Modeling of submerged groynes in 1D hydraulic computations

M. Sc. Thesis
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Preface

This report is written in the light of my graduation at Twente University and is part of the completion of my study Civil Engineering. In the foregoing half year this report grew to what it is today.

Also I would like to take this opportunity to thank the members of my graduation committee, dr. J.L. de Kok, ir A.J. Paarlberg and dr.ir. J.S. Ribberink for all their support, advice and time.

Finally, I would also like to thank my parents for their help and support throughout my study in Enschede. Last but not least I would like to thank my roommates for making life in Hengelo bearable.

Summary

The groyne maintenance of the river Elbe has been neglected for years. As a result the groynes in the Elbe are in bad shape. This makes it a good opportunity to fit the river to meet today's demands making it desirable to be able to estimate the effect of the groynes on the water depth of the river. On the other hand negative side effects are not clear. In river management a Decision support system (DSS) can help to get an overview of the impact of measures on the functions ecology, safety and shipping. A measure that can be used to influence the water level is the adjustment of height, width and spacing (distance between groynes) of the groynes. However, it is not yet possible to model changes made to groynes in a hydraulic 1D-model on a large scale without detailed 2D modelling. For practical reasons in the Elbe-DSS the effect of submerged groynes on the water level is estimated by interpolating between a maximum and minimal roughness of the channel. A 1D hydraulic model is used for the large-scale, because a 2D-model is not very flexible and data demanding. Furthermore the results of the hydraulic model are used in other models as well which do not need the level of detail a 2D-model delivers.

The goal of this research is to estimate the effects of submerged groynes and adjustments made to these groynes on the water level in a hydraulic 1D-model through roughness on a large scale.

The research starts with the comparison of a number of groyne equations from literature which fall into two categories, namely the weir equations and "obstacle in the flow" equations. Only groyne equations that are able to work in submerged conditions and allow for the groyne height to be altered are selected. With the remaining groye equations tests are done in a 1D hydraulic model to investigate whether their behaviour meets the expectations. It is expected that the effect of the groynes on the water level approaches zero as the groyne height approaches zero and that the effect of the groynes on the water level reduces as the groyne spacing increase.

This resulted in six different groyne equations which are able to meet the criteria to be used in a 1D hydraulic model. Groyne equations that did not make the final selection were amongst others a weir equation used in SOBEK **(28)**, an equation used in WAQUA to model the effect of a barrier **(30)** and a very commonly used weir equation in this report referred to as Mosselman **(27)**.

The six groyne equations that passed the selection are investigated in a river test case. To this end, a representative cross-section of the river Waal is used. In this test case adjustments are made to the groyne height, spacing and width to find out the absolute effect of the adjustment of groynes on the water depth.

The resulting groyne equations show similar development of the effect on the water depth when it comes to changing the length of groynes and changing the spacing of the groynes. However, the absolute values are not the same. The changing of the groyne height is the only measure which shows two different developments of the effect on the water depth. Apart from estimating the effect of the groynes on the water depth it is also

possible to express their effects on the water level in a roughness coefficient. Figure 6.2 shows that the effect on the water level of adjustment made to the groyne spacing should not be estimated through linear interpolation of the roughness.

It is recommended that further investigation is done with respect to the effect on the depth of the interface shear, effects of the morphology at low discharges and effects on morphology when the groynes are adjusted. Furthermore test should be done to establish which groyne equation comes closest to reality as until now no measurement are available to validate the groyne equations. These measurement can also be used to improve a new method, namely the “Momentum Balance” (M-B,). Also a solution must be found to be able to use the groyne equations in non-uniform flow conditions.

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1. Introduction

In river management many factors have to be taken into account. This is also true for the river Elbe. The Elbe begins in the Czech Republic and ends in Hamburg and is one of the longer rivers of Middle-Europe with a length of nearly 1100 kilometers (figure 1.1). During those 1100 kilometers the bed level of the Elbe has a declination of 1384 meters. As river management can be very complex tools have been developed to help make decisions.

Figure 1.1; Elbe river basin

These factors are:

1. Ecology; The Elbe has many branches. Many of these branches have a high natural level. This nature is of ecological importance to Europe. Therefore policy developed for the Elbe has to be in line with the water frame directive (European Union 2000) and the flora-fauna-habitat directive (EWG 1992).

2. Shipping; The Elbe also has a social-economic value. Shipping has a positive impact on the economy. It is important that the Elbe can be navigated during most of the time of the year. For ships to be able to navigate the Elbe a minimum depth has to be guaranteed. Because there are no weirs in the Elbe except at the end of the Elbe (Geesthacht) the only ways of having deep enough water for most of the year is by using groynes, making the river narrower or dredging the river. On the other hand the water level must not rise too much during high discharges because this could cause ships to have problems passing under bridges.

3. Flood safety; The Elbe must meet the existing safety demands. This means the Elbe must be able to respond adequately to high discharges to avoid a repeat of the flooding in 2002. High waters increase the chance of a dike breach which in turn can lead to the loss of lives and great material damage.

1.1 The DSS

For the Elbe River a decision support system (DSS) was developed (Berlekamp et al., 2005). With the help of a DSS it is possible to look at the impact of different scenarios on the factors shipping, ecology and flood safety. A scenario is a combination of different measures. With the DSS it is possible to make sensible decisions to tackle complex problems and take the desired measures. Obviously, the reliability and the possibilities of the tools used in a DSS control the usefulness of a DSS. The focus in this research will be on influencing the water level with high discharges.

1.2 Influencing the water level

The water level of a river can be influenced with various measures.

- Changing the height of the dikes
- Changing the layout of the groyne field
- Changing the size of the flood plains
- Changing the vegetation in the flood plains
- Changing or adding retention areas

With these measures the water level and water depth can be influenced. This means the number of navigable days on a river, the number of days that parts of nature are inundated and the risk of flooding can be changed. In this research the focus will be on groynes and their effects on the water level of the river.

In the Elbe DSS it is not possible to model the influence of the groynes accurate, or rather the influence of adjustments of the groyne geometry. By adjusting the groyne geometry it is possible to influence the water level of a river to a certain extent. This makes it desirable to be able to predict the influence of adjusting the groyne geometry

Groynes are mainly used to protect the banks of the river against erosion or to keep the channel navigable with low discharges keeping the channel navigable for more days a year. The application of groynes causes a part of the channel to get blocked and increases the roughness of the river as well. This leads to a higher water level of the river. This means that changing the groyne geometry will have an impact on both the shipping and the flood safety.
To be effective, groynes need to be placed in groups. These groups are referred to as groyne fields. Figure (1.2) shows an outline of a groyne field. The dimensions mentioned in this figure are used throughout this report when referring to a groyne field.
These dimensions are:

- S (m), the spacing between groynes.
- B (m), the width of the groyne (field).

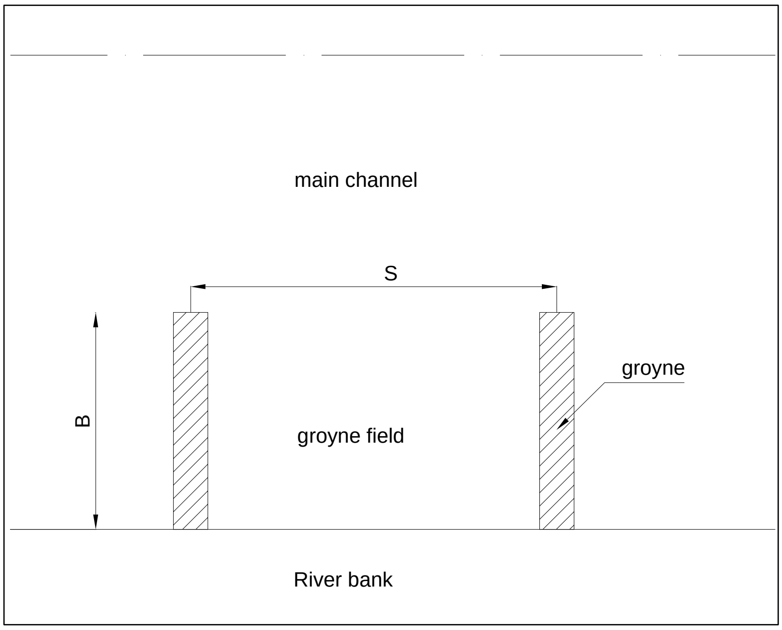

Figure 1.2; detail of a groyne field, top view

To influence the water level of a river by using groynes the following measures can be taken:

