	**Cd**	**h (m)**	**U_v (m/s)**	**U_s (m/s)**	**U (m/s)**	**i**
Fenzl (1962)		0,00238	1808,0	0,051	1,04	0,123			0,121	0,00250
		0,00238	1808,0	0,051	1,04	0,058			0,054	0,00250
		0,00238	1808,0	0,051	1,04	0,086			0,08	0,00241
		0,00238	1808,0	0,152	1,04	0,153			0,052	0,00285
		0,00238	1808,0	0,152	1,04	0,159			0,052	0,00249
		0,00238	1808,0	0,152	1,04	0,168			0,06	0,00263
		0,00238	1808,0	0,152	1,04	0,175			0,062	0,00270
		0,00238	1808,0	0,051	1,04	0,154			0,157	0,00249
		0,00238	452,0	0,051	1,01	0,112			0,196	0,00215
		0,00238	452,0	0,051	1,01	0,059			0,117	0,00239
		0,00238	452,0	0,051	1,01	0,091			0,147	0,00214
		0,00238	452,0	0,051	1,01	0,088			0,152	0,00229
		0,00238	452,0	0,152	1,01	0,167			0,126	0,00254
		0,00238	452,0	0,152	1,01	0,18			0,137	0,00246
		0,00238	452,0	0,051	1,01	0,145			0,213	0,0023
		0,00238	200,0	0,051	1,03	0,087			0,207	0,00193

		0,00238	200,0	0,152	1,03	0,162			0,165	0,00244
		0,00238	200,0	0,051	1,03	0,122			0,253	0,0019
		0,00238	200,0	0,152	1,03	0,177			0,177	0,00247
		0,00238	200,0	0,051	1,03	0,153			0,289	0,00188
		0,00238	113,0	0,051	1,17	0,127			0,241	0,00163
		0,00238	113,0	0,051	1,17	0,093			0,249	0,0017
		0,00238	113,0	0,051	1,17	0,064			0,198	0,00182
		0,00238	113,0	0,152	1,17	0,156			0,205	0,00241
		0,00238	11	0,152	1,17	0,181			0,226	0,00255
		0,00238	113	0,152	1,17	0,17			0,224	0,00246
Tsujimoto et al. (1991)	OHP1	0,0015	2500	0,0418	3,14	0,08	0,047	0,151	0,0945	0,00100
	OHP2	0,0015	2500	0,0419	3,14	0,10	0,046	0,195	0,1308	0,00100
	OHP3	0,0015	2500	0,039	3,14	0,11	0,0463	0,217	0,1572	0,00100
	OHP4	0,0015	2500	0,033	3,14	0,07	0,0871	0,284	0,1844	0,00300
	OHP5	0,0015	2500	0,029	3,14	0,09	0,0929	0,390	0,2919	0,00300
	OHP6	0,0015	2500	0,0265	3,14	0,10	0,0972	0,485	0,3854	0,00300
	OHP7	0,0015	2500	0,0238	3,14	0,08	0,1565	0,585	0,452	0,00700
	OHP8	0,0015	2500	0,0245	3,14	0,08	0,1547	0,622	0,4836	0,00700
Rowinski et al. (2002)	1,1,3	0,000825	10000	0,165	1,29	0,2475	0,08	0,473	0,211	0,0087
	1,2,1	0,000825	10000	0,165	1,27	0,2236	0,176	0,394	0,2332	0,0174
	2,1,1	0,000825	2500	0,165	1,33	0,2386	0,217	0,095	0,1793	0,0087
	2,2,1	0,000825	2500	0,165	1,22	0,2131	0,335	0,148	0,2928	0,0174
	3,1,1	0,000825	2500	0,165	1,28	0,2386	0,204	0,270	0,2243	0,0087
	3,2,1	0,000825	2500	0,165	1,22	0,1962	0,337	0,072	0,2948	0,0174
	4,1,1	0,000825	2500	0,165	1,35	0,2421	0,239	-0,013	0,1587	0,0087
	4,2,1	0,000825	2500	0,165	1,29	0,2077	0,318	-0,208	0,2098	0,0174
Carollo et al (2005)	I-1	0,0045	28000	0,07	1,00	0,128			0,35	0,00200
	I-2	0,0045	28000	0,057	1,00	0,163			0,521	0,00200
	I-3	0,0045	28000	0,054	1,00	0,19			0,681	0,00200
	I-4	0,0045	28000	0,051	1,00	0,202			0,757	0,00200
	I-5	0,0045	28000	0,049	1,00	0,217			0,816	0,00200
	I-6	0,0045	28000	0,048	1,00	0,231			0,87	0,00200
	I-7	0,0045	28000	0,047	1,00	0,245			0,918	0,00200
	I-8	0,0045	28000	0,044	1,00	0,258			0,976	0,00200
	I-9	0,0045	28000	0,045	1,00	0,272			1,047	0,00200
	II-1	0,0045	31000	0,061	1,00	0,112			0,358	0,00100
	II-2	0,0045	31000	0,06	1,00	0,121			0,383	0,00100
	II-3	0,0045	31000	0,058	1,00	0,127			0,435	0,00100
	II-4	0,0045	31000	0,06	1,00	0,135			0,471	0,00100
	II-5	0,0045	31000	0,08	1,00	0,095			0,211	0,00200
	II-6	0,0045	31000	0,06	1,00	0,112			0,358	0,00200
	II-7	0,0045	31000	0,06	1,00	0,119			0,389	0,00200
	II-8	0,0045	31000	0,058	1,00	0,124			0,446	0,00200
	II-9	0,0045	31000	0,058	1,00	0,133			0,479	0,00200

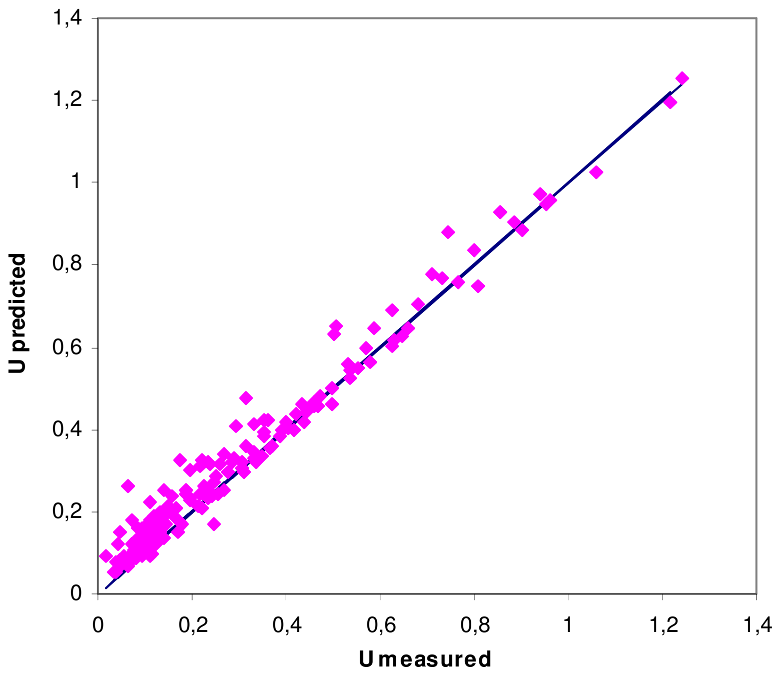
II-10	0,0045	31000	0,078	1,00	0,092	0,218	0,00500
II-11	0,0045	31000	0,057	1,00	0,108	0,372	0,00500
II-12	0,0045	31000	0,059	1,00	0,115	0,403	0,00500
II-13	0,0045	31000	0,056	1,00	0,121	0,457	0,00500
II-14	0,0045	31000	0,056	1,00	0,129	0,493	0,00500
II-15	0,0045	31000	0,075	1,00	0,089	0,225	0,01000
II-16	0,0045	31000	0,052	1,00	0,101	0,397	0,01000
II-17	0,0045	31000	0,056	1,00	0,11	0,421	0,01000
II-18	0,0045	31000	0,055	1,00	0,116	0,477	0,01000
II-19	0,0045	31000	0,048	1,00	0,119	0,526	0,01000
II-20	0,0045	31000	0,054	1,00	0,122	0,522	0,01000
II-21	0,0045	31000	0,072	1,00	0,088	0,288	0,01500
II-22	0,0045	31000	0,07	1,00	0,085	0,236	0,02000
II-23	0,0045	31000	0,053	1,00	0,075	0,26	0,02500
II-24	0,0045	31000	0,058	1,00	0,072	0,278	0,03000
II-25	0,0045	31000	0,051	1,00	0,068	0,295	0,03500
II-26	0,0045	31000	0,048	1,00	0,065	0,308	0,04000
II-27	0,0045	31000	0,047	1,00	0,062	0,323	0,04500
II-28	0,0045	31000	0,046	1,00	0,061	0,329	0,05000
III-1	0,0045	44000	0,067	1,00	0,104	0,386	0,00100
III-2	0,0045	44000	0,072	1,00	0,11	0,421	0,00100
III-3	0,0045	44000	0,073	1,00	0,116	0,477	0,00100
III-4	0,0045	44000	0,071	1,00	0,123	0,527	0,00100
III-5	0,0045	44000	0,063	1,00	0,17	0,761	0,00100
III-6	0,0045	44000	0,059	1,00	0,198	0,903	0,00100
III-7	0,0045	44000	0,0678	1,00	0,082	0,245	0,00200
III-8	0,0045	44000	0,065	1,00	0,103	0,39	0,00200
III-9	0,0045	44000	0,082	1,00	0,14	0,321	0,00200
III-10	0,0045	44000	0,08	1,00	0,146	0,344	0,00200
III-11	0,0045	44000	0,071	1,00	0,109	0,425	0,00200
III-12	0,0045	44000	0,072	1,00	0,115	0,481	0,00200
III-13	0,0045	44000	0,072	1,00	0,122	0,532	0,00200
III-14	0,0045	44000	0,07	1,00	0,178	0,725	0,00200
III-15	0,0045	44000	0,058	1,00	0,168	0,77	0,00200
III-16	0,0045	44000	0,063	1,00	0,199	0,888	0,00200
III-17	0,0045	44000	0,059	1,00	0,196	0,912	0,00200
III-18	0,0045	44000	0,068	1,00	0,081	0,218	0,00500
III-19	0,0045	44000	0,063	1,00	0,101	0,397	0,00500
III-20	0,0045	44000	0,07	1,00	0,107	0,433	0,00500
III-21	0,0045	44000	0,072	1,00	0,112	0,494	0,00500
III-22	0,0045	44000	0,065	1,00	0,119	0,545	0,00500
III-23	0,0045	44000	0,057	1,00	0,164	0,789	0,00500
III-24	0,0045	44000	0,058	1,00	0,191	0,936	0,00500

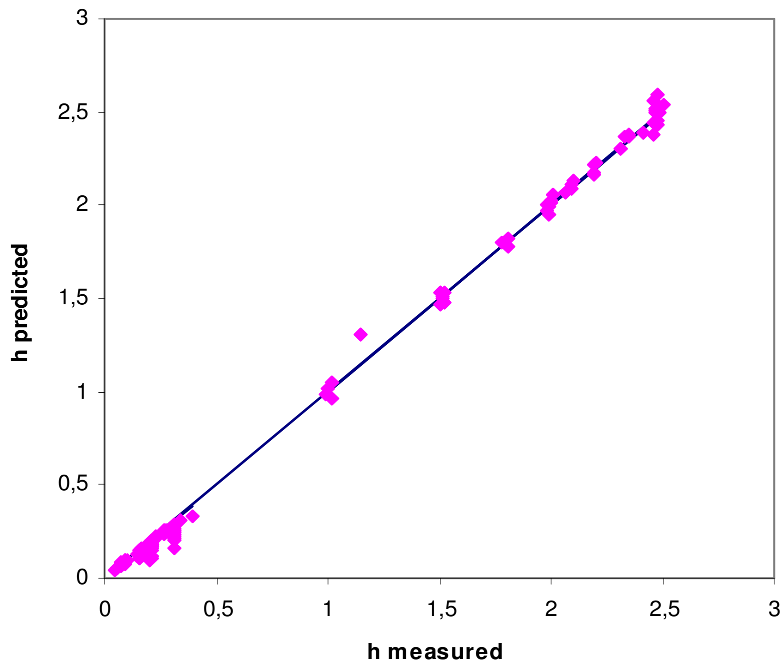
	III-25	0,0045	44000	0,066	1,00	0,079			0,251	0,01000
	III-26	0,0045	44000	0,062	1,00	0,098			0,41	0,01000
	III-27	0,0045	44000	0,077	1,00	0,125			0,36	0,01000
	III-28	0,0045	44000	0,07	1,00	0,103			0,45	0,01000
	III-29	0,0045	44000	0,08	1,00	0,135			0,371	0,01000
	III-30	0,0045	44000	0,071	1,00	0,108			0,512	0,01000
	III-31	0,0045	44000	0,063	1,00	0,115			0,564	0,01000
	III-32	0,0045	44000	0,066	1,00	0,168			0,77	0,01000
	III-33	0,0045	44000	0,056	1,00	0,159			0,814	0,01000
	III-34	0,0045	44000	0,059	1,00	0,183			0,964	0,01000
	III-35	0,0045	44000	0,05	1,00	0,186			0,961	0,01000
	III-36	0,0045	44000	0,065	1,00	0,076			0,264	0,01500
	III-37	0,0045	44000	0,064	1,00	0,073			0,275	0,02000
	III-38	0,0045	44000	0,064	1,00	0,071			0,283	0,02500
	III-39	0,0045	44000	0,063	1,00	0,068			0,296	0,03000
	III-40	0,0045	44000	0,062	1,00	0,067			0,3	0,03500
	III-41	0,0045	44000	0,061	1,00	0,065			0,39	0,04000
	III-42	0,0045	44000	0,061	1,00	0,064			0,314	0,04500
	III-43	0,0045	44000	0,06	1,00	0,061			0,33	0,05000

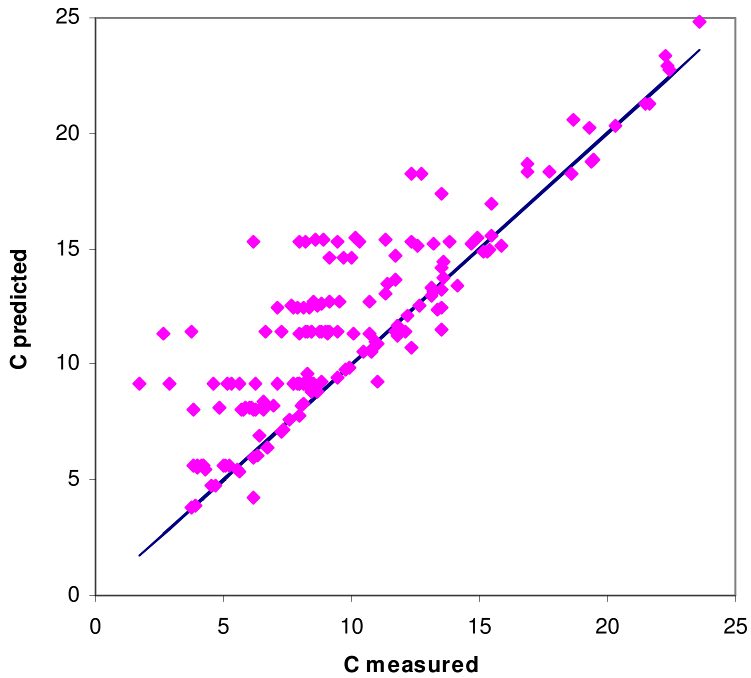
Appendix C. Comparison descriptions with rigid data

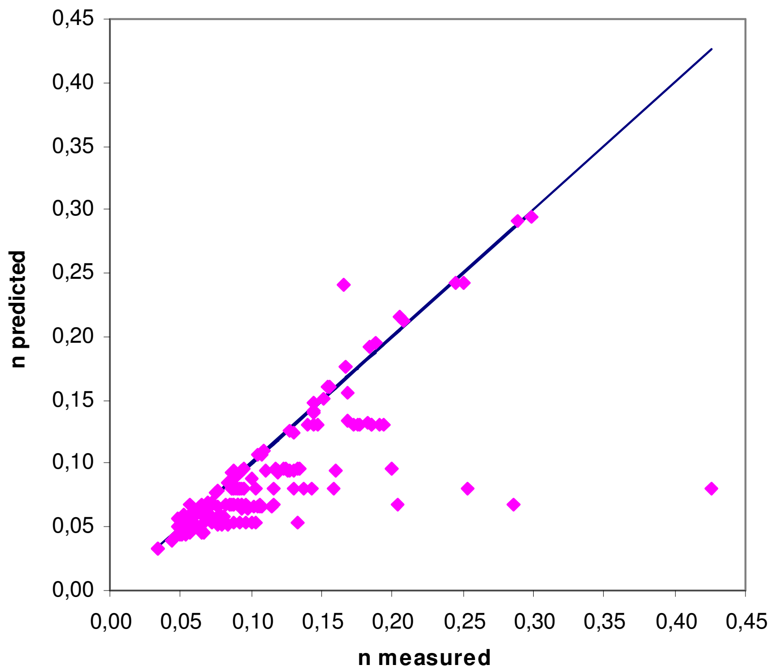
The following graphs show the calculated and measured values for the velocity, water level, Chézy coefficient and Manning coefficient, for the seven different resistance descriptions compared with data derived from rigid vegetation.