- Changing the width of the groyne field; This changes the width of the channel. Increasing the width of the groyne field leads to a narrower channel and higher water levels. This has a positive impact on shipping (except around bridges), but a negative impact on the flood safety. Increasing the length of the groynes has an effect on the morphology as well. Due to the narrowing of the main channel the flow velocity will increase and the main channel will erode and deepen. Decreasing the width of the groyne field has the opposite effect.
- Changing the height of the groynes; Lowering of the groynes leads to lower water levels as long as the groynes are submerged. This increases the flood safety. With low discharges this can have a negative influence on the amount of navigable days. This also leads to sedimentation of the main channel, because more water will flow over the groyne field. This leads to lower flow velocities above the main channel than before resulting in sedimentation. Increasing the height of groynes has the opposite effect.
- Changing the spacing between the groynes; This can also refer to the removal or placing of groynes. Increasing the spacing between the groynes can lead to contraction of the flow just before the groynes and broadening of the flow just after the groynes with low discharges. This causes the flow to accelerate and decelerate around the groynes. This is disturbing for shipping. Shortening of the groyne spacing reduces this effect. Increasing the spacing between the groynes also leads to lower water levels and sedimentation of the main channel due to the decrease of the flow velocity in the main channel. Decreasing the groyne spacing leads to higher water levels and erosion of the main channel.

1.3 Modeling groynes

Because in the case of river management the DSS is used on a large area (a scale of 500-600 km for the Elbe) it is not possible to use very complicated hydraulic models. This is not only because the calculation time would be very long. The input must have a high level of detail as well. For many parts of the river information with this level of detail will not be available or very hard to acquire. Moreover, it is not certain that a more complex model will give better results. Other models, for instance models that predict the development of vegetation, linked to the hydraulic model do not need the level of detail provided by a 2D model. For these reasons a hydraulic 1D model is used in the DSS.

Generally in a 1D hydraulic model the changes made to a groyne are implemented by changing the cross-section. In the available data however the groynes are not always clearly pointed out. This means the groynes have to be modeled in another way. The only other valid option seems to model the hydraulic effect of the groynes as roughness influence or additional energy loss.

In the current Elbe-DSS this is done as well by assuming a maximum and a minimum roughness of a combination of the main channel and the groyne field (summer bed) expressed as a Manning value (Berlekamp et al., 2005). Manning values in between are calculated by means of interpolation. This method is not tested and probably is not very accurate. Moreover this method is not able to make a distinction between the removal of a groyne and the lowering of a groyne.

During the previous literature research (Leeuwen, 2005) numerous ways of representing groynes (groyne equations) in a hydraulic model were shown. The most common used methods are the representation of a groyne as a weir or as an obstacle in the flow. However, there are many weir equations to chose from. This is to a lesser extent also true for the obstacle in the flow. As a consequence various groyne equations are used in practice. However it is mostly unclear why a certain groyne equation is preferred above others. Also it is not always clear what the field of application of a certain groyne equation is.

1.4 Aim of the research

“To be able to estimate the hydraulic effects of submerged groynes and adjustments made to groynes on the water level using a 1D hydraulic model via roughness.”

1.5 Research constraints

To prevent the research from being to broad and impossible to complete in the given time the research has been restricted. These restrictions are:

- The bed is assumed fixed. This means morphology is neglected in this research.
- The discharge is assumed to be constant in time (steady flow).
- The focus is on high water level situations. With high water level situations the groynes are submerged
- The modeled channel is assumed to be straight and will have an infinite length. Combined with a steady flow this leads to uniform flow conditions.

1.6 Research questions

The aim of the research leads to the following questions:

1. **What equations exist to represent groynes in a 1D hydraulic model?**

   It needs to be established what equations are able to represent groynes (groyne equations) in a 1D hydraulic model. Not only must thiss equation be able to represent a groyne, but the groyne equation must also allow to make adjustments to the groyne. Apart from that it is important that the equation can be used without doubts about the values of the parameters. This leads to the following sub-questions.

   Is it possible to adjust the groyne in the groyne equation?
   Are all the parameters values of the groyne equation known?

2. **Can the groyne equations be used to model a groyne field in a hydraulic 1D-model?**

   The groyne equations that are found, must be tested to analyze whether they behave in a logical manner in a hydraulic 1D-model. This can be done by adjusting the groyne height and the distance between the groynes in tests. The sub-questions that need to be answered are:

   How does the groyne equation react in the 1D hydraulic model to adjustments of the groyne height?
   How does the groyne equation react in the 1D hydraulic model to adjustments of the groyne spacing?

3. **What are the effects of the groynes on the water level?**

   The groyne equations used to represent a groyne field will most likely give different results. Interesting is to see if the difference is substantial and what this means for the prediction of the effect on the water level in a river.

   How much do the results of the different groyne equations differ?
   Can these differences be explained?
   what groyne equation should preferably be used?

4. **Can a groyne and adjustments made to a groyne be expressed as roughness?**

   In the current Elbe-DSS the summer bed has a roughness value. Therefore the effects of a groyne on the water level must be expressed as roughness to allow it to be used in the Elbe-DSS.

1.7 Research strategy

To reach the aim of the research the strategy shown in figure 1.3 is followed.

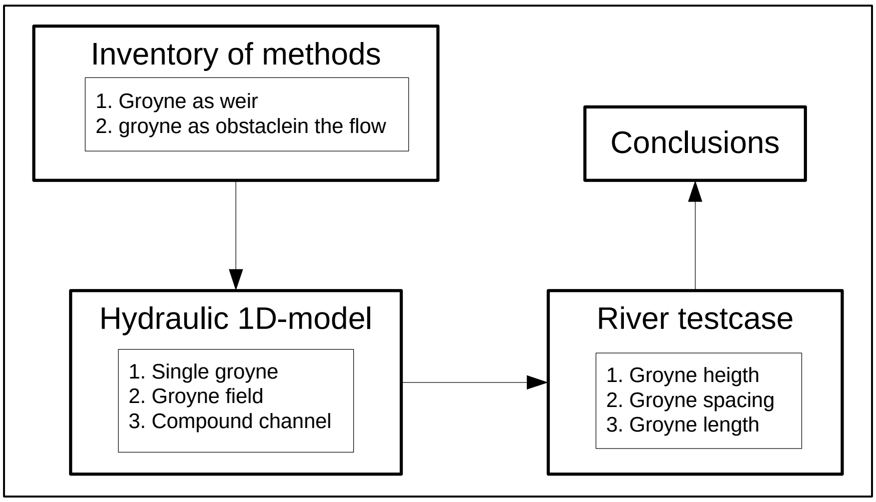

Figure 1.3; research strategy

In the following text the steps taken in figure 1.3 are explained in more detail. This text is a reading guide as well.

1. Inventory of methods; in *chapter two* and *chapter three* an inventory is made of groyne equations which are able to describe the effects of groynes in a hydraulic 1D model. A start has been made in a previously done literature study. In this literature study two methods were distinguished. The equations in the inventory are categorized according to these two methods. These methods are:
    a. Schematization of groynes as weirs
    b. Schematization of groynes as obstacles in the flow.

2. 1D hydraulic model; in *chapter four* step a 1D hydraulic model is set-up. This model is a compound channel divided in a main channel and a groyne field. The groyne equations presented in the inventory are analyzed in this model. The effect of the groyne equation is analyzed in three different situation:
    1) Channel with a single groyne; as this groyne is over the full width of the channel the groyne model acts as a weir.
    2) Channel with a series of groynes; this is a representation of a groyne field.
    3) Compound channel; this consists of the groyne field as in situation 2) and a main channel.

   In these three situations the effect of groynes on the water depth is analyzed by looking at the influence of:
    a. Changes made to the groyne height in the model.
    b. Changes made to the spacing between the groynes in the model.

3. The river test case; in *chapter five* tests are done with a for the river Waal representative cross-section (figure 1.4) as the necessary information about this river is available whereas for the river Elbe this information is not available. The groyne equations analyzed in chapter 4 are used to do the tests. The tests consist of the changing of the layout of the groyne field to analyze the effects of the groynes on the water depth. In the tests changes are made to:
    - The groyne height.
    - The groyne spacing.
    - The groyne length.

4. The river test case is followed by a synthesis in *chapter 6*, discussion in *chapter 7* and the conclusions and recommendations in *chapter 8*.

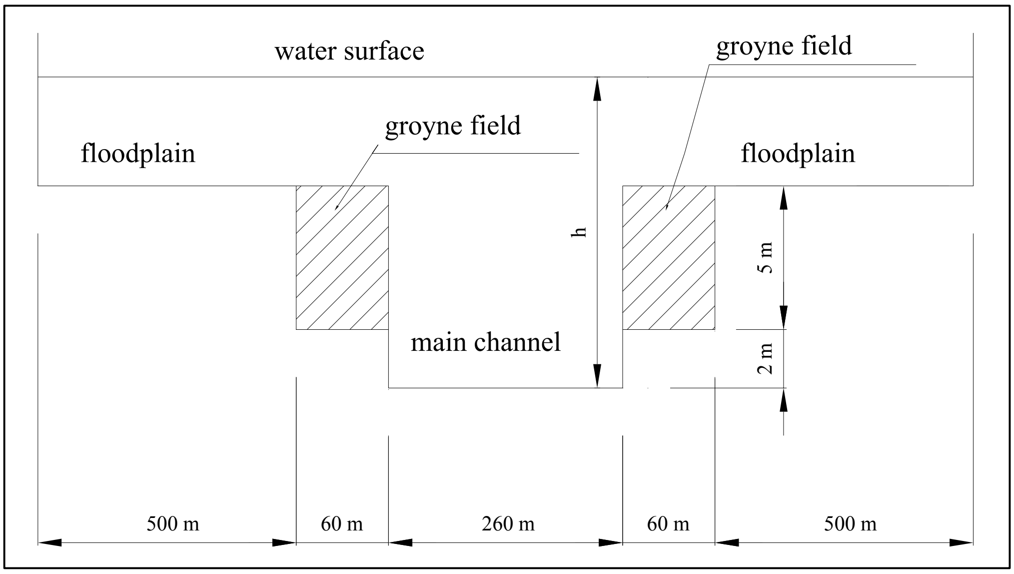

Figure 1.4; River Waal cross-section (after Yossef, 2005)

2. Schematization of groynes as weirs

In this research the river is modeled as a compound channel. This also means that the interchange of water between the groyne field and the main channel is neglected. Therefore the groyne field is basically a channel with a groyne over the full width of the channel. This can only be used for a submerged groyne and is just like a river with a weir. Furthermore, a weir leads just like a groyne to an increase of the water level. Although a groyne looks a lot like a sharp-crested weir, the influence of a groyne could proof to have more similarities with for example broad-crested weirs, but first the difference between the types of weirs will be explained. Attention will also be paid to the difference between an imperfect and perfect weir.

2.1 Types of weirs

The way the discharge over a weir is described is not only dependent on the properties of the weir but depends on the water height downstream of the weir as well. First the weirs will be divided into groups according to their properties, and then the difference between perfect and imperfect weirs will be discussed.

2.1.1 Types of weirs by dimensions

Types of weirs can be identified based on the ratio of the water depth above the weir and the length of the weir in the flow direction H/L (Govinda Rao and Muralidhar, 1963 and Jain, 2001). This is illustrated in figure (2.1).

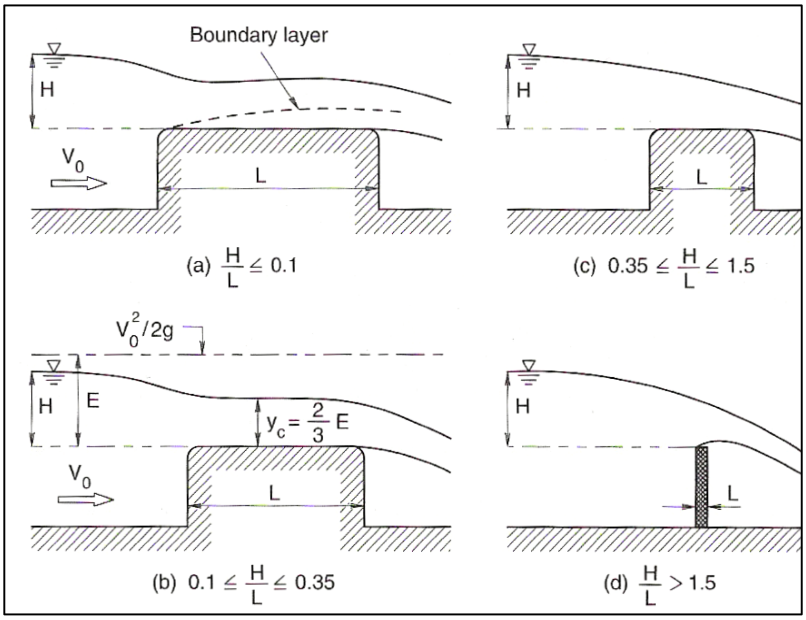

Figure 2.1; Weirs classified according to H/L ratio (Jain, 2001).
H is the upstream water height above the crest and L the crest length as illustrated above.

1. Long-crested weir; $H/L < 0,1$
2. Broad-crested weir; $0,1 < H/L < 0,35$
3. Narrow-crested weir; $0,35\ H/L < 1,5$
4. Sharp-crested weir; $1,5 < H/L$

In this case only the last three types are interest. The difference in H/L ratio leads to other behavior of the flow over the weir. The longer the crest the smaller the influence of the water depth downstream of the weir is on the water depth upstream. On the broad-crested weir parallel flow occurs near the middle of the crest. On the narrow-crested weir the streamlines are curved and parallel flow does not occur. In the case of the sharp-crested weir the flow does not reattach to the crest.

2.1.2 Perfect and imperfect weirs.

whether a weir is called perfect or imperfect depends on the downstream water height with respect to the weir. The weir is called imperfect if the discharge over a weir is influenced by the downstream water height. Otherwise it is called a perfect weir. A broad-crested weir is perfect if the water height on the crest equals the critical depth. This means that the discharge over the weir is optimal. The critical depth is equal to 2/3 of the energy height. In the case of a sharp-crested weir it is not that precisely defined when a weir is perfect or imperfect. A sharp-crested weir is called perfect if the water downstream of the weir has an effect on the water depth. This happens when the downstream water height is approximately as high or higher then the crest level.

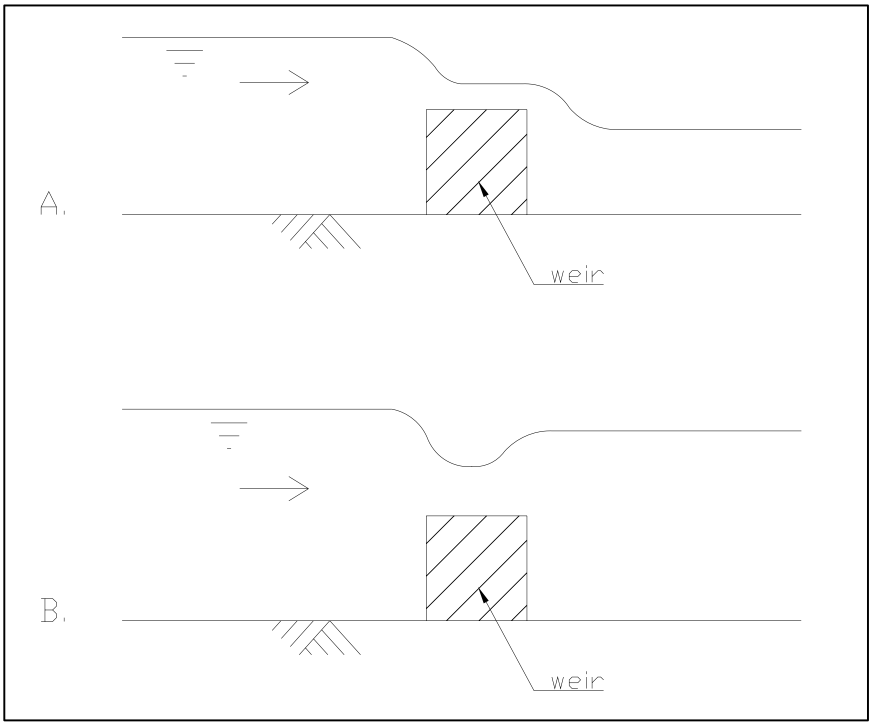

Figure 2.2; the perfect and imperfect weir

A. The perfect weir, downstream water height has no influence on upstream water height

B. The imperfect weir, downstream water height does have influence on upstream water height

In this study the imperfect weirs are the most interesting, because in case of a groyne field the water depth downstream is high enough to influence the water depth upstream of the weir. However, some discharge relations for imperfect weirs are related to equations for perfect weirs. For this reason the equations for perfect weirs will be included as well.