C.1 Description of Klopstra (1997), a defined by Meijer (1998)

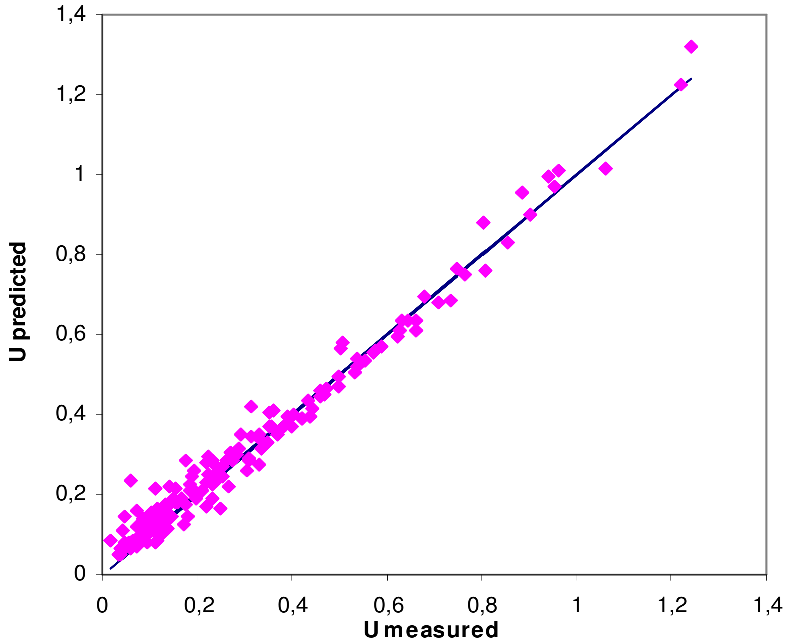


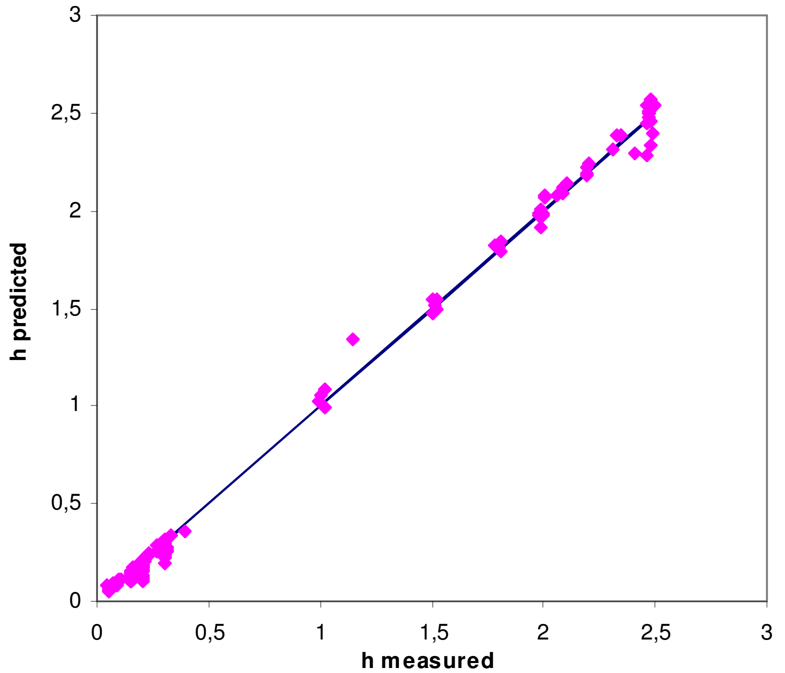


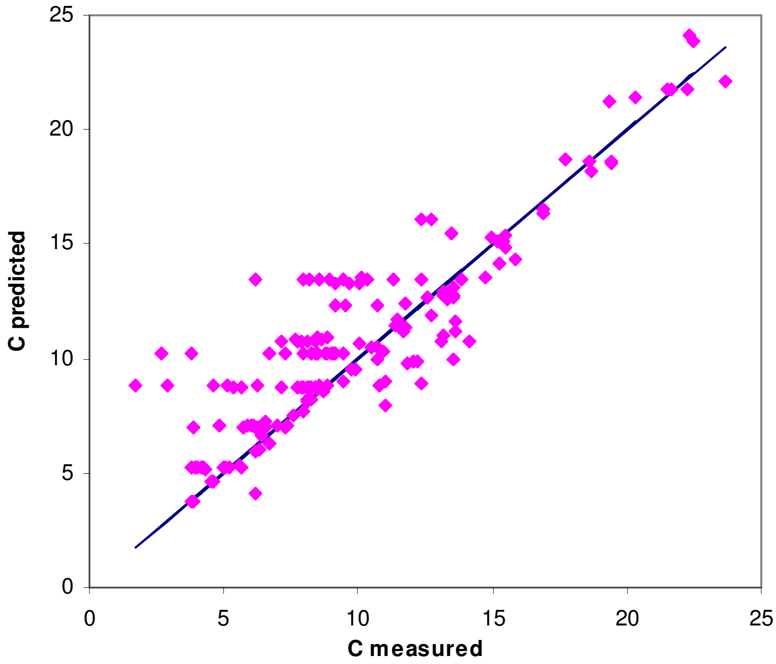

C predicted
C measured

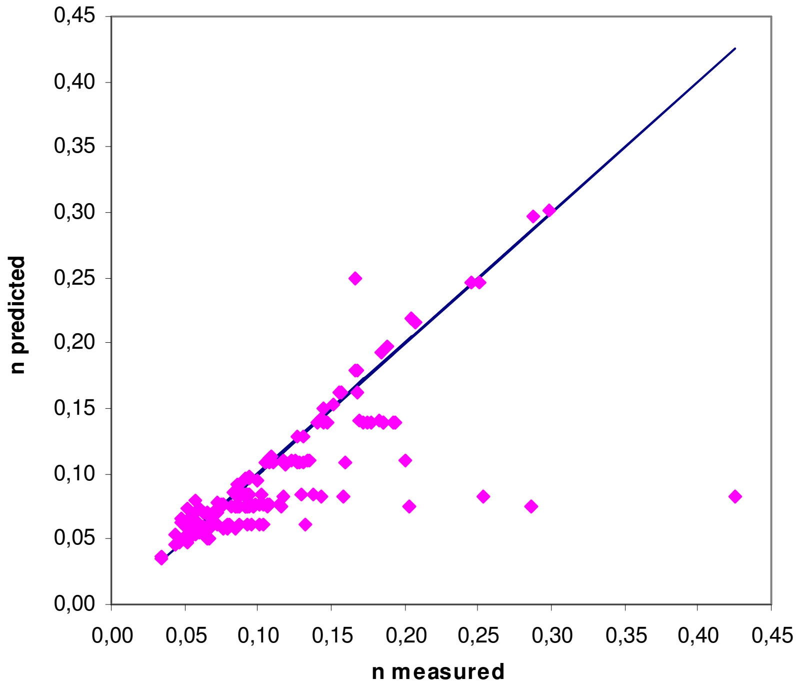

n predicted
n measured

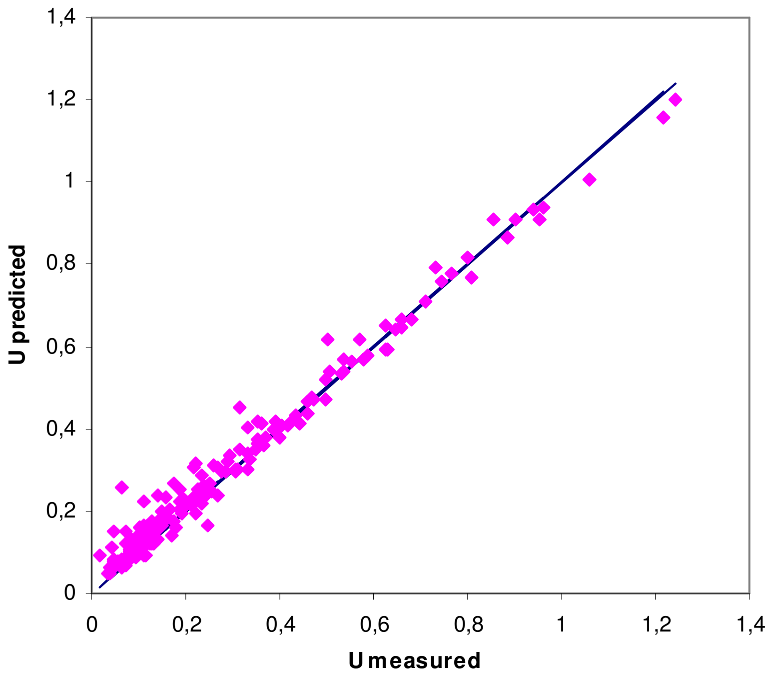
C.2. Description of Klopstra (1997), a defined by Van Velzen et al. (2003)

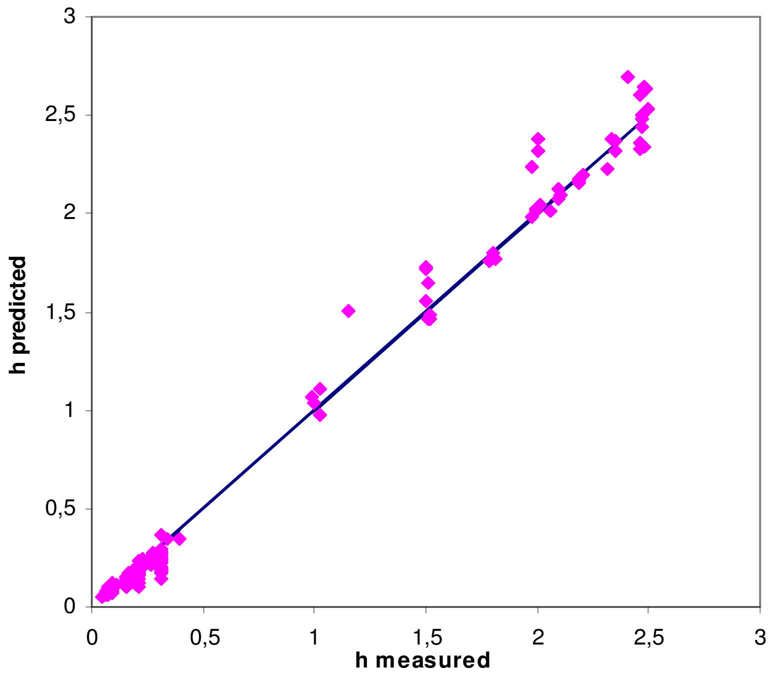


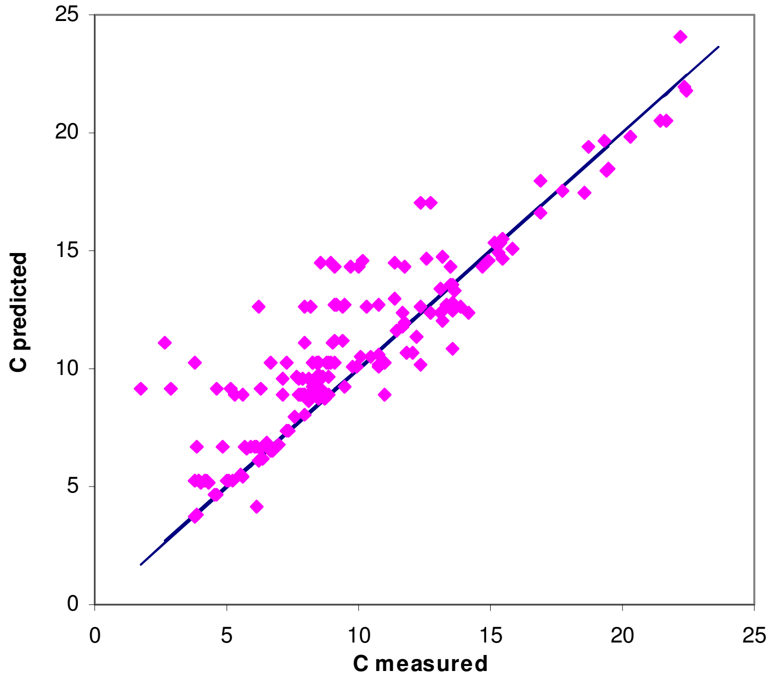



C predicted
C measured
0
5
10
15
20
25

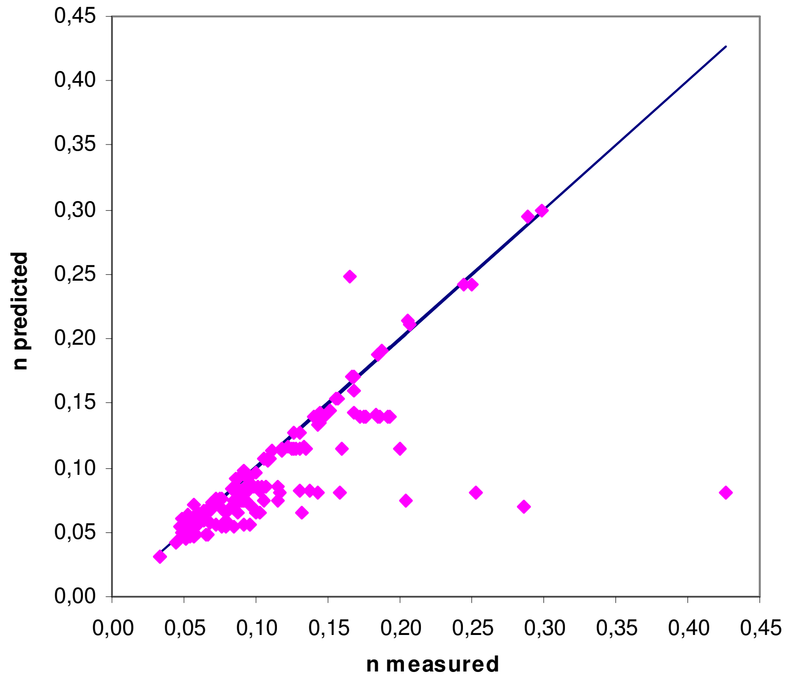

n predicted
n measured
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45


1,4
1,2
1
0,8
0,6
0,4
0,2
0
U predicted
0
0,2
0,4
0,6
0,8
1
1,2
1,4
U measured

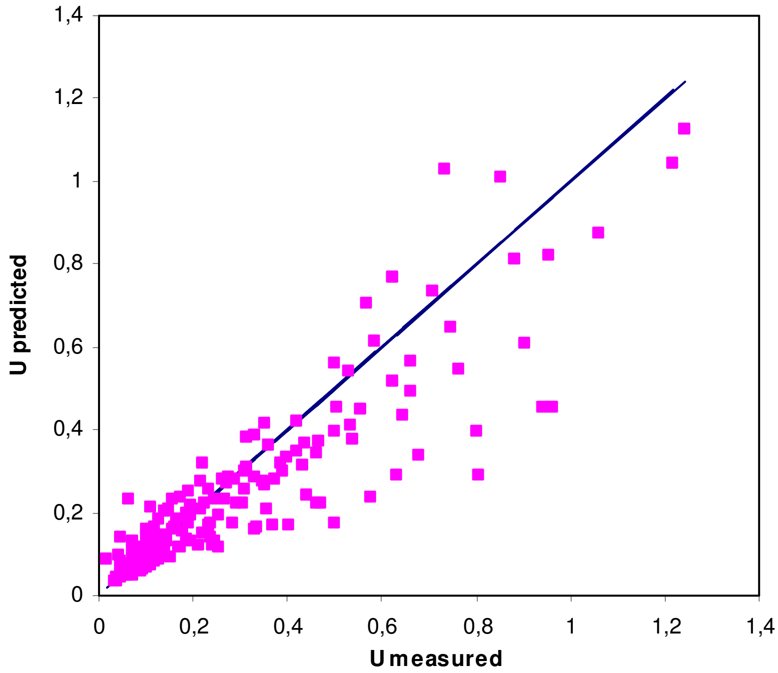

3
2,5
2
1,5
1
0,5
0
h predicted
0
0,5
1
1,5
2
2,5
3
h measured



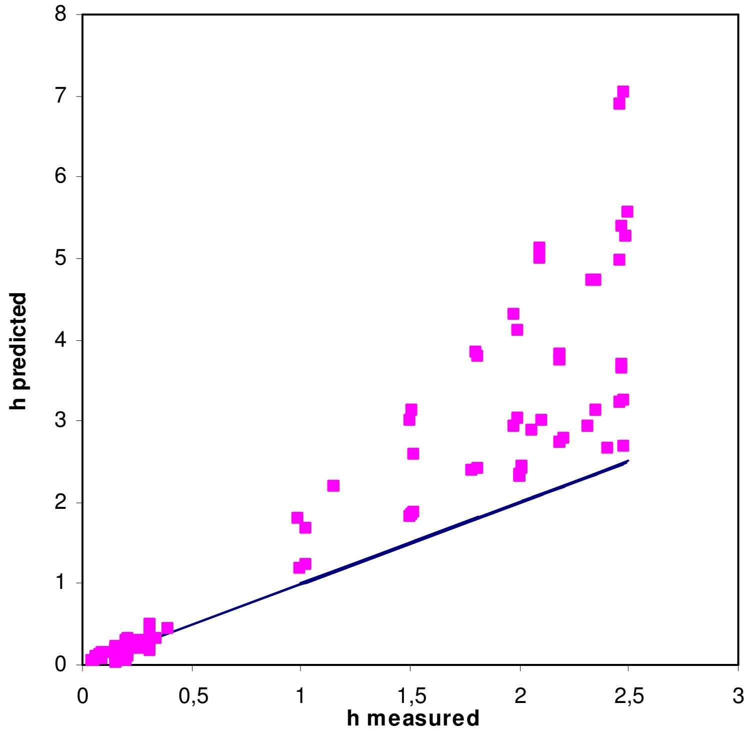
25
20
15
10
5
0
0
5
10
15
20
25
C predicted
C measured