2.2 Standard dimensions for weirs.

To make it easier to understand the dimensions used in the weir discharge equations in the following chapters all equations will be rewritten in the dimensions as shown in figure (2.3).

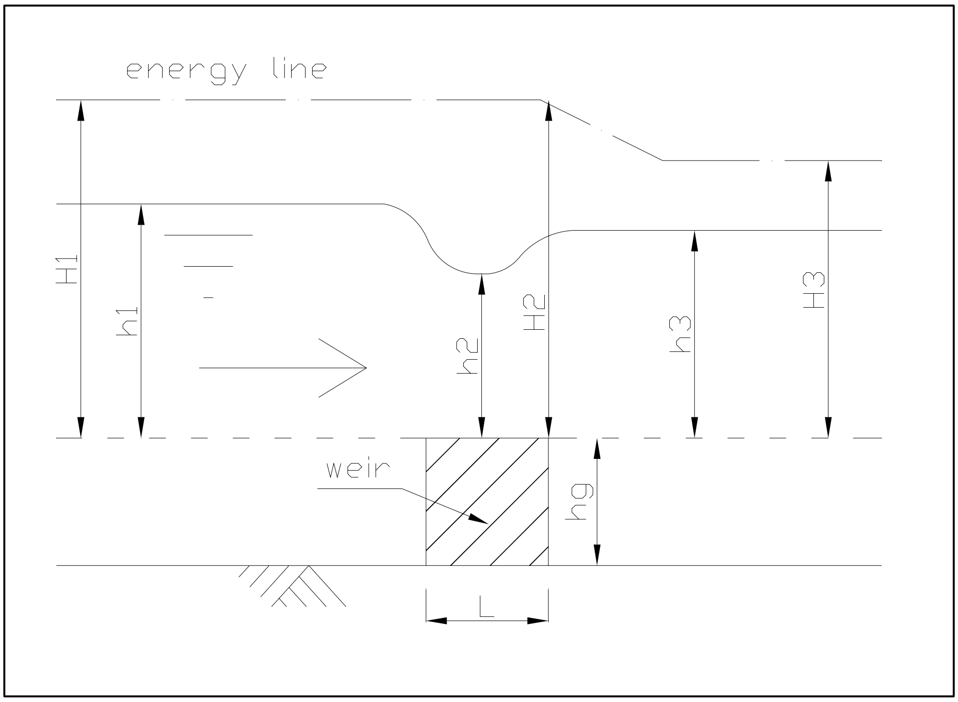

Figure 2.3; Standard dimensions weir/groyne

The parameters shown in figure (2.3) are:

h_1	= water height upstream of the weir relative to the crest of the groyne (m)
H_1	= energy height upstream of the weir relative to the crest of the groyne(m)
L	= length of the crest in direction of the flow (m)
h_g	= height of the groyne (m)
h_2	= water height above the groyne (m)
H_2	= energy height above the groyne (m)
h_3	= water height downstream of the weir relative to the crest of the groyne (m)
H_3	= energy height downstream of the weir relative to the crest of the groyne (m)

Still some formulas are written in other dimensions. If that is the case the number of the figure this formula applies to is written directly after the formula.

2.3 Broad-crested weir discharge equations

In this paragraph discharge equations for the perfect and the imperfect broad-crested weir are described. In the case of the broad-crested weir parallel flow occurs on top of the weir. This means the pressure distribution on top of the weir can be assumed hydrostatic.

2.3.1 The perfect broad-crested weir equations

A way to come to an expression for the discharge over a broad-crested weir is by assuming that the water depth on the weir equals the critical depth and by neglecting the energy loss between the upstream section and the section of the critical depth (h_c) (Jain, 2001). This means, according to the Bernoulli equation:

$$H_1 = h_1 + \frac{u_1^2}{2g} = h_2 + \frac{u_2^2}{2g} = H_2 \qquad \textbf{(1)}$$

With:
u = depth-average flow velocity (m^2/s)
g = acceleration due to gravity (m/s^2)

The simplest form to describe the flow over a weir is:

$$q = h_2 \cdot u_2 \rightarrow q = h_2 \cdot \sqrt{2g \cdot (H - h_2)} \qquad \textbf{(2)}$$

In case of a perfect weir the downstream water depth will not have an effect on the water depth on the weir. This water depth however is restricted to a maximum. This maximum can be obtained by differentiating the equation with h_2 and equating it to zero. This way the critical depth is found. The critical depth is equal to 2/3 of the energy height (H) . Thus an equation for the discharge over a perfect broad-crested weir can also be described with:

$$q = \sqrt{g h_c^3} = \sqrt{g\left(\frac{2}{3}H_1\right)^3} = \sqrt{\frac{8}{27} g H_1^{3/2}} = 0.385\sqrt{2g}H_1^{3/2} \text{ (m}^2\text{/s)} \qquad \textbf{(3)}$$

To account for friction and contraction often a discharge coefficient (m_d) is added:

$$q = 0.385 m_d \sqrt{2g} H_1^{3/2} \text{ (m}^2\text{/s)} \qquad \textbf{(4)}$$

This equation is not applicable to imperfect weirs because the downstream water height does not have influence on the outcome of the equation. However an equation for an imperfect situation will have more or less the same form.

2.3.2 The imperfect broad-crested weir discharge equation

A useful way to describe the discharge over a groyne seems to be via an equation that describes the discharge over an imperfect broad-crested weir. Most discharge equations found for an imperfect broad-crested weir were not specific for the broad-crested weir but for the sharp-crested weir as well. These equations are described in the section (2.3.3).

One method that is specific for the imperfect broad-crested weir is described in Van Rijn (1990) and is based on Carnot's rule. With Carnot's rule it is possible to calculate the energy loss caused by the deceleration of the flow. This is done by way of a momentum balance. The balance is taken from the crest of the weir to a short distance downstream of the weir. The water pressure distribution on the crest and against the weir is assumed hydrostatic. This leads to a momentum balance as illustrated in figure (2.4):

$$\begin{aligned} P_2 - P_3 &= \rho \cdot u_3^2 \cdot \left(h_3 + h_g\right) - \rho \cdot u_2^2 \cdot h_2 \\ &= \rho\left(\frac{q^2}{h_3 + h_g} - \frac{q^2}{h_2}\right) \qquad \text{(kg)} \end{aligned} \tag{5}$$

With:

$$P_2 = \frac{1}{2}\rho \cdot g \cdot \left(h_2 + h_g\right)^2 \quad \text{(kg)} \tag{6}$$

$$P_3 = \frac{1}{2}\rho \cdot g \cdot \left(h_3 + h_g\right)^2 \quad \text{(kg)} \tag{7}$$

This momentum balance states that the deceleration of the flow must be caused by a pressure difference between section 2 and 3. This leads to a resulting force, which in case of deceleration points upstream. With the help of this momentum balance it is possible to estimate the water height and as a consequence the energy height of the flow on the weir as well. Since the energy height of the flow on the weir is the same as the energy height of the flow upstream of the weir (see figure 3.1) it is possible to estimate the water height drop over the weir.