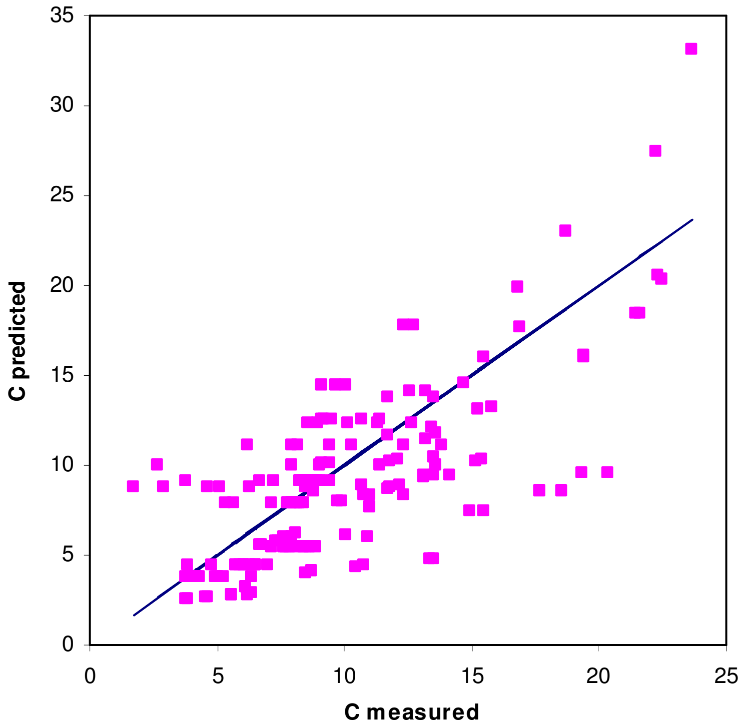
0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45
n predicted
n measured

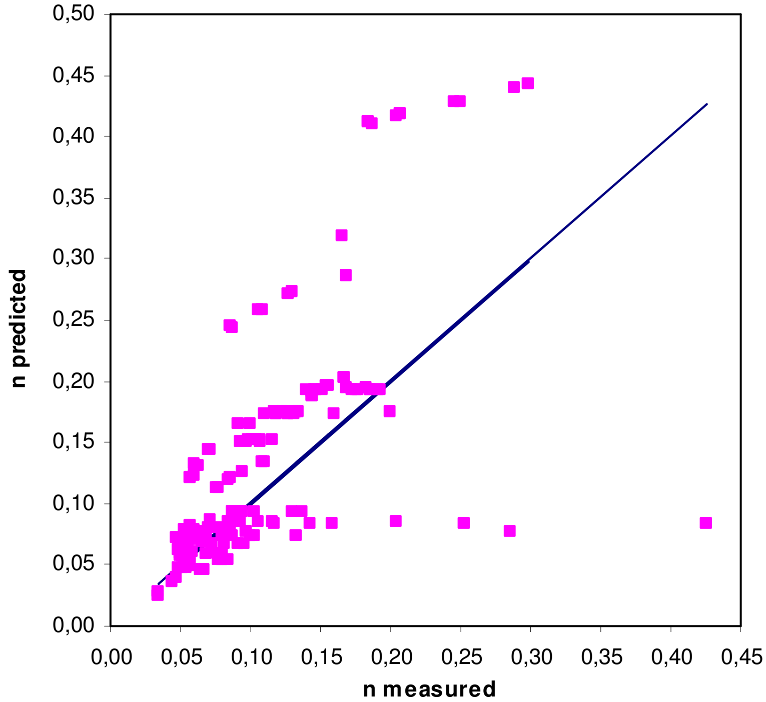


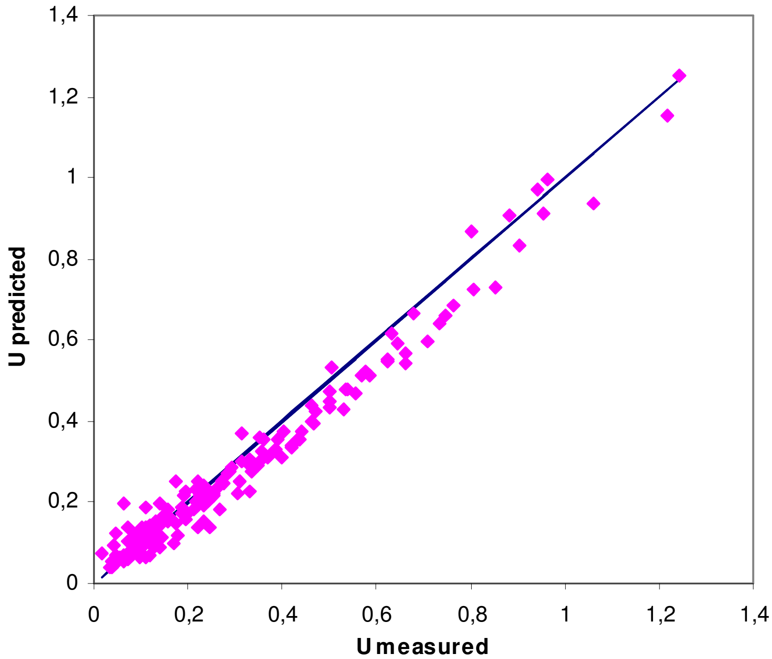
U predicted
U measured
0
0,2
0,4
0,6
0,8
1
1,2
1,4

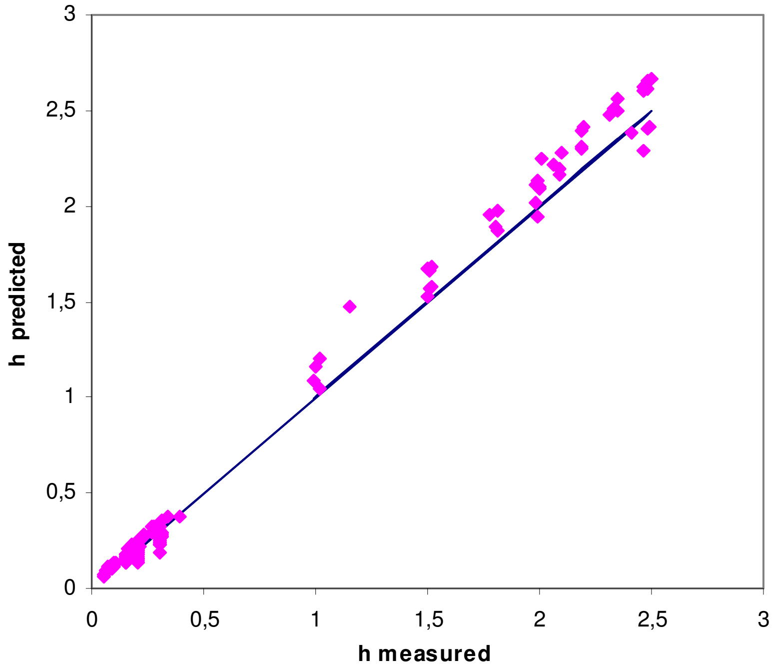


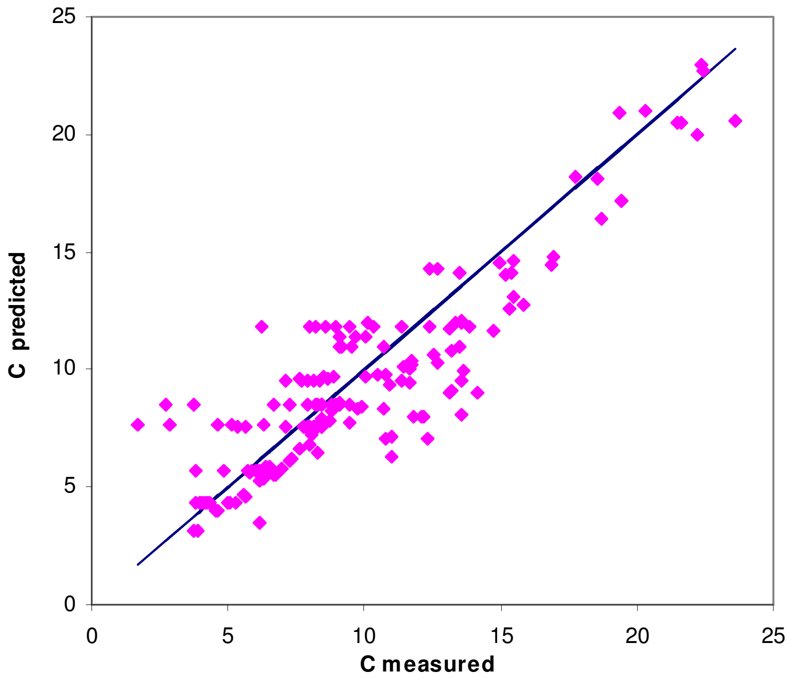
h predicted
h measured
0
1
2
3
4
5
6
7
8
0,5
1,5
2,5

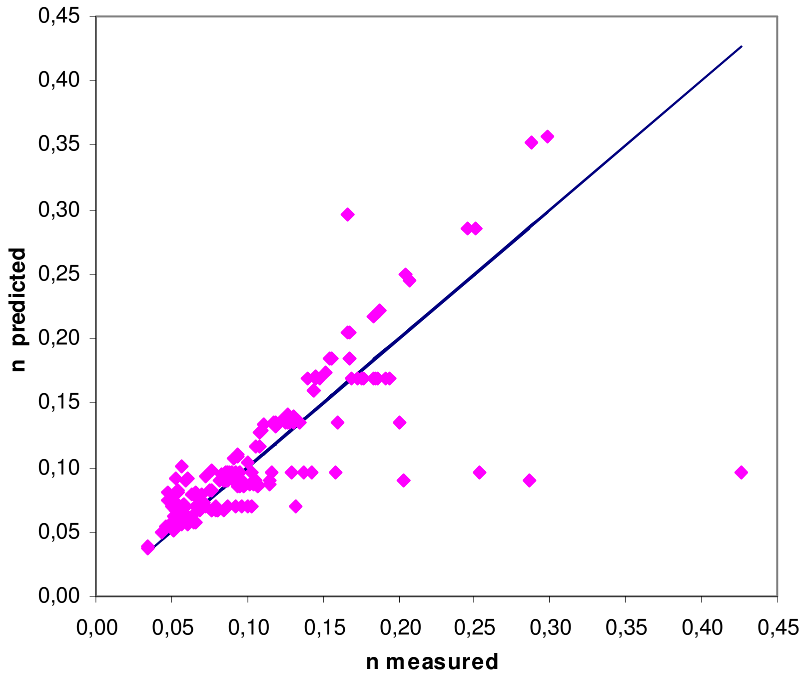

35
30
25
20
15
10
5
0
0
5
10
15
20
25
C predicted
C measured

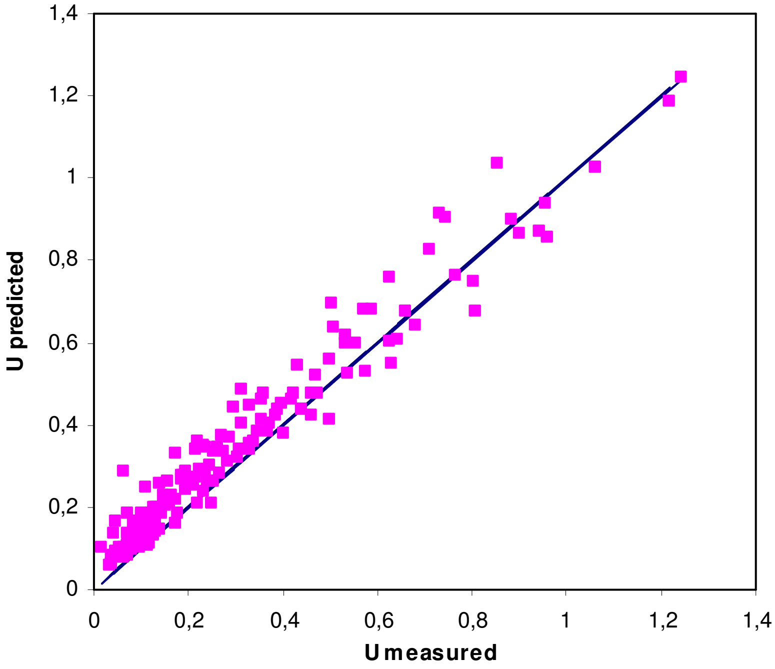

0,50
0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45
n predicted
n measured

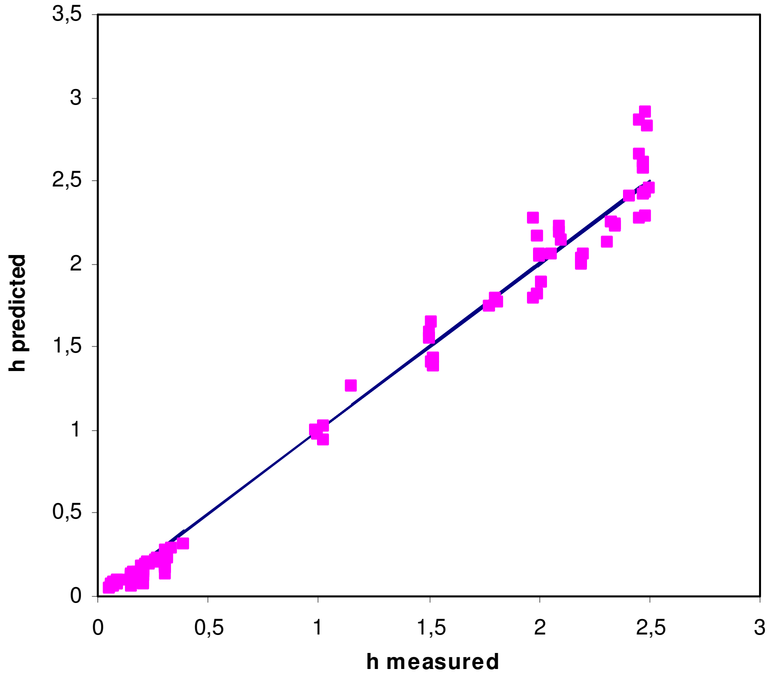

U predicted
U measured
0
0,2
0,4
0,6
0,8
1
1,2
1,4

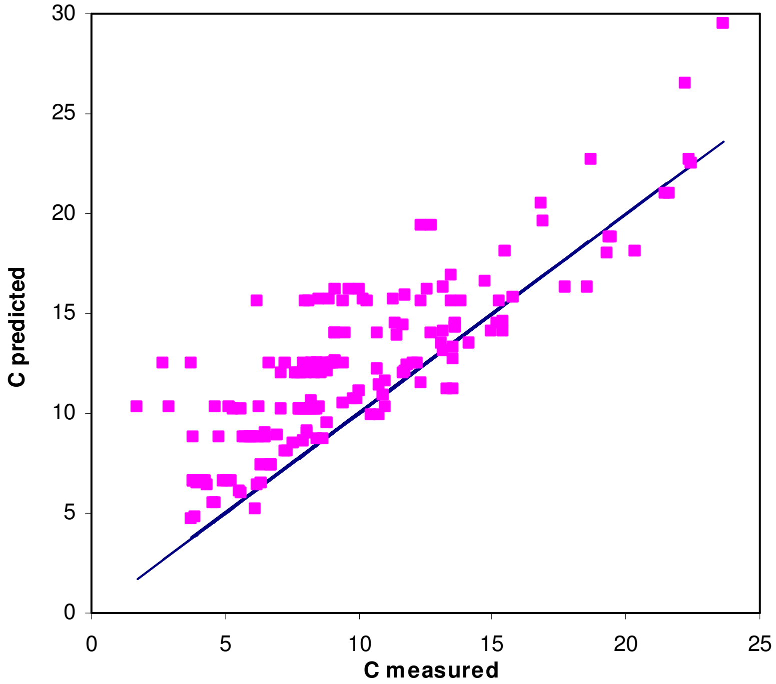

h predicted
h measured
0
0,5
1
1,5
2
2,5
3

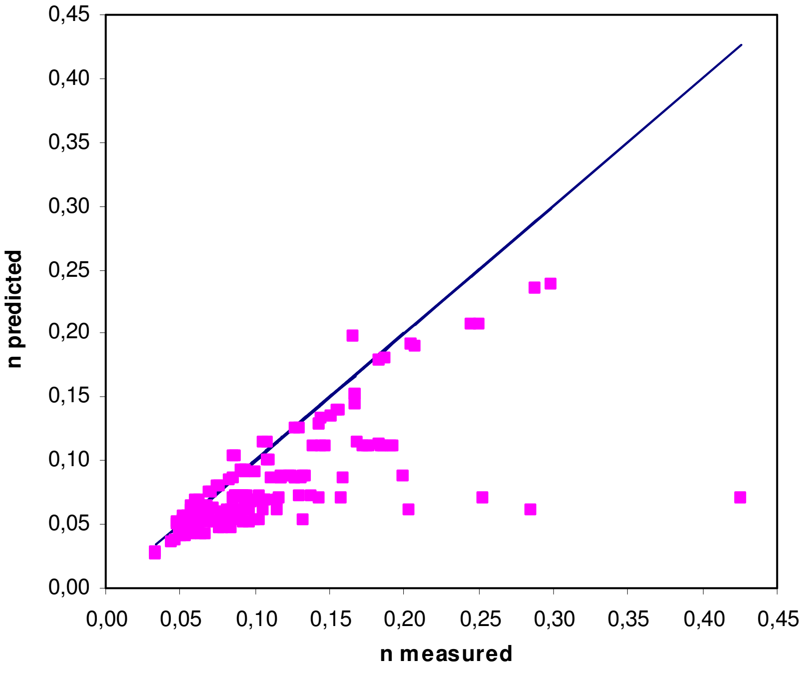

C predicted
C measured
0
5
10
15
20
25

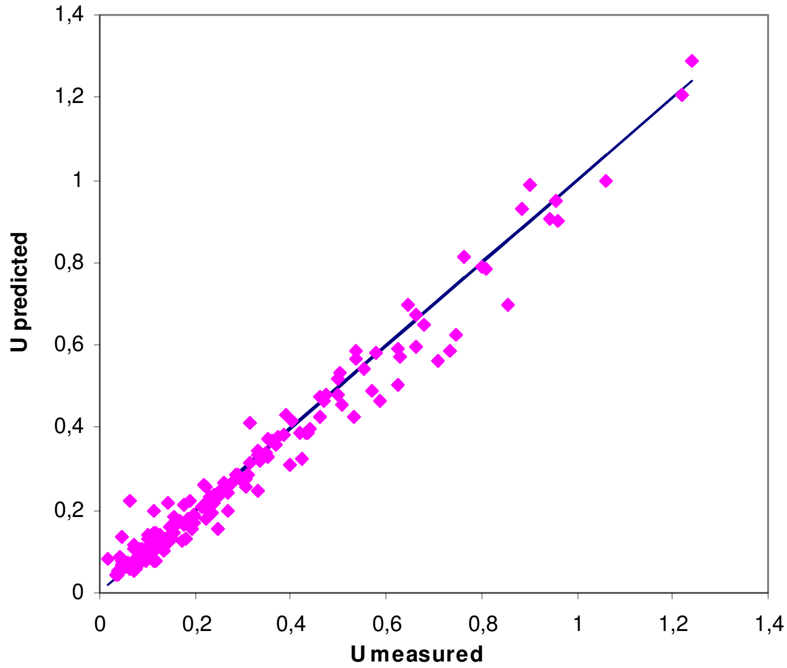

n predicted
n measured
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45


U predicted
U measured
0
0,2
0,4
0,6
0,8
1
1,2
1,4

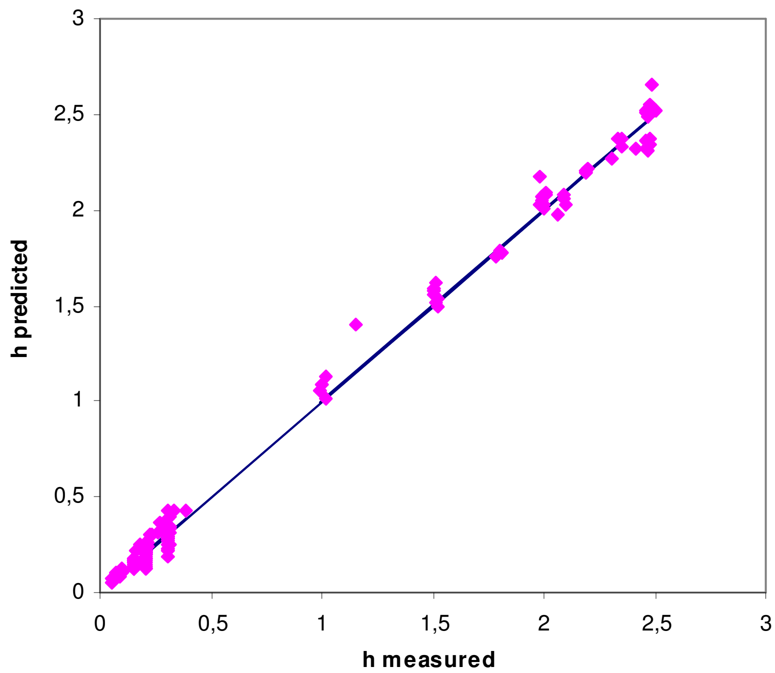

h predicted
h measured
0
0,5
1
1,5
2
2,5
3
3,5


C predicted
C measured
0
5
10
15
20
25
30

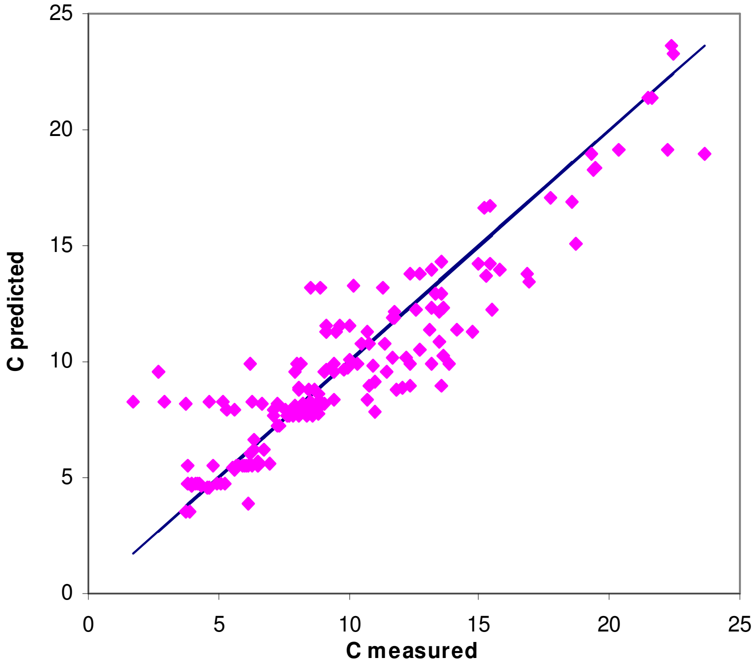

n predicted
n measured
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45



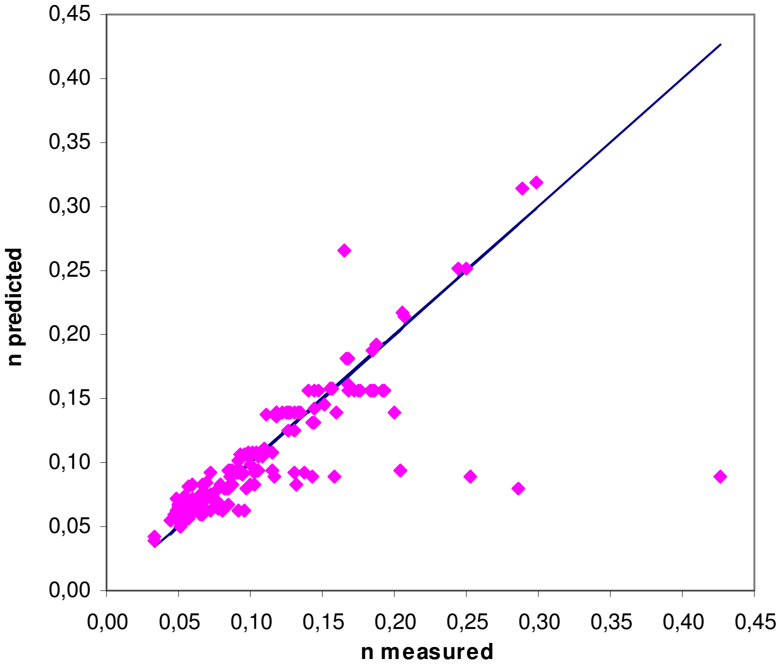
U predicted
U measured
0
0,2
0,4
0,6
0,8
1
1,2
1,4



h predicted
h measured
0
0,5
1
1,5
2
2,5
3



25
20
15
10
5
0
C predicted
0
5
10
15
20
25
C measured



0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
n predicted
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45
n measured

Appendix D. Equations used in Table 7 and Table 8

The parameters shown in Table 7 and Table 8 are calculated with the following equations:

$$R^2 = \left(\frac{\sum(x-\bar{x})(y-\bar{y})}{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2} \right)^2$$

Where R^2 is going through zero.

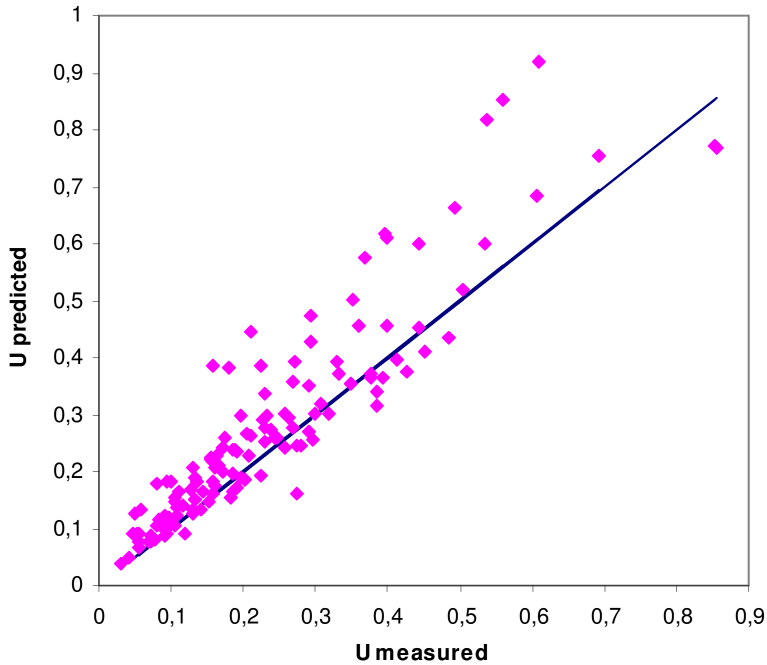
$$\mu = \frac{1}{n} \sum_{i=1}^{n} \left(x_m - x_p \right)$$

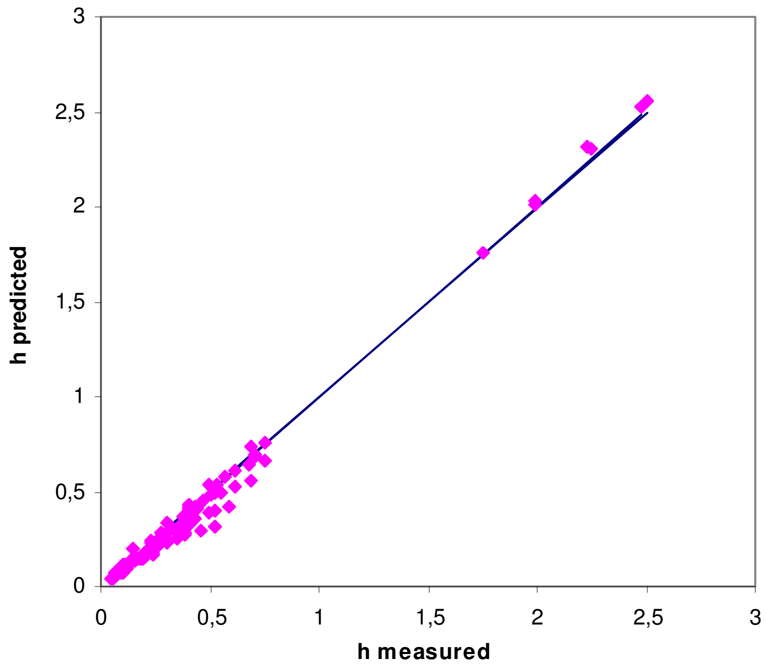
$$\sigma = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(\left(x_m - x_p \right) - \mu \right)^2}$$

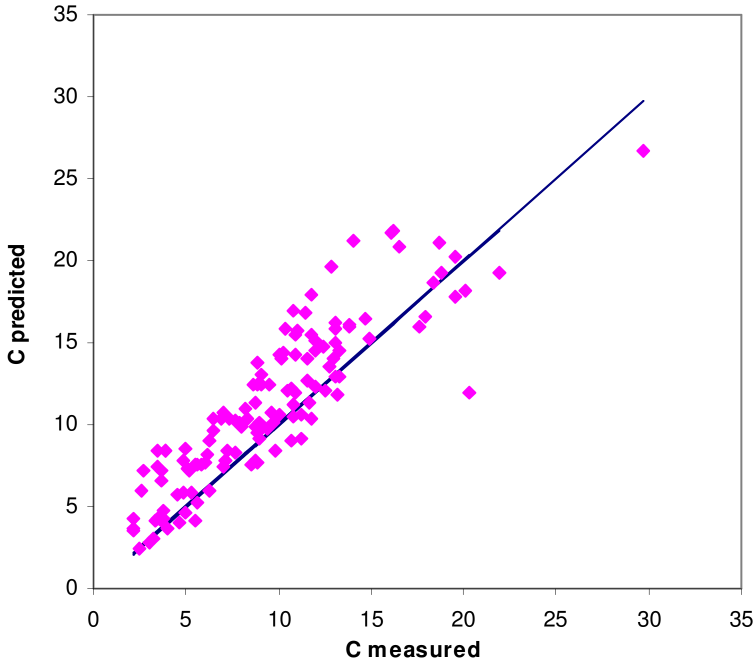
Appendix E. Comparison descriptions with flexible data

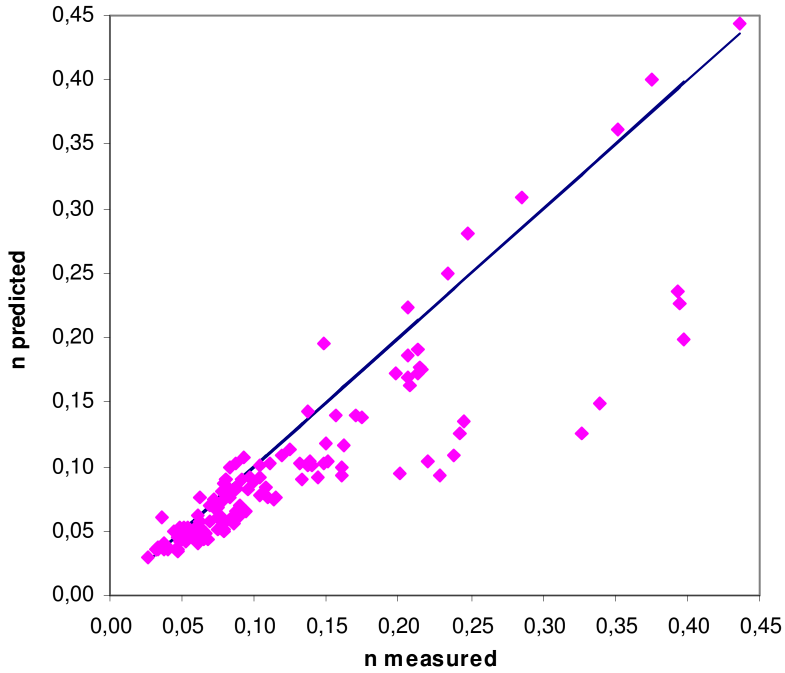
The following graphs show the predicted and measured values for the velocity, water level, Chézy coefficient and Manning coefficient for the seven different resistance descriptions with data derived from flexible vegetation.

E.1. Description of Klopstra (1997) with a given by Meijer (1998)