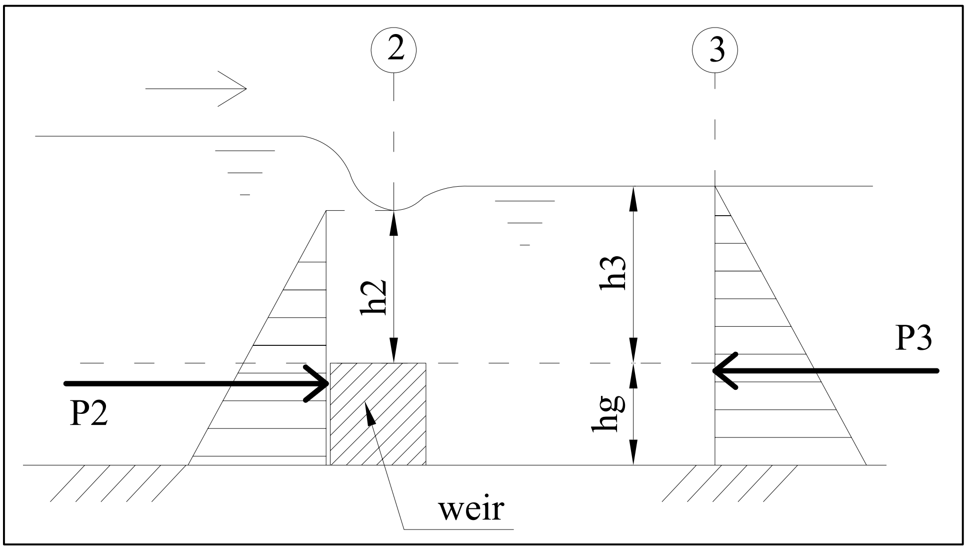

Figure 2.4; Momentum balance on the weir to downstream of the weir (Van Rijn, 1990)

2.4 Sharp-crested weir discharge equations

In this section the equations for imperfect and perfect sharp-crested weirs will be described. Sharp-crested weirs are basically vertical plates mounted at right angles to the flow. The plate has a sharp-edged crest. In case of sharp-crested weirs the flow on top of the weir will not have a hydrostatic pressure distribution.

2.4.1 The perfect sharp-crested weir

While this seems an unimportant situation actually quite a few equations for imperfect situations, sharp- and broad-crested, are related to the discharge equation of the perfect sharp-crested weir. Using figure (2.5) the discharge over a sharp-crested weir can be expressed as (Henderson, 1966):

$$q = \int_{V_0^2/2g}^{H+V_0^2/2g} \sqrt{2gh}\,dh = \frac{2}{3}\sqrt{2g}\left[\left(\frac{V_0^2}{2g}+H\right)^{3/2} - \left(\frac{V_0^2}{2g}\right)^{3/2}\right] \quad [Figure\ 2.5] \qquad \textbf{(8)}$$

With:

V$_0$ = water velocity upstream of the weir (m/s)
H = water height upstream of the weir relative to the crest (m)
h = water height relative to the energy line, measured downwards (m)

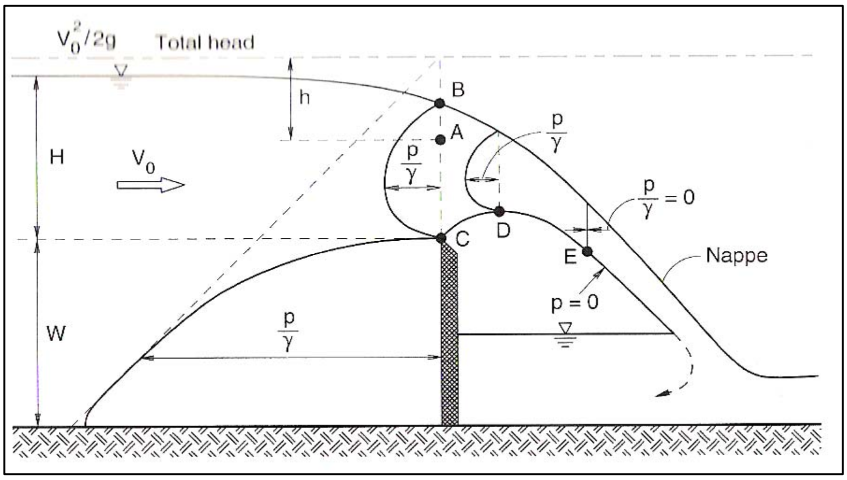

Figure 2.5; flow over a sharp-crested weir (Jain, 2001)

The discharge is calculated by expressing the flow velocity in the water depth (h). By integrating this expression relative to the energy line from the crest of the weir to the water depth (h) the discharge over the weir is obtained. This is possible if the pressure distribution is assumed hydrostatic. By rewriting formula **(8)** a weir equation of a sharp-crested weir (q_f) with discharge coefficient m_d is made:

$$q_f = \frac{2}{3}\sqrt{2g}\left[\left(\frac{V_0^2}{2gH}+1\right)^{3/2} - \left(\frac{V_0^2}{2gH}\right)^{3/2}\right]H^{3/2} = \frac{2}{3}m_d\sqrt{2g}H^{3/2} \qquad \textbf{(9)}$$

In which:

$$m_d = C_c\left[\left(\frac{V_0^2}{2gH}+1\right)^{3/2} - \left(\frac{V_0^2}{2gH}\right)^{3/2}\right] \qquad \textbf{(10)}$$

With:

C$_c$ = Contraction coefficient, expresses the energy loss due to contraction of the flow (-).

The contraction coefficient C_c and the ratio $\frac{V_0^2}{2gH}$ are both among other things dependent on boundary geometry and the ratio H/W. In this case the contraction coefficient is 1.0 because only the situation over the full width of the channel is taken into account.

A commonly used expression for the discharge coefficient m_d for a weir with a perfect discharge is from Rehbock (1929):

$$m_d = 0{,}611 + 0{,}075\frac{h_1}{h_g} + \frac{0{,}36}{h_1\sqrt{\rho g/\sigma} - 1} \quad (-) \qquad \textbf{(11)}$$

With:
σ = surface tension (N/m^2)

If $h_1 > h_*$ than the surface tension can be neglected. The discharge coefficient m_d then equals:

$$m_d = 0{,}611 + 0{,}075\frac{h_1}{h_g} \quad (-) \qquad \textbf{(12)}$$

The value of h_* is the height corresponding to the minimum value of m_d. The h_* can be acquired by first differentiating m_d by h_1. The h_* is found by equating the derivative to zero. This leads to:

$$h_* = \sqrt{\frac{\sigma}{\rho g}} + 2.12\left(\frac{h_g^2\sigma}{\rho g}\right)^{1/4} \quad (\mathrm{m}) \qquad \textbf{(13)}$$

Unfortunately the discharge coefficient by Rehbock is only useful for values of $h_1/h_g \le 5$. It can not be used for low values of h_g because in that case m_d will go towards infinity.

Discharge coefficient by Swamee

As mentioned Rehbock's (1929) discharge coefficient **(11)** is not valid for low values of h_g. With low values of h_g the formula for the discharge coefficient by Rehbock goes towards infinity. Therefore Rouse (1963) formulated a discharge coefficient for low values of h_g:

$$m_d = 1.06\left(1 + \frac{h_g}{h_1}\right)^{3/2} \quad (-) \qquad \textbf{(14)}$$

This formula is applicable for $h_1/h_g \ge 15$. This still leaves a gap for $5 \le h_1/h_g \le 15$. Based on the formula by Rehbock **(11)**, experimental data of Kandaswamy and Rouse (1957) and the discharge coefficient by Rouse **(14)** (1963) for low values of h_g eventually Swamee (1988) formulated an expression that is suited for any value of h_1/h_g:

$$m_d = 1{,}06\left[\left(\frac{14{,}1h_g}{8{,}15h_g + h_1}\right)^{10} + \left(\frac{h_1}{h_1 + h_g}\right)^{15}\right]^{-1/10} \quad (-) \qquad \textbf{(15)}$$

In figure (2.6) can be seen how this formula fills the gap between the discharge coefficient by Rouse (1963) and Rehbock (1929).