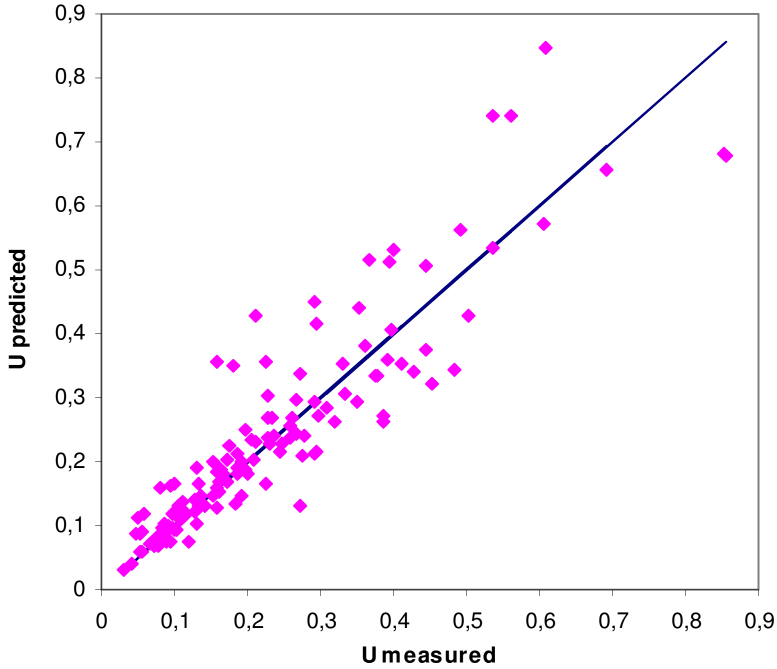


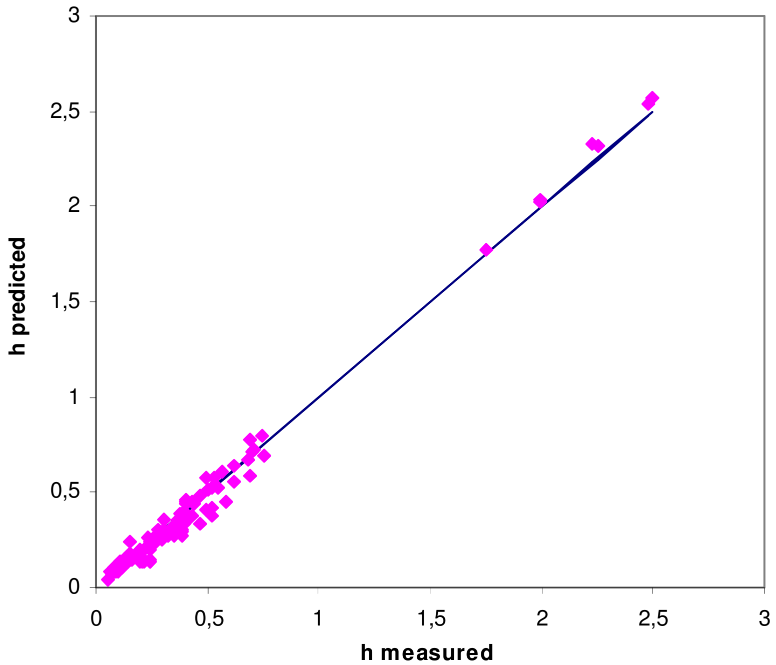


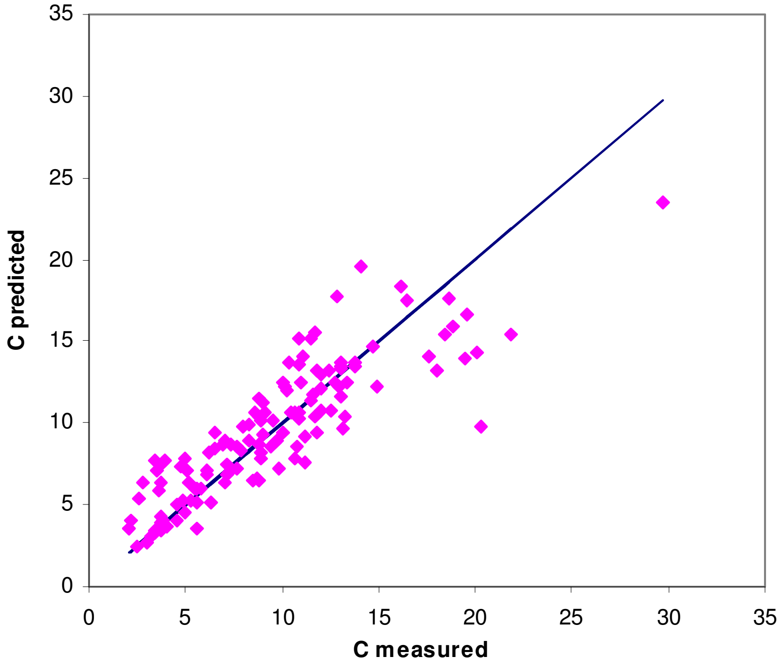

35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
C predicted
C measured


0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45
n predicted
n measured

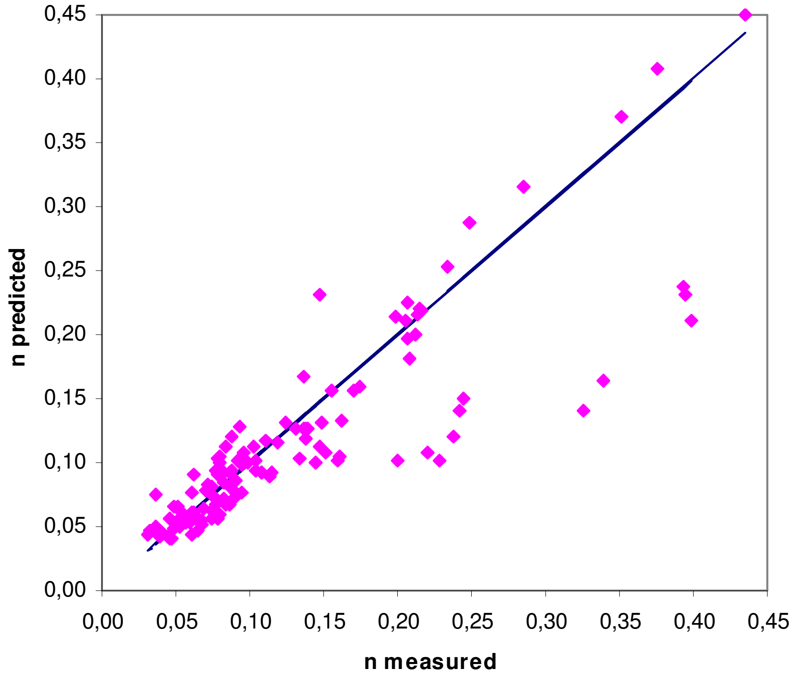
E.2. Description of Klopstra (1997) with a defined by Van Velzen et al. (2003)





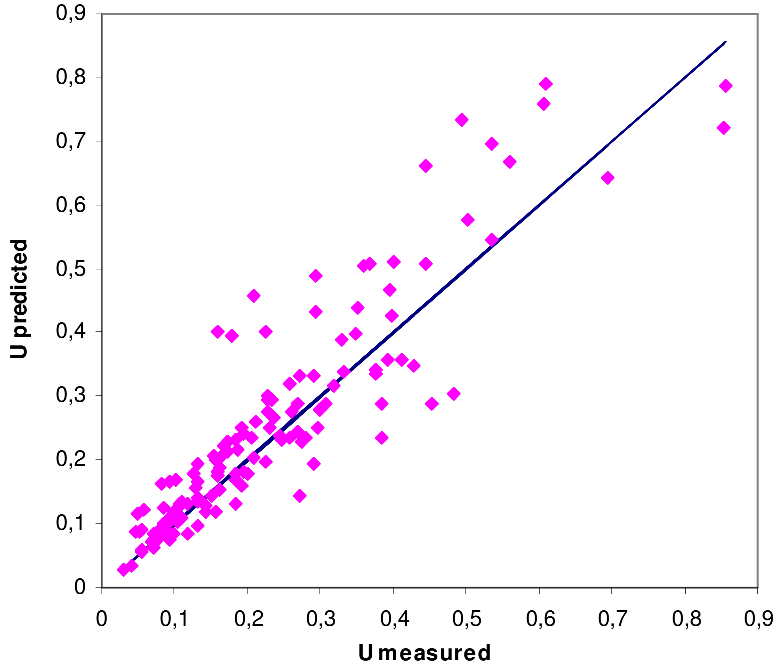


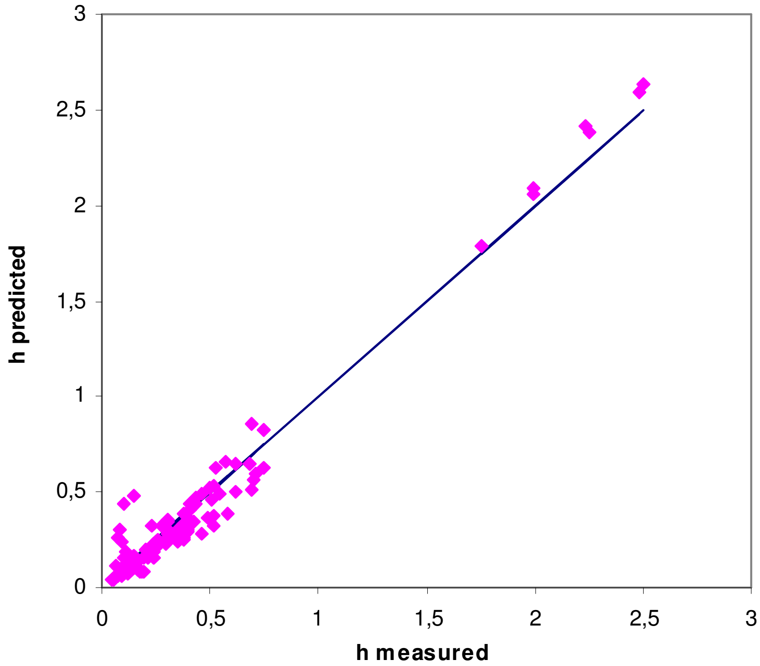
C predicted
C measured
0
5
10
15
20
25
30
35

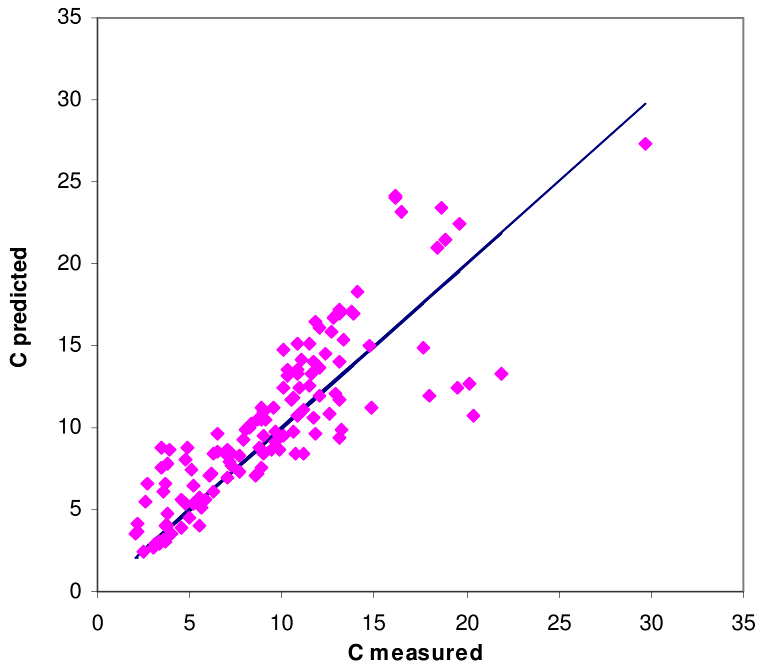


n predicted
n measured
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45

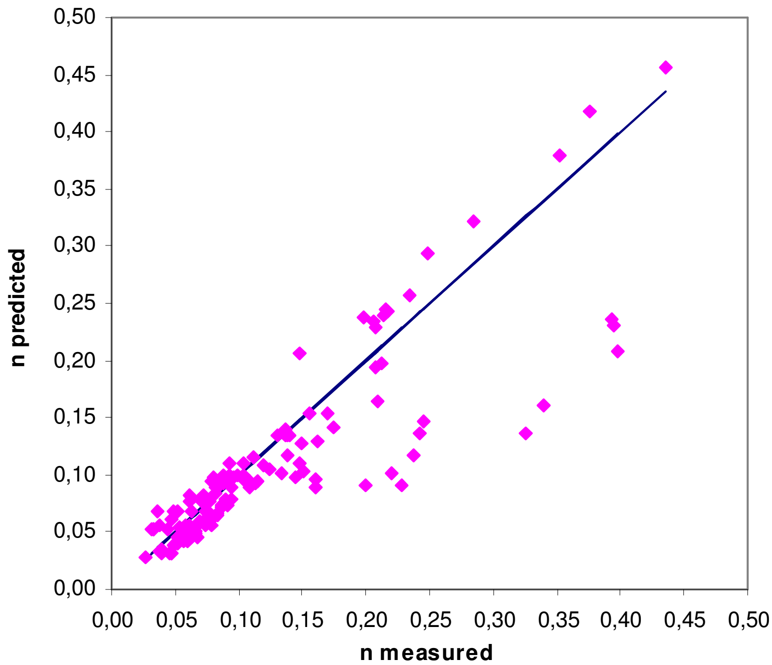
E.3. Description of Klopstra (1997) with the a given by Huthoff (2007)





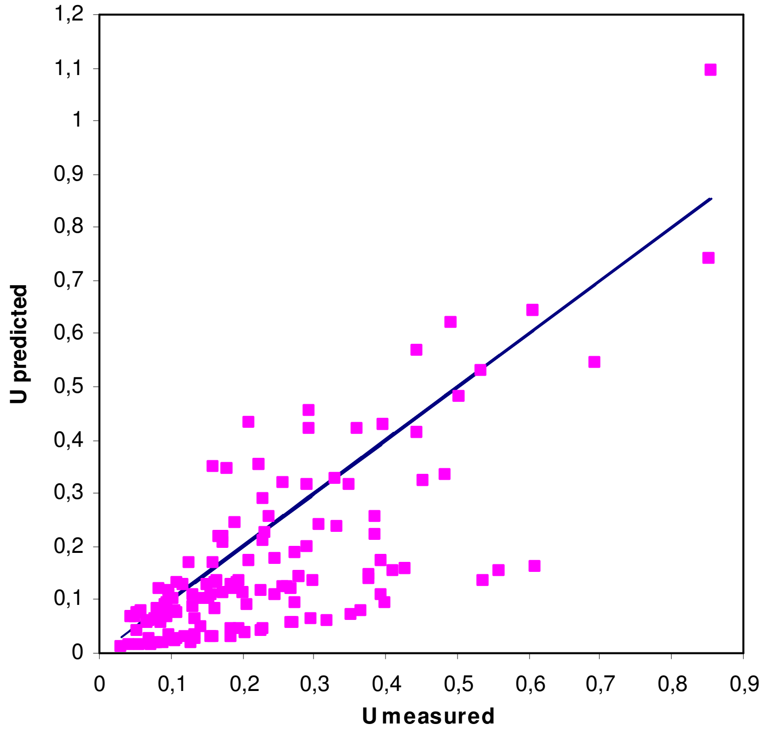


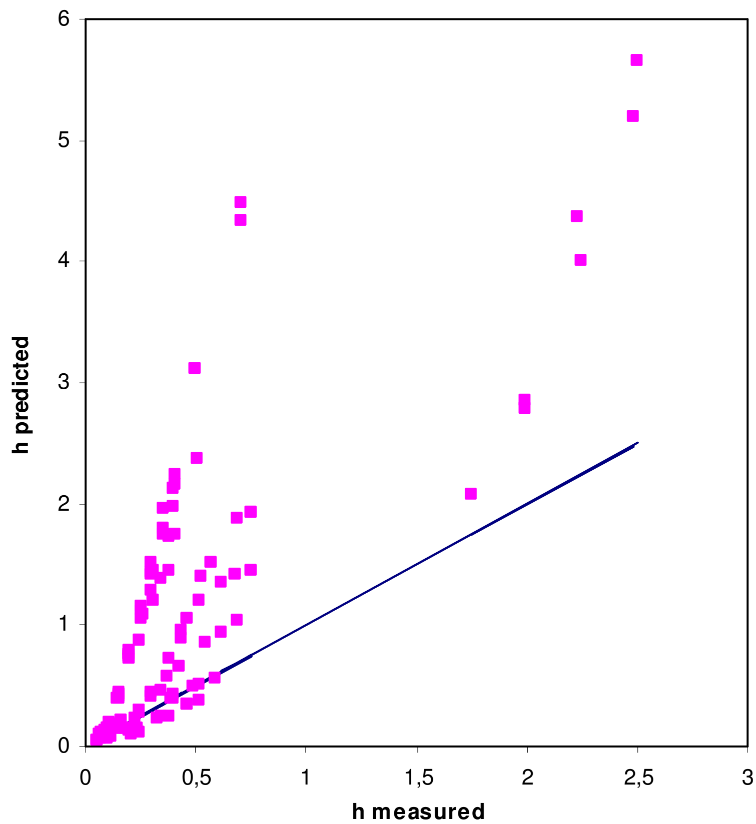
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35
C predicted
C measured

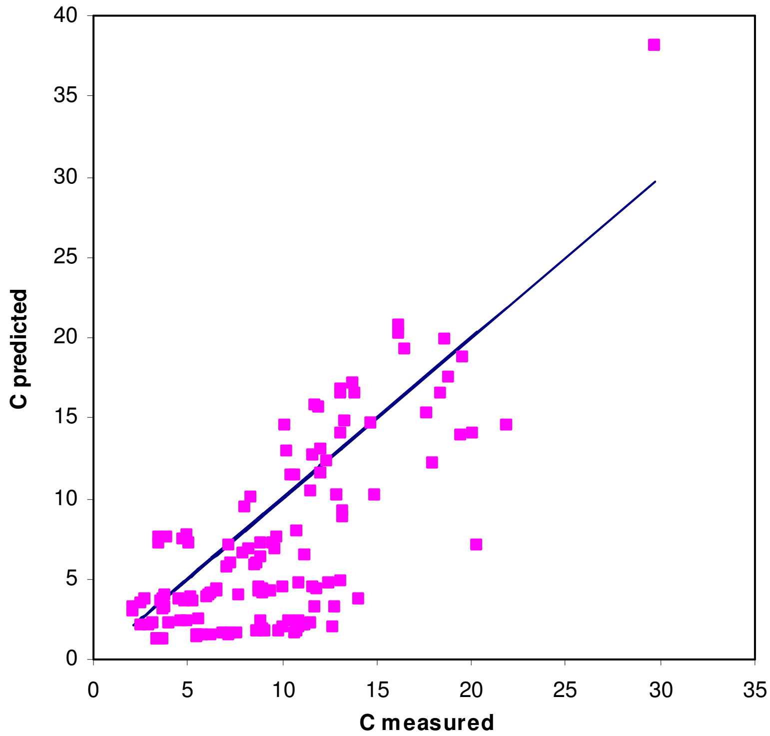


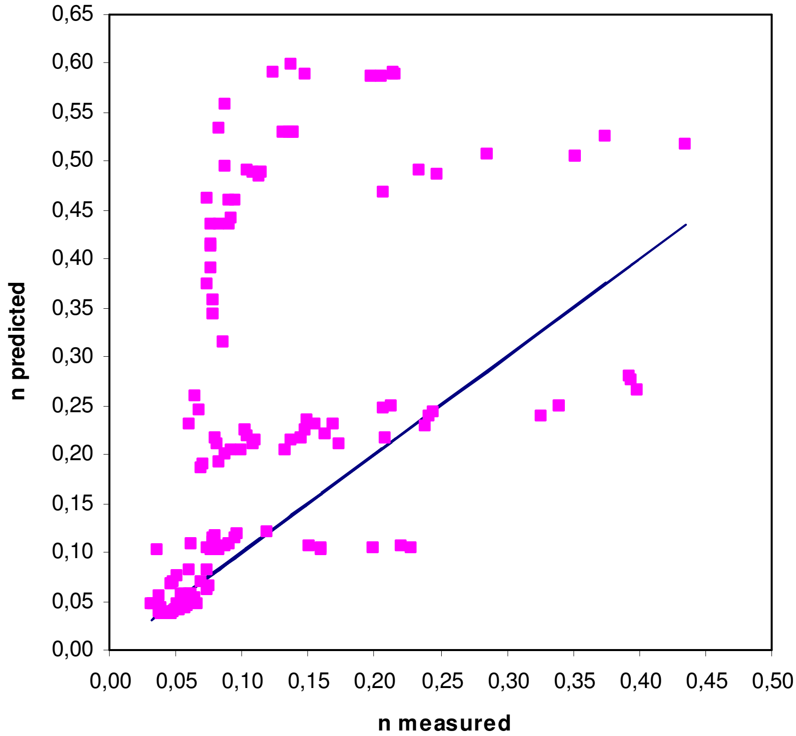
0,50
0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45
0,50
n predicted
n measured

E.4. Description of Stone and Shen (2002)

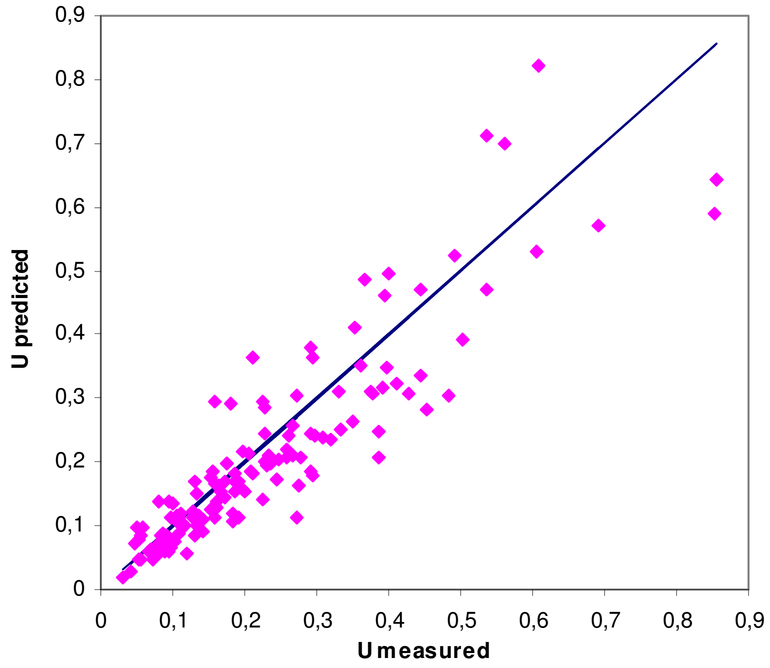


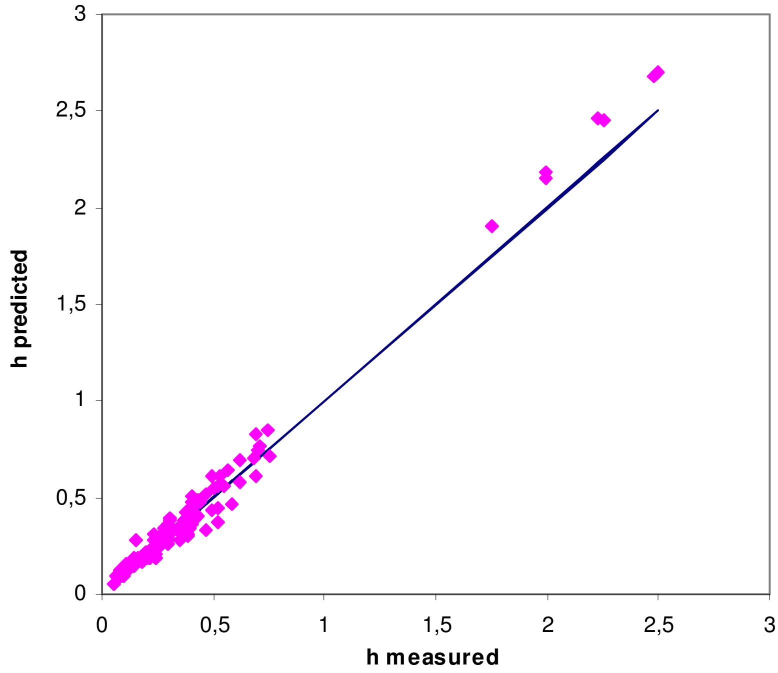


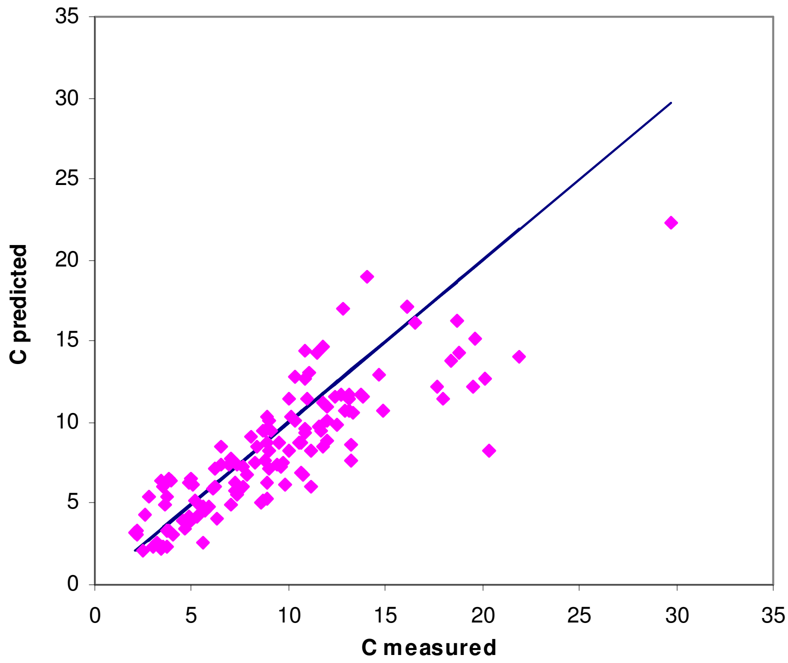

C predicted
C measured
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
30
35

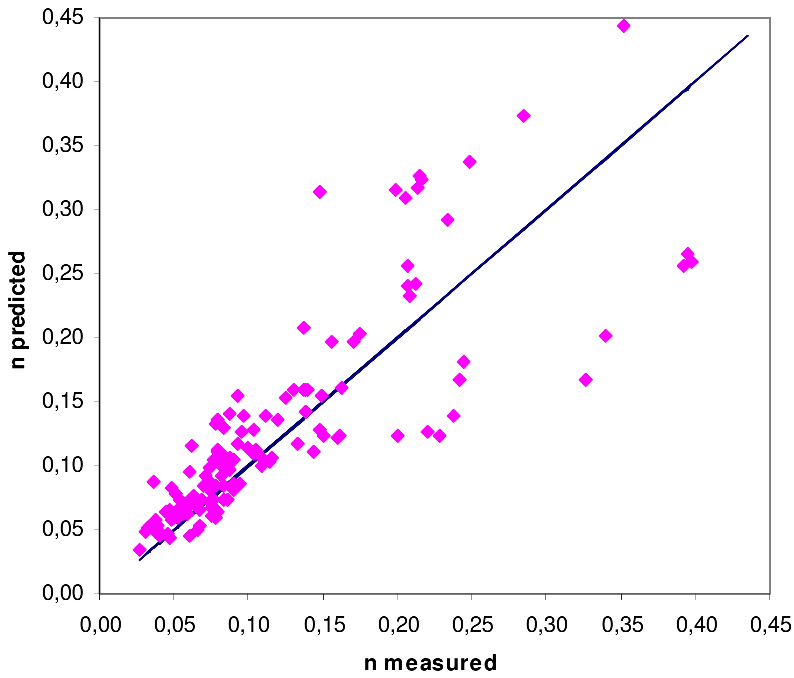

n predicted
n measured
0,65
0,60
0,55
0,50
0,45
0,40
0,35
0,30
0,25
0,20
0,15
0,10
0,05
0,00
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45
0,50

E.5. Description of Van Velzen et al. (2003)

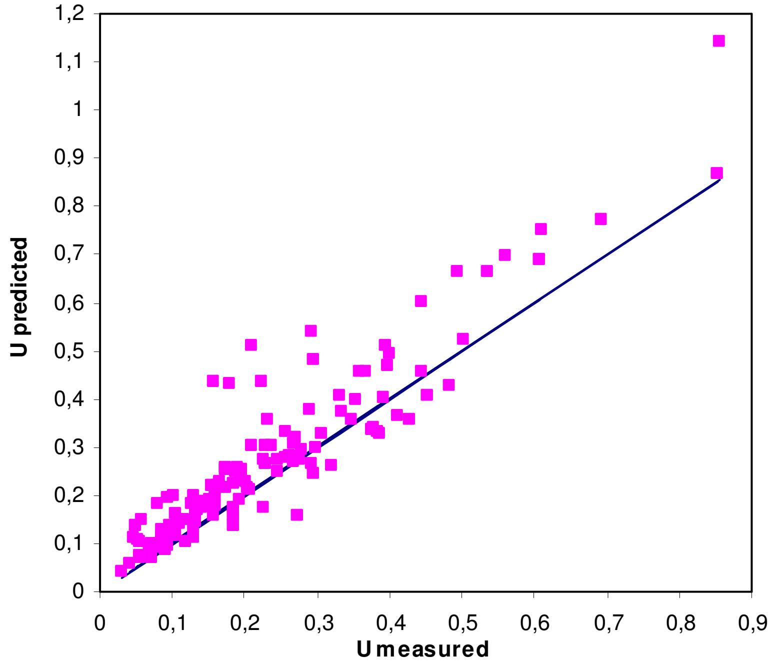


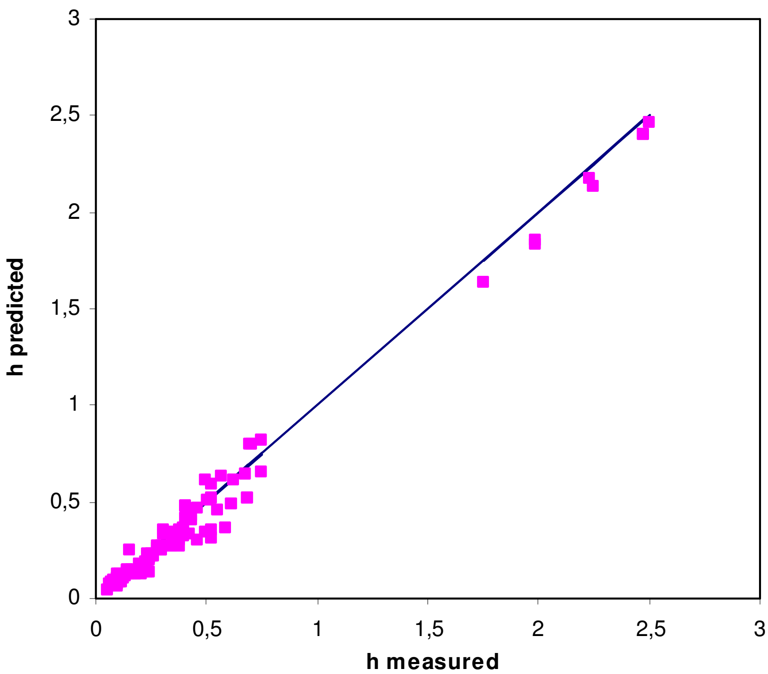


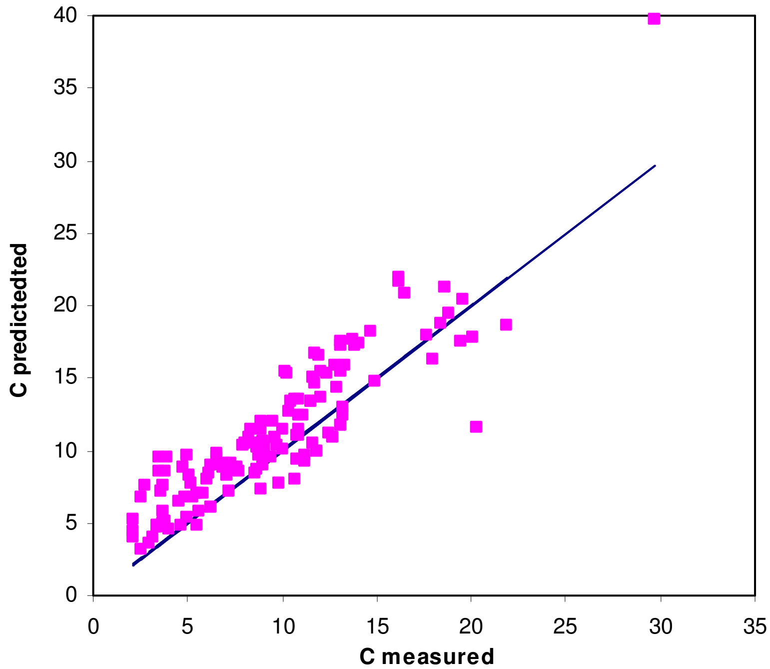

C predicted
C measured
0
5
10
15
20
25
30
35


n predicted
n measured
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45

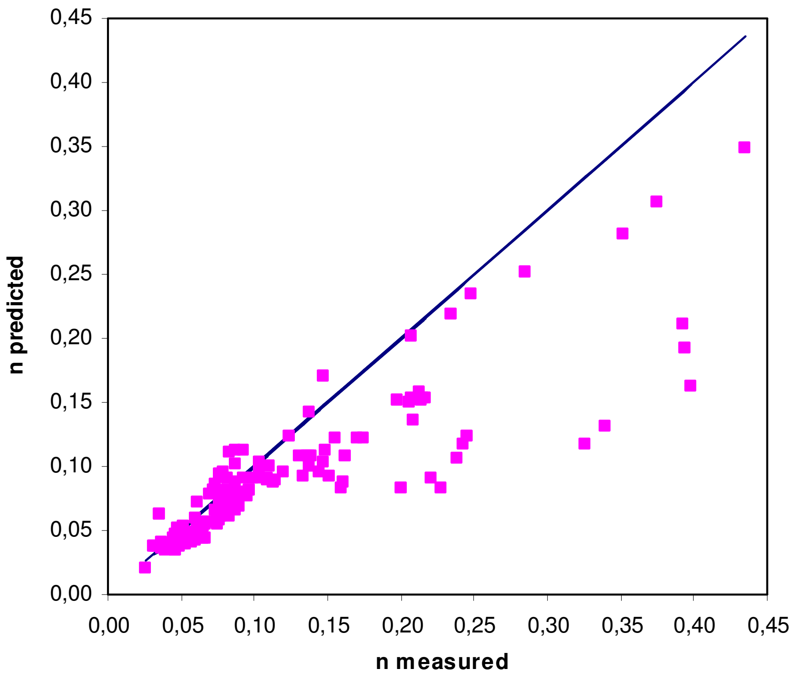
E.6. Description of Baptist et al. (2006)