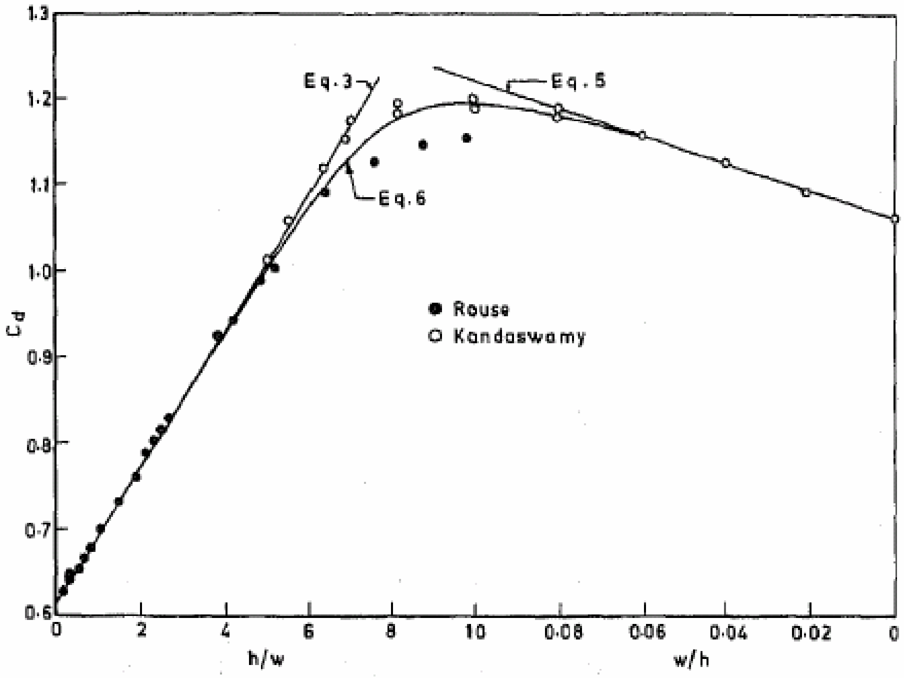

Figure 2.6; relation between discharge coefficient and h_g/h_l ratio (Swamee, 1988)
$h_g = w$, $h_l = h$, $C_d = m_d$
equation numbers in the figure do not relate to this report

2.4.2 The imperfect sharp-crested weir

The till now described formulas for sharp-crested weirs are, as can be seen in figure (2.5), valid in a situation with a perfect weir. The following equations are all related to the formula of the perfect sharp-crested weir **(9)**.

Villemont

According to Villemont (1947) the discharge over an imperfect sharp-crested weir can be estimated with:

$$\frac{q}{q_f} = \left[1 - \left(\frac{h_3}{h_1}\right)^n\right]^{0,385} \rightarrow q = q_f\left[1 - \left(\frac{h_3}{h_1}\right)^n\right]^{0,385} \quad (\mathrm{m^2/s}) \qquad \mathbf{(16)}$$

With:
h_1 = upstream water level above weir (m)
h_3 = downstream water level above weir (m)
q_f = perfect discharge for head h_1, see also formula **(9)** (m^2/s)
n = exponent, 3/2 for rectangular weirs (-)

The origin of this formula is not explained, but is most likely obtained with the help of measurements. The measurements are implemented by using a ratio of h_3 and h_1.

Abou-Seida and Quraishi

Abou-Seida and Ouraishi (1976) report an almost similar equation:

$$\frac{q}{q_f} = 1 - \left(\frac{h_3}{2h_1}\right)\sqrt{1 - \frac{h_3}{h_1}} \rightarrow q = q_f\left[1 + \left(\frac{h_3}{2h_1}\right)\sqrt{1 - \frac{h_3}{h_1}}\right] \text{ (m}^2\text{/s)} \qquad \textbf{(17)}$$

These two equations are based on the free-flow or perfect discharge of the weir as described in section 2.2.1 formula (**9**). This means that the discharge coefficient as described in the section 2.2.1 must be taken into account as well.

Lakshmana Rao

Similar to Abou-Seida et al. and Villemont, Lakshmana Rao (1975) describes the relation between the discharge of an imperfect sharp crested weir and the perfect discharge of that same weir as:

$$q = \Psi q_f \text{ (m}^2\text{/s)} \qquad \textbf{(18)}$$

With:

Ψ = reduction factor (-)

According to S. Wu and N. Rajaratnam (1996) this reduction factor ψ can be described by the following equation:

$$\Psi = 1.0 + 1.162(h_3/h_1) - 1.33\sin^{-1}(h_3/h_1) \quad (r^2 = 0.934) \qquad \textbf{(19)}$$

This relation is based on test results with a submerged sharp-crested weir. The formula for ψ was acquired by plotting h_3/h_1 against ψ (figure 2.7) and can be used for values of h_3/h_1 up to 0.95.

For h_3/h_1 larger than about 0.9 Rajaratnam and Muralidhar (1969) found ψ to be equal to:

$$\Psi = \frac{0.955}{m_d}\frac{h_3}{h_1}\sqrt{1 - \frac{h_3}{h_1}} \text{ (-)} \qquad \textbf{(20)}$$

If the product of formulas (**19**) and (**20**) is taken, the discharge over a imperfect sharp-rested weir becomes (Rajaratnam and Muralidhar, 1969):

$$q = 0.90 h_3 \sqrt{g(h_1 - h_3)} \text{ (m}^2\text{/s)} \qquad \textbf{(21)}$$

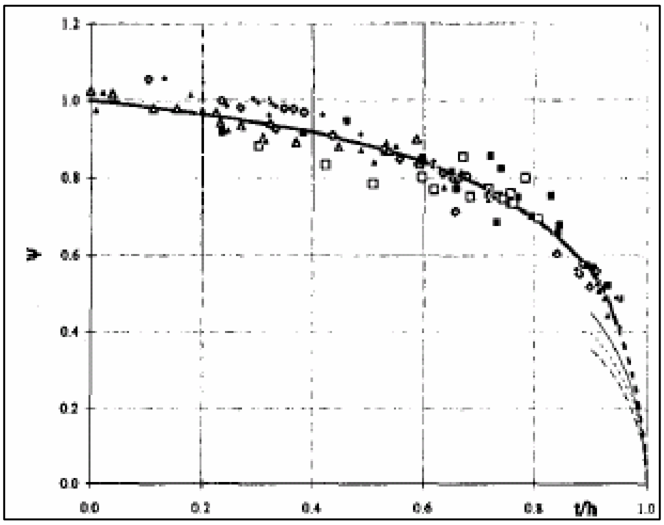

Figure 2.7; variation of ψ with h_3/h_1 (= t/h) ratio (S. Wu and N. Rajaratnam,1996).

2.5 The general weir discharge equations

Many found equations are applicable to broad-crested and sharp-crested weirs alike. In this section those equations are described.

2.5.1 The perfect general weir

Swamee took the discharge equation for a perfect sharp-crested weir as a starting point for describing the discharge over a general weir by combining a discharge equation valid for various weir heights with a coefficient valid for various crest lengths.

The crest of a weir can have different lengths. This leads to different behavior of the discharge. According to Swamee (1988) the m_d for flow over finite crest weirs can be expressed as:

$$m_d = 0{,}5 + 0{,}1\left[\frac{(h_1/L)^5 + 1500(h_1/L)^{13}}{1 + 1000(h_1/L)^3}\right]^{1/10} \quad (-) \qquad \mathbf{(22)}$$

With:

L = length of the weir in the direction of the flow (m) (see figure 2.3).

This formula is only applicable if $h_1/L \leq 1{,}5$. For higher ratio of h_1/L the ratio h_1/h_g should be taken into account as well.

The next formula is a combination of formula **(15)** which takes various crest heights into account and formula **(22)** which takes different crest lengths into account.

Using these two formulas a discharge coefficient for a generalized rectangular weir equation can be written as:

$$m_d = 1.06\left\{\left(\frac{14.14h_g}{8.15h_g + h_1}\right)^{10} + \left(\frac{h_1}{h_1 + h_g}\right)^{15} + 1.834\left[1 + 0.2\left(\frac{\left(\frac{h_1}{L}\right) + 1500\left(\frac{h_1}{L}\right)^{13}}{1 + 1000\left(\frac{h_1}{L}\right)^{3}}\right)^{1/10}\right]^{-10}\right\}^{-1/10} \quad (-) \qquad \textbf{(23)}$$

This discharge coefficient is suited for the perfect sharp-crested weir discharge equation **(9)**.

2.5.2 The imperfect general weir

If the crest of a groyne is compared to that of a weir it is not equal to that of a sharp-crested weir, but also not to that of a broad-crested weir. Therefore in this paragraph discharge equations are described that are applicable to weirs ranging from broad-crested to sharp-crested. In this section discharge equations by "Van Rijn", "Mosselman and Struiksma" and equations used in SOBEK and WAQUA are described.

Van Rijn

The derivation to get to the discharge over a weir by van Rijn is the same as the derivation in section (2.3.1) until formula **(2)** which leads to:

$$q = h_2\sqrt{2g}\left(H_1 - h_2\right)^{1/2} \ (\mathrm{m^2/s}) \qquad \textbf{(24)}$$

The coefficient m_d can be used to translate the equation with h_2 into an equation with h_3. This leads to the discharge over an imperfect weir per unit width as stated by Van Rijn (1990):

$$q = m_d h_3\sqrt{2g}\left(H_1 - h_3\right)^{1/2} \ (\mathrm{m^2/s}) \qquad \textbf{(25)}$$

With:

h_3 = downstream water height above the weir (m)

m_d = discharge coefficient (-)

This equation is valid for broad-crested and sharp-crested weirs. The type of weir is expressed in the discharge coefficient m_d. For a well designed weir the value of the discharge coefficient is in the range1 $\le m_d \le 1.2$. However, for very rough weirs or with a high contraction of the flow values lower than 1 are possible (Van Rijn, 1990).