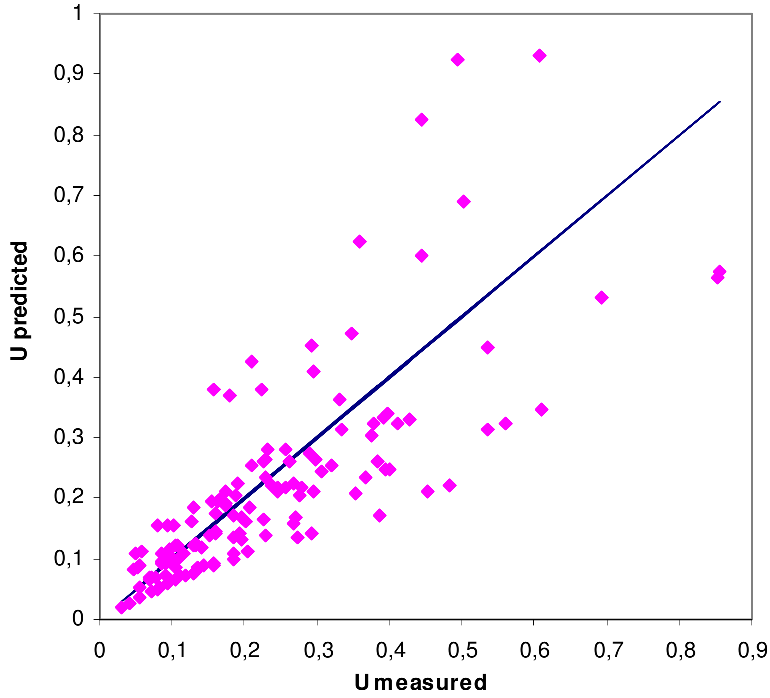


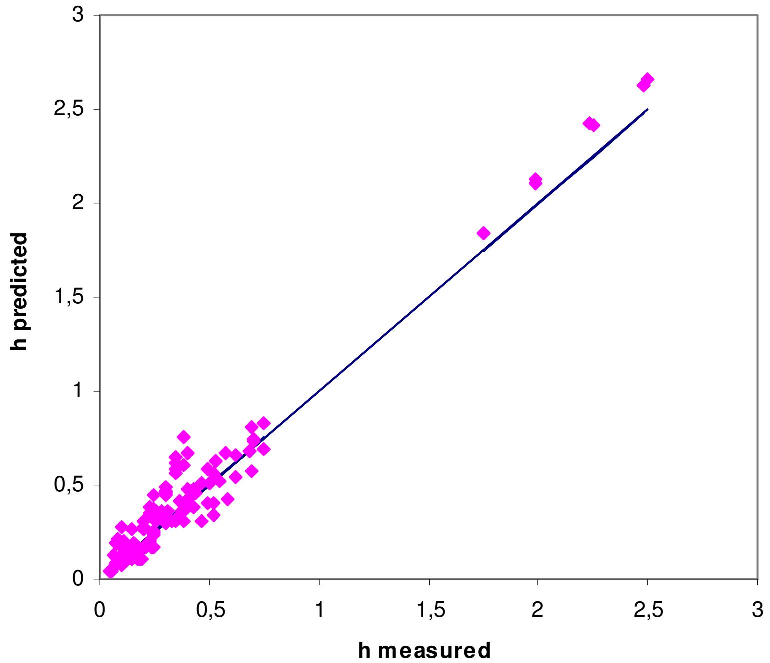
C predictedted
C measured

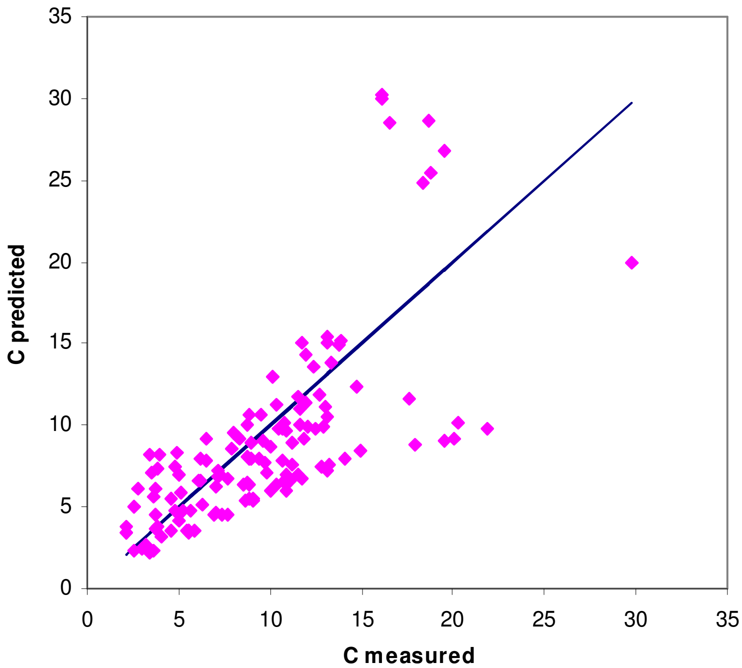


n predicted
n measured

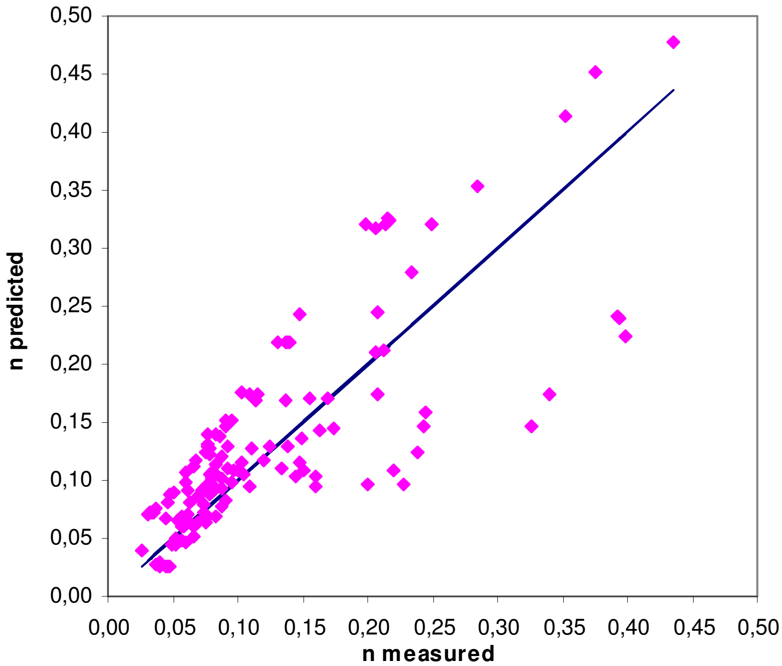
E.7. Description of Huthoff (2007)







C predicted
C measured
0
5
10
15
20
25
30
35



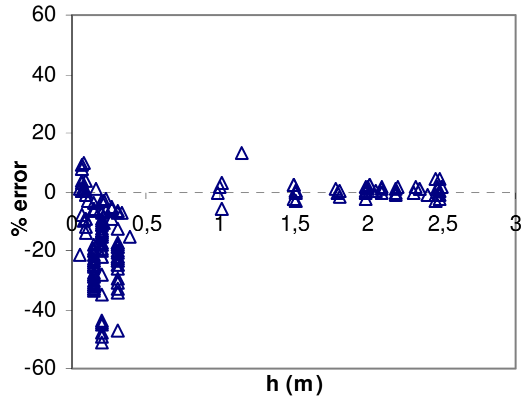
n predicted
n measured
0,00
0,05
0,10
0,15
0,20
0,25
0,30
0,35
0,40
0,45
0,50

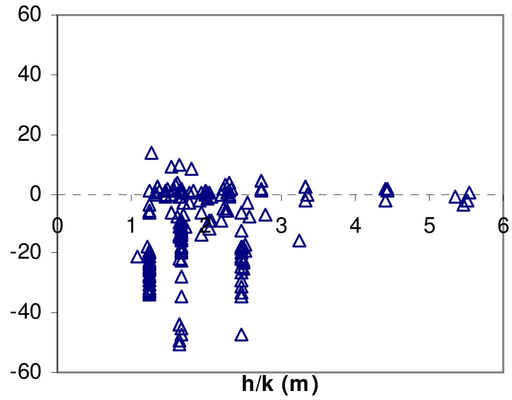
Appendix F. Mean error water level compared with rigid data

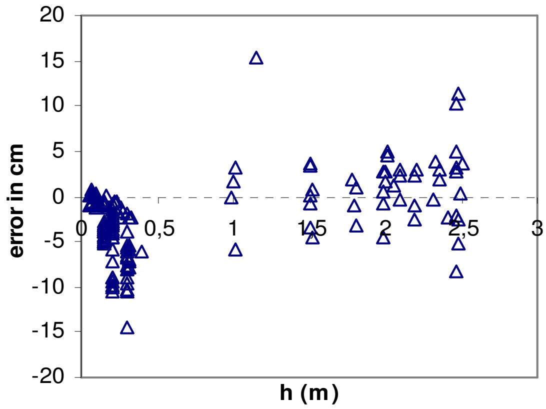
The following graphs show the mean error of the calculated and measured water depth against the water depth or the submergence ratio. The mean error is calculated by:

$$\frac{h_c - h_m}{h_m} \cdot 100$$

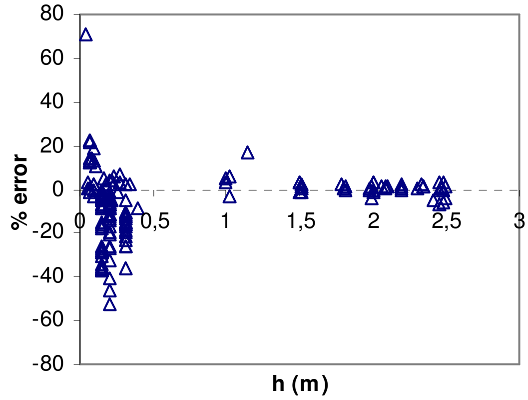
F.1. *Description of Klopstra (1997), a defined by Meijer (1998)*

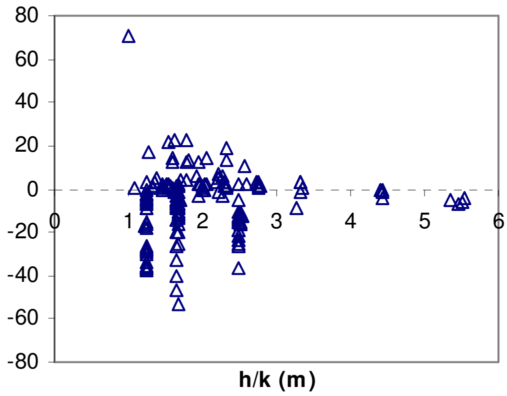


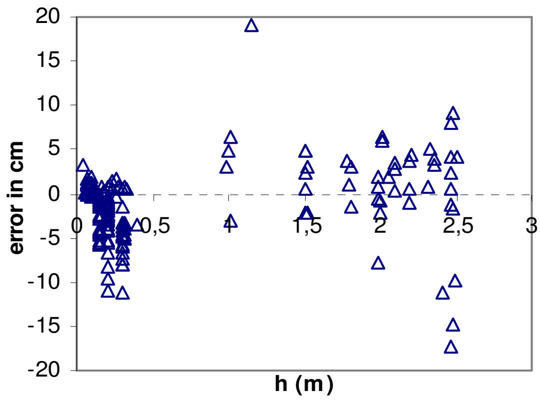




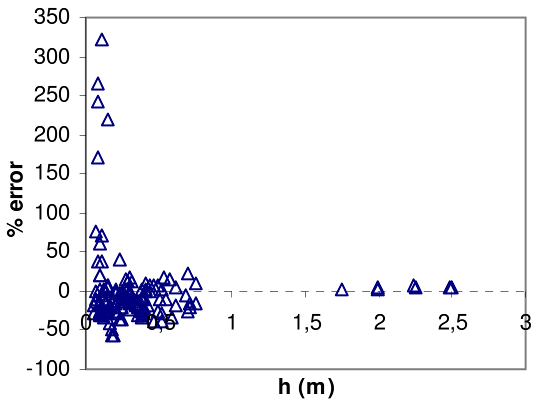
F.2. Description of Klopstra (1997), a defined by Van Velzen et al. (2003)

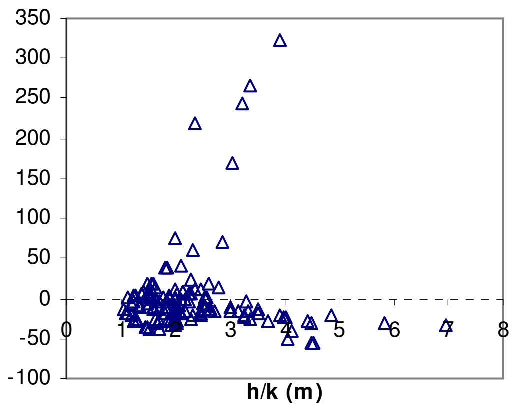


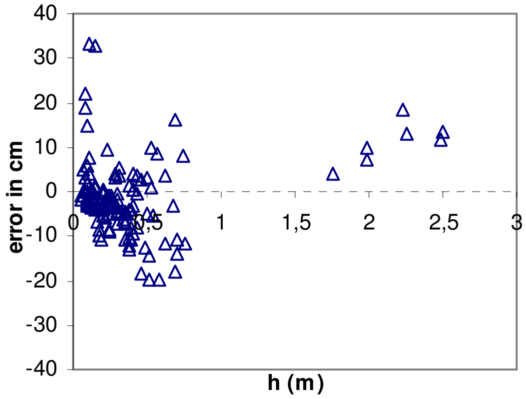


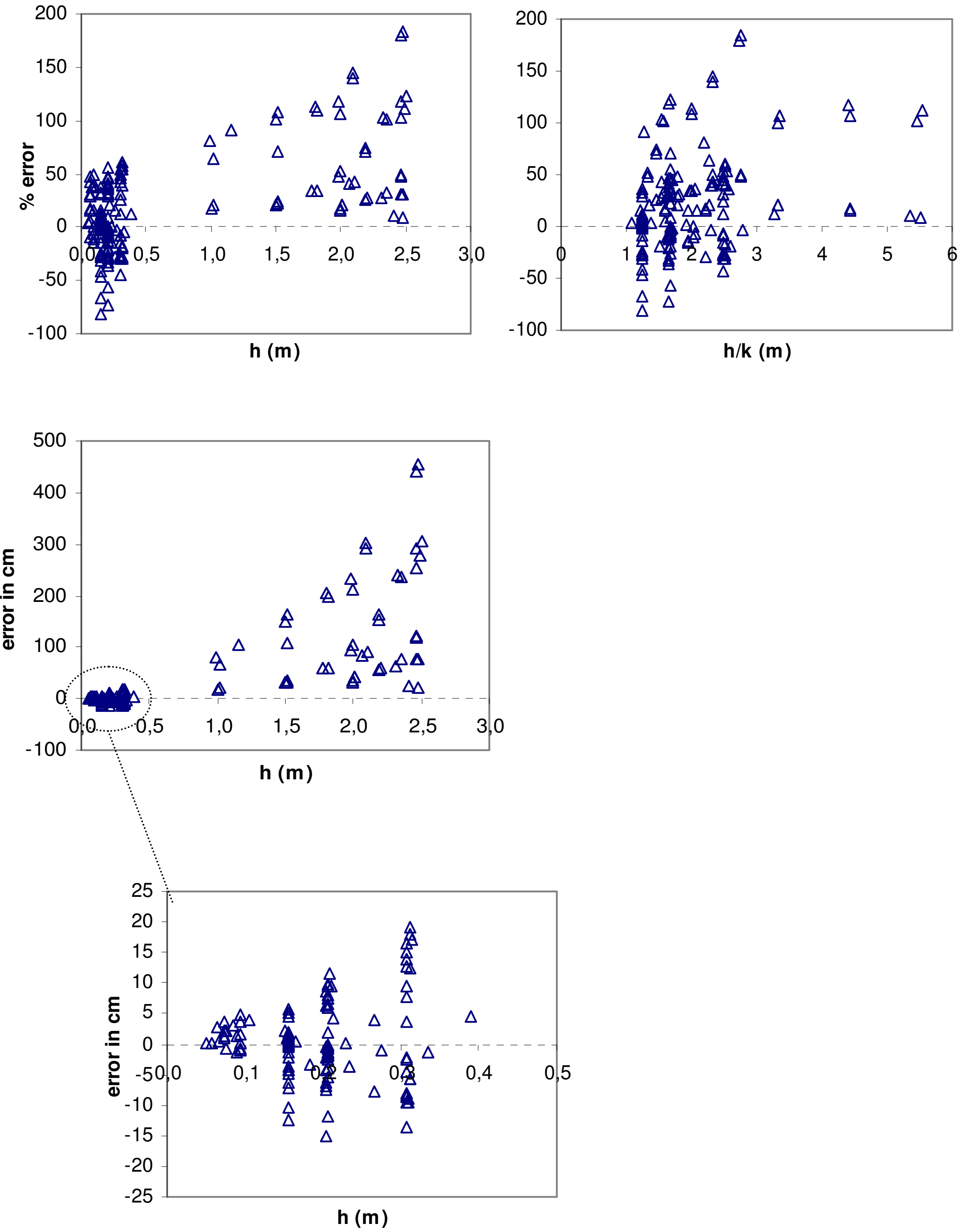


F.3. Description of Klopstra (1997), a defined by Huthoff (2007)

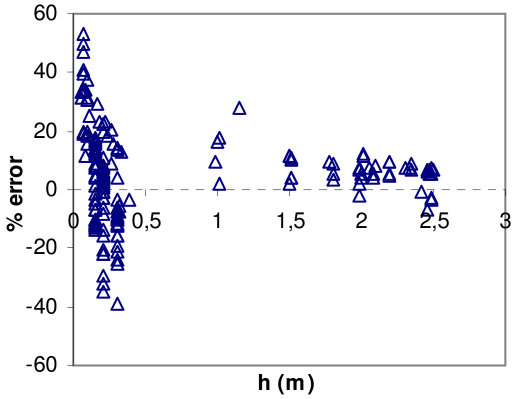


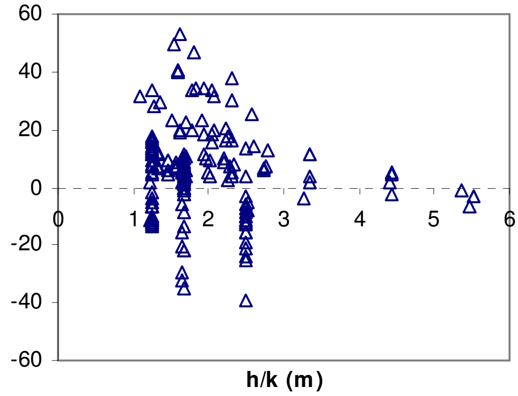


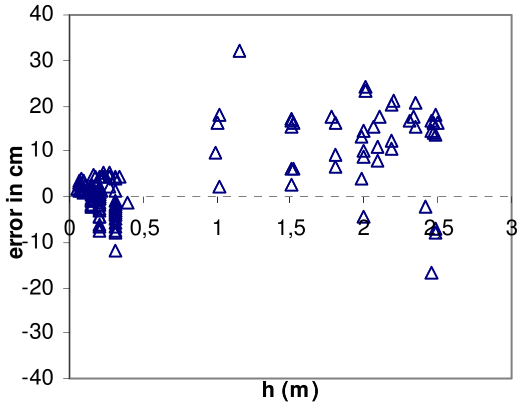

40
30
20
10
0
-10
-20
-30
-40
error in cm
0
0,5
1
1,5
2
2,5
3
h (m)


% error
h (m)
h/k (m)
error in cm
h (m)
error in cm
h (m)

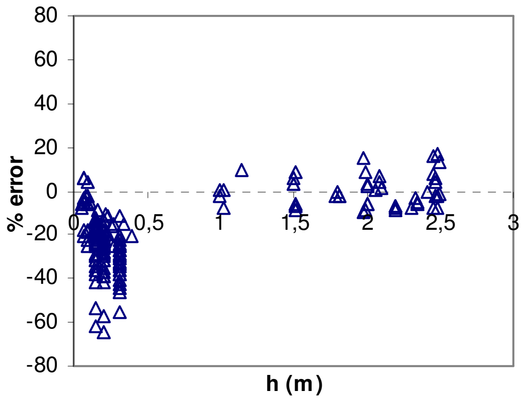
F.5. *Description of Van Velzen et al. (2003)*