Mosselman and Struiksma

According to Mosselman and Struiksma (1992) the discharge over an imperfect weir can be described as:

$$q = \begin{cases} m_d \cdot (h_t - h_g) \cdot \sqrt{2g}\ (\cdot \Delta h)^{1/2}\ if\ h_t > h_g \\ 0 \qquad else \end{cases} \quad (\mathrm{m^2/s}) \tag{26}$$

With:

h_t = total downstream water height $= h_3 + h_g$ (m)

h_g = weir height (m)

Δh = pressure drop over the weir = $h_1 - h_3$ (m)

Using similar dimensions as used in the van Rijn equation formula **(26)** becomes:

$$q = m_d \cdot h_3 \cdot \sqrt{2g}\,(h_1 - h_3)^{1/2} \quad (\mathrm{m^2/s}) \tag{27}$$

Although this formula looks a lot like the previously described discharge equation (**24**) in this case the water depth (h) is used instead of the energy height (H) upstream of the weir. Unfortunately it is not very clear what the range of this discharge coefficient is. Based on an article (Yossef, 2005) there is reason to believe that it should not exceed 1.

SOBEK

The equation used in SOBEK to calculate the discharge over a weir is, like the equation by Van Rijn, applicable to sharp-crested and broad-crested weirs. The formula is (Veen, Pakes and Schutte, 2002):

$$q = 0.385 \cdot C_w f \sqrt{2g}\,(H_1 - h_g)^{3/2} \quad (\mathrm{m^2/s}) \tag{28}$$

With:

C_w = correction factor, 1.0 for broad-crested weir, 1.2 for sharp-crested weir

f = imperfect discharge reduction factor

The value of the coefficient C_w represents the type of weir. The coefficient *f* is only used if the weir is imperfect. A weir is considered imperfect if the submergence limit m_f is exceeded:

$$m_f = \frac{H_3 - h_g}{H_1 - h_g}\ \textbf{(-)} \tag{29}$$

A broad-crested weir is considered imperfect if $m_f \geq 0.82$ and a sharp-crested weir is considered imperfect if $m_f \geq 0.01$ is (Veen, Pakes and Schutte, 2002). When the submergence limit is crossed, the imperfect discharge reduction factor can be obtained with the help of figure (2.8). To be able to obtain *f* it is necessary to know the h_3/h_1 ratio.

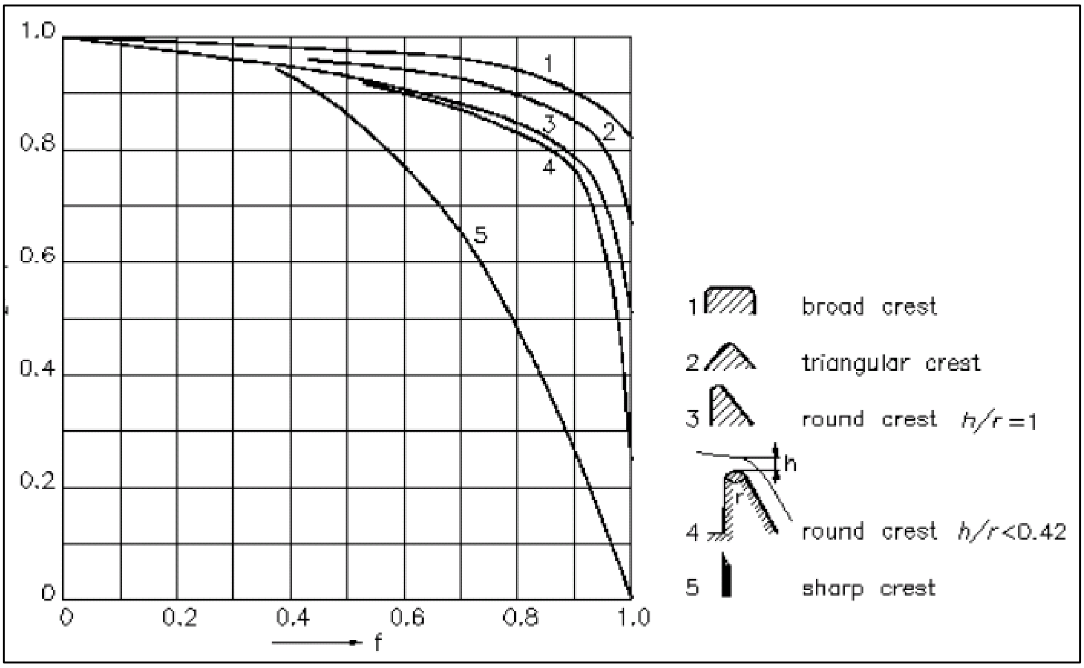

Figure 2.8; Curves to acquire the imperfect discharge reduction factor f.
The y-axis is the ratio of the water level upstream and the water level downstream of the weir (h3/h1).

The value for the water depth (h) used to calculate the energy height is related to the crest level of the weir. However the energy height is related to a reference level. This value of the reference level is unknown. However this formula is only used to decide whether a weir is imperfect or not. Furthermore the ratio of H_1 and H_3 is most likely closer to one than to 0.82 even if the bottom of the main channel is used as reference level. This is caused by the relative high contribution to the energy height of the water depth compared to the flow velocity.

WAQUA
In WAQUA (RIZA, 2003) the discharge is calculated over several barriers. Specifications of the barrier are not given. These are most likely related to the discharge coefficient.

Only the situation with imperfect discharge is taken into account. In this situation $h_3 > 2/3H_1$. The discharge can be expressed as:

$$q = 0.58 \cdot m_d \cdot H_1 \sqrt{2g} (h_1 - h_3)^{1/2} \text{ (m}^2\text{s)} \qquad \textbf{(30)}$$

The discharge coefficient is decided based on the estimation of an experienced user or actual measurements at the construction and varies roughly between 0.6 and 1.0.

2.6 Pre-selection of weir equations to model groynes

In the sections (2.4) and (2.5) an inventory was made of equations which could prove to be useful to describe the discharge over a weir. In **table 2.1** these equations are presented by weir category by using the codes SW for sharp-crested weir, BW for broad-crested weir and GW for general weir. These categories are divided again using the authors of the formula. If an author has several formulas these are numbered in order of appearance. Not all equations presented in **table 2.1** are able to meet the requirements of this research. To be useful an equation must meet the following demands:

1. It must be able to act as an imperfect weir.
2. It must be possible to change the height of the weir in the equation.
3. The equation must be complete. All coefficients must be known, if need be by way of a relation with for example the water depth.

Based on these criteria a pre-selection of weir equations can be made. This is presented in **table 2.1**. If an equation scores a "no" in a single category it is excluded from further investigation. As can be seen in **table 2.1** there are still 8 equations left that can be used to describe the discharge over an imperfect weir. With the help of some tests this number is likely to be reduced even further until a few equations that are useful to model a groyne are left.

Table 2.1; pre-selection of weir discharge equations.

Weir type	**Formula nr**	**Code**	**criteria**			**Remarks**
			1	2	3	
BW	**5**	**CAR**	yes	yes	yes	
SW	15		no	yes	yes	not suitable for imperfect conditions, not tested with for example Villemont
	16	**VIL**	yes	yes	yes	
	17	**ABOU**	no	yes	yes	
	19		no	yes	yes	not able to describe imperfect situations with a h_2/h_3 ratio above 0,95
	21	**RAJ**	yes	yes	yes	
GW	22		no	yes	no	crest length is not known, see 15
	23		no	yes	no	crest lenght is not known, see 15
	25	**RYN**	yes	yes	yes	
	27	**MOS**	yes	yes	yes	
	28	**SOB**	yes	yes	yes	
	30	**WAQ**	yes	yes	yes	

3 Schematization of groynes as obstacles in the flow

In this chapter the groynes will be viewed upon as an obstacle in the flow. This is done by using a momentum balance. First a perfect situation is observed. This is followed by an imperfect situation. The chapter will end with a description of an experimental investigation of Yossef (2004). This is done because it is a new approach which works a bit different than the other groyne models.