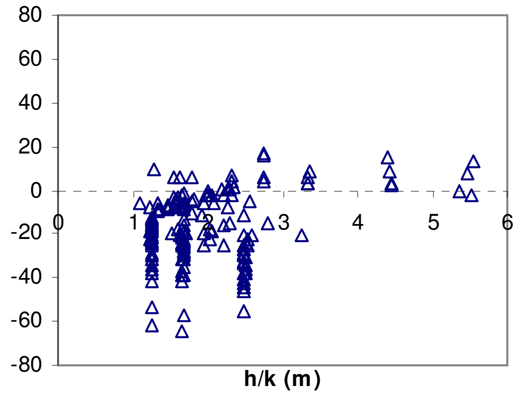


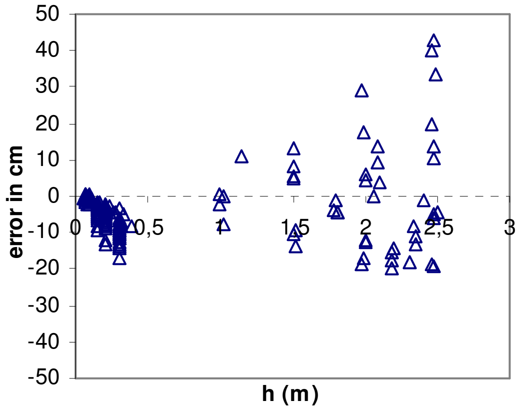




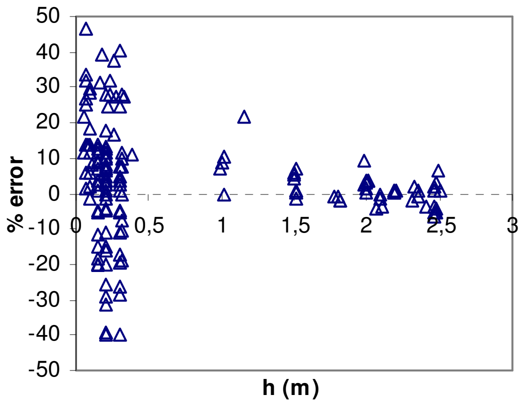
F.6. *Description of Baptist et al. (2006)*

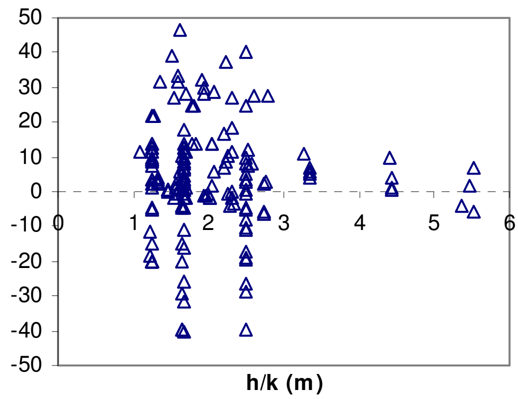


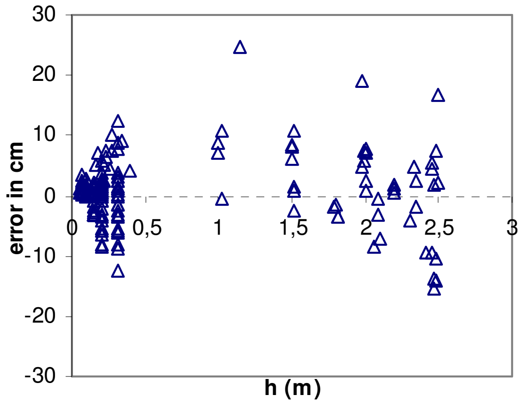




F.7. Description of Huthoff (2007)





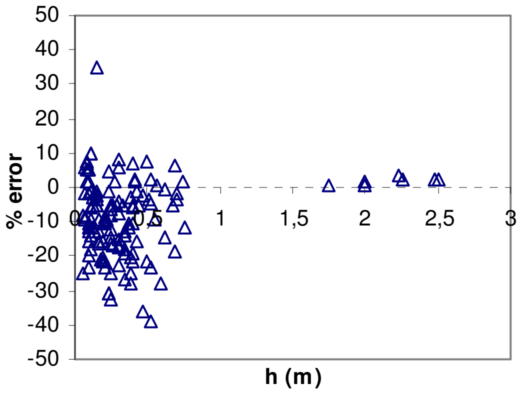


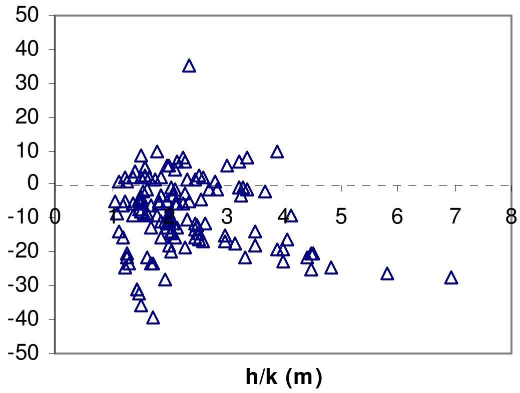
Appendix G. Mean error water level compared with flexible data

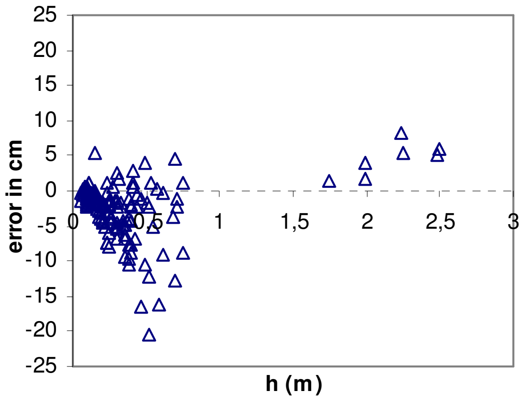
The following graphs show the mean error of the calculated and measured water dept against the water depth or the submergence ratio. The mean error is calculated by:

$$\frac{h_c - h_m}{h_m} \cdot 100$$

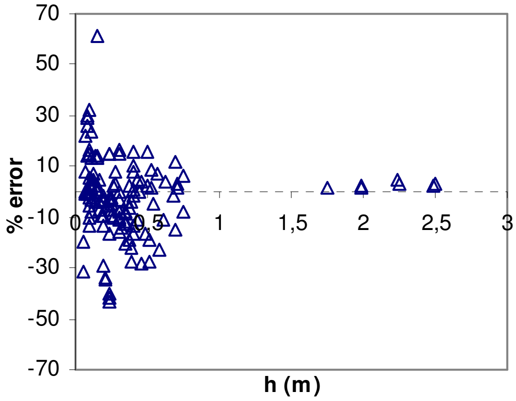
G.1. Description of Klopstra (2003), a defined by Meijer (1998)

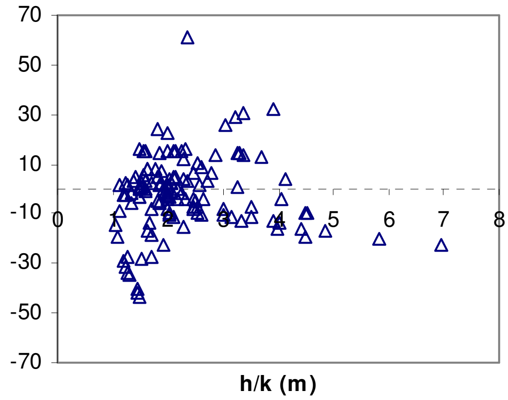


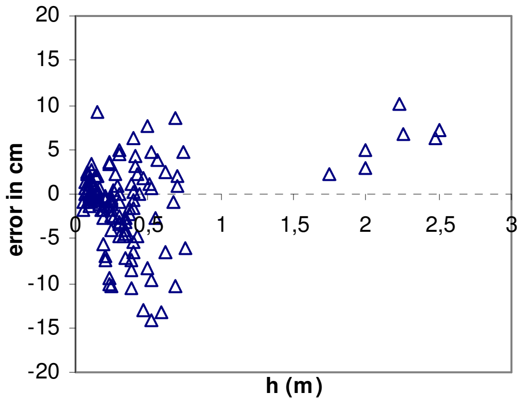




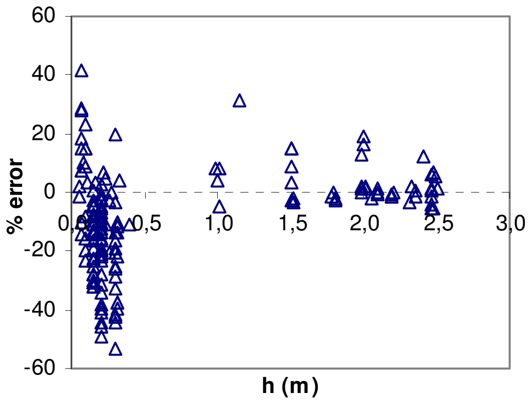
G.2. Description of Klopstra (2003), a defined by Van Velzen et al. (2003)

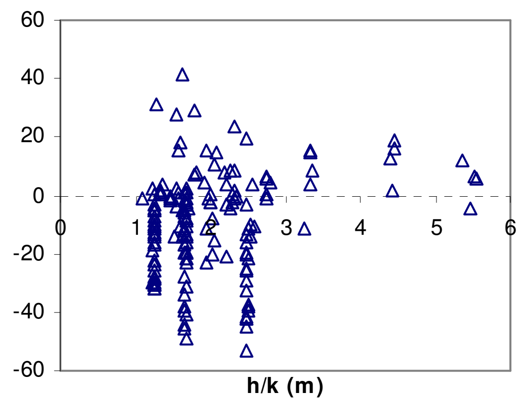


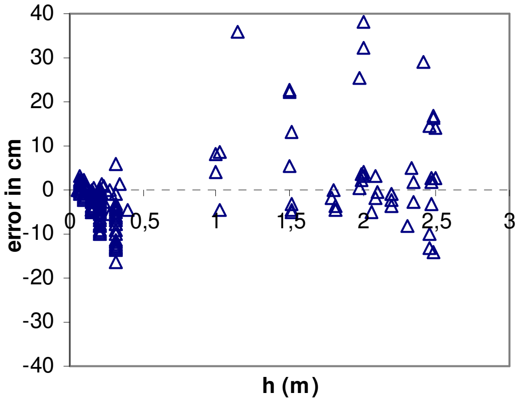




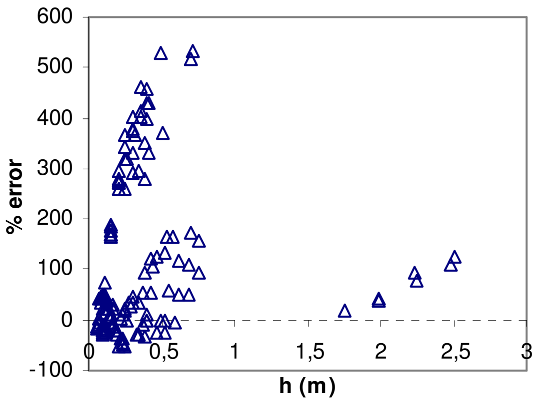
G.3. Description of Klopstra (2003) with the a given by Huthoff (2007)

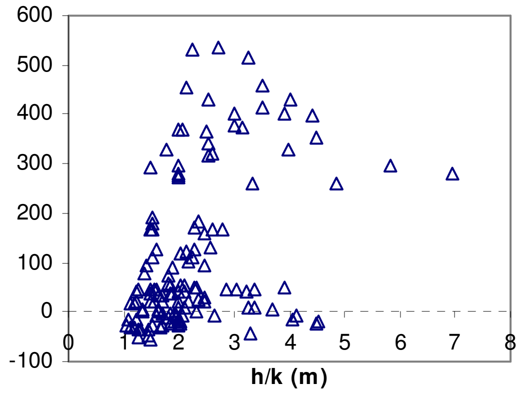


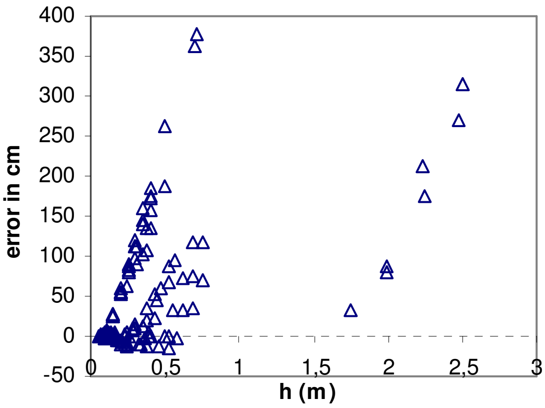




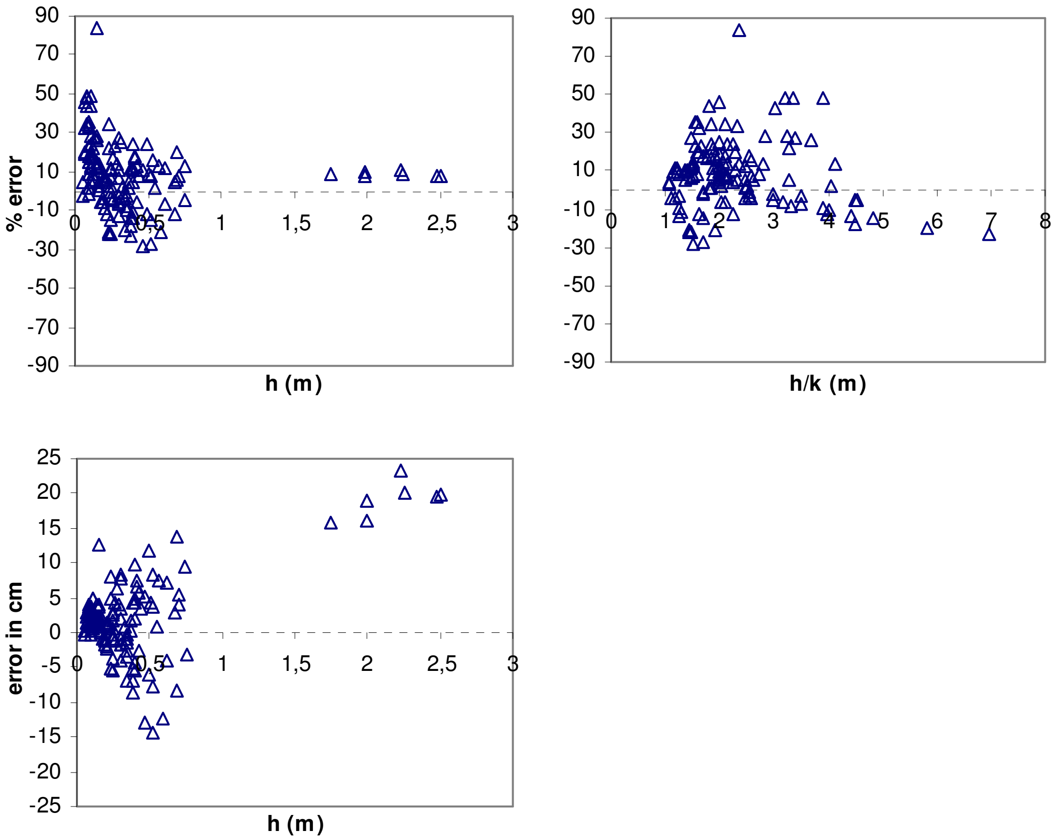
G.4. Description of Stone and Shen (2002)



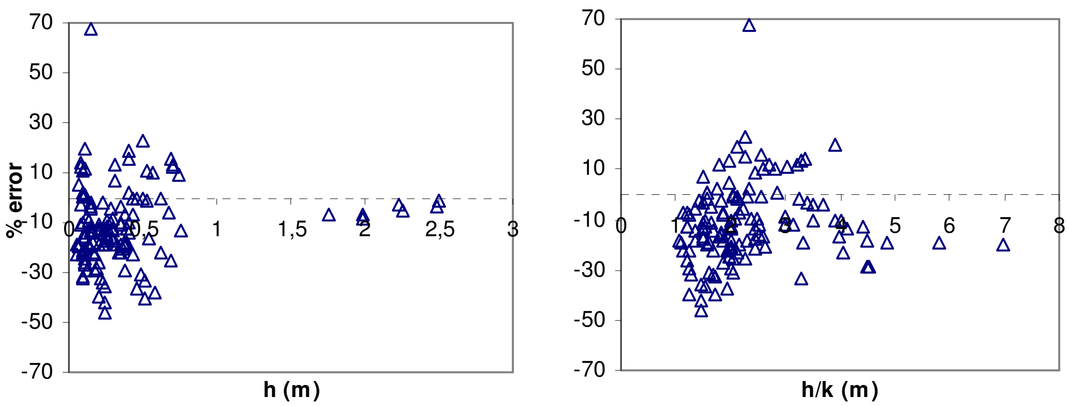


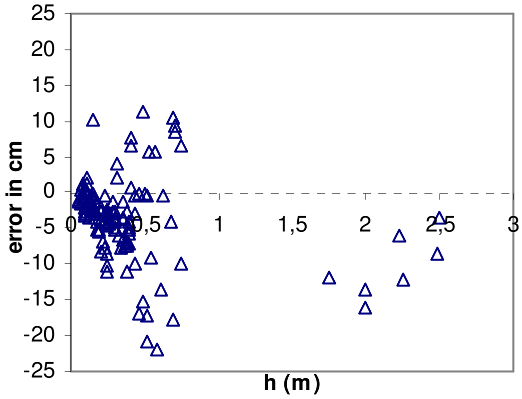


G.5. Description of Van Velzen et al. (2003)



G.6. Description of Baptist et al. (2006)





G.7. Description of Huthoff (2007)