3.1 Obstacle in the perfect situation

With a perfect situation exactly the same is meant as in chapter two. If the obstacle is long enough parallel flow occurs on top of it. This means the pressure distribution on top of the obstacle is hydrostatic. Therefore the momentum balance in the situation of a broad-crested weir will look as figure (3.1).The pressure distribution at the downstream end of the obstacle is hydrostatic so the force acted out on the water by the obstacle can be calculated using the hydrostatic distribution. In this case the word ‘obstacle’ can still be replaced by for instance ‘weir’. Although figure (3.1) looks a lot like figure (2.4) it is not the same. In figure (2.4) the momentum balance is taken from downstream of the weir to the weir, and in figure (3.1) from upstream of the weir to the weir.

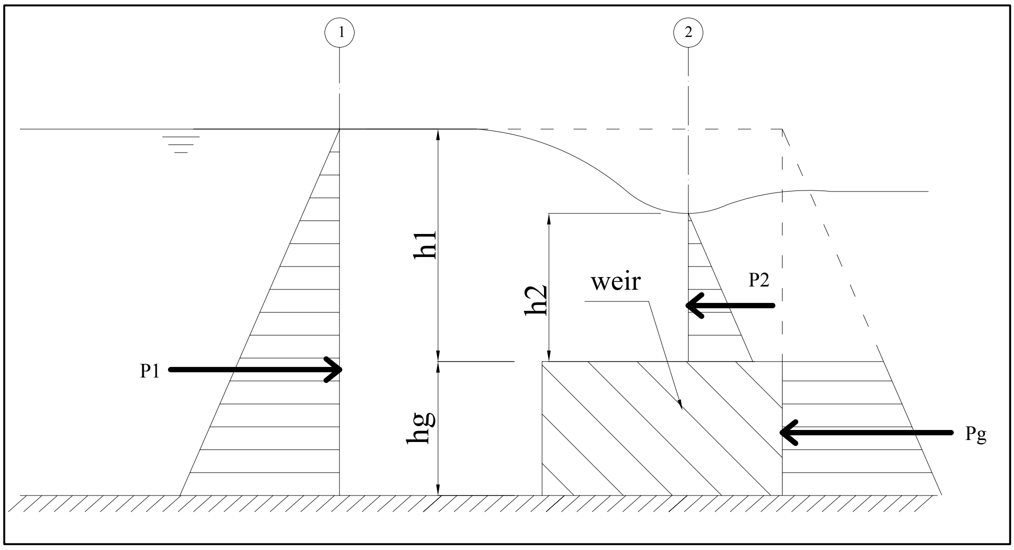

Figure 3.1; momentum balance for a broad-crested weir (Ven Te Chow, 1959)

As seen in figure 3.1 the flow over an obstacle is influenced by several forces. Because the distance over which the balance is situated is short, the friction forces are very low and can be neglected. This leads to this momentum equation (V.T. Chow, 1959):

$$\frac{q\rho}{g}\left(\frac{q}{h_2}-\frac{q}{h_1}\right)=P_1-P_2-P_g \quad \text{(kg/m)} \qquad \textbf{(31)}$$

With:

$$P_1 = \frac{1}{2}\rho(h_1 + h_g)^2 \qquad \text{(kg/m)} \tag{32}$$

$$P_2 = \frac{1}{2}\rho h_2^2 \qquad \text{(kg/m)} \tag{33}$$

$$P_g = \frac{1}{2}\rho(h_g + h_1)^2 - \frac{1}{2}\rho h_1^2 = \frac{1}{2}\rho h_g(2h_1 + h_g) \qquad \text{(kg/m)} \tag{34}$$

As this momentum balance is from upstream of the obstacle to on top of the obstacle this momentum balance is only useful to describe a perfect situation. This has to do with the fact that an imperfect situation is influenced by the downstream water level as well and in this balance no force downstream of the obstacle is taken into account.

To be able to use the before mentioned momentum balance effectively a relation between h_1 and h_2 needs to be established, otherwise it is possible to find several solutions for h_1 and h_2 for any arbitrary discharge. In Ven Te Chow (1959) for instance this is done by assuming $2h_2 = h_1$. With the help of figure (3.1) and this assumption a discharge equation for a perfect weir is derived in Ven Te Chow (1959):

$$q = 0.433\sqrt{2g}\left(\frac{h_1 + h_g}{h_1 + 2h_g}\right)^{1/2} h_1^{3/2} \ \text{(m}^2\text{/s)} \tag{35}$$

This value for h_2 is based on experiments by Doeringsfeld and Barker (1941) and is an average.

3.2 Obstacle in the imperfect situation

In section 3.1 the discharge over a perfect broad-crested weir is described using the momentum balance. To be useful for an imperfect weir however the balance must go from upstream of the weir to downstream of the weir. Doing so gives a balance which is almost similar to figure (3.1). To make things easier this time the slope is neglected. This means there are no losses due to skin friction. This momentum balance is based on theory, but *not found in this form in the literature* and thus as far as is known not previously used to model a groyne.

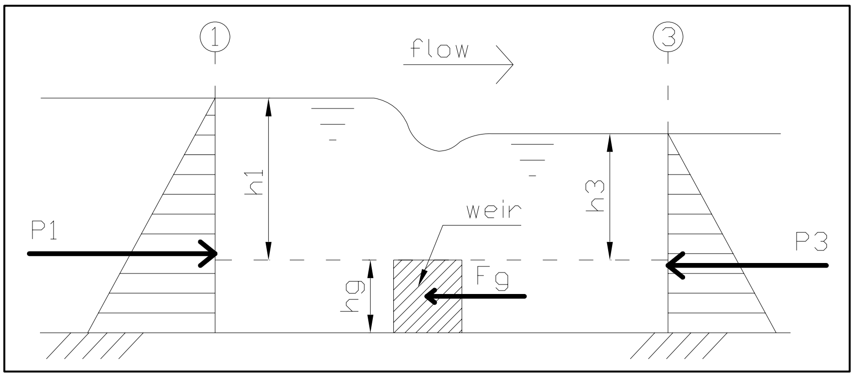

Figure 3.2; Momentum balance over a weir

This leads to the following momentum balance as illustrated in figure (3.4):

$$\frac{Q\rho}{g}\left(u_3 - u_1\right) = P_1 - P_3 - F_g \quad \text{(kg)} \tag{36}$$

With:

$$P_1 = \frac{1}{2}\rho \cdot B \cdot \left(h_1 + h_g\right)^2 \text{ (kg)} \tag{37}$$

$$P_3 = \frac{1}{2}\rho \cdot B \cdot \left(h_3 + h_g\right)^2 \text{ (kg)} \tag{38}$$

$$F_g = \frac{1}{2}\rho \cdot C_D A_g u_{hg}^2 \quad \text{(kg)} \tag{39}$$

$$A_g = h_g \cdot B \text{ (m}^2\text{)} \tag{40}$$

The force exerted by the weir on the water F_g is symbolized as an arrow because the water pressure distribution is not hydrostatic. A_g is the area of the weir perpendicular to the flow. C_D is the drag coefficient. The value of the drag coefficient depends on the shape of the object in the flow. In the case of a weir, which can be considered as a plate perpendicular to the flow, the drag coefficient has a minimum value of 1.05 and a maximum of 2.05 (Fox & McDonald, 1998). The value is dependent on the width of the plate "b" and the length of the plate "h" as illustrated in figure (3.3).

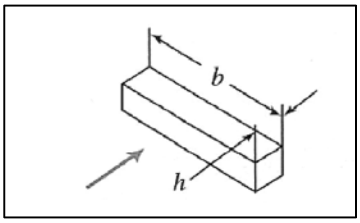

Figure 3.3; plate in the flow (Fox & McDonald, 1998)

Under the assumption that the resistance of a groyne to the flow is low a value of 1.05 for the C_D is used. The flow velocity u_{hg} is the average velocity of the flow at the same height of the obstacle. This is because the velocity at the height of the obstacle will be lower than the depth average velocity. This results in a lower drag force F_g.

3.3 Experimental investigation by Yossef (2004)

In this section the method developed by Yossef is described. This method also considers the groyne to be an obstacle in the flow. The main difference with the previous model is that this method is based on the results of an experiment done with a 1:40 physical model of the river Waal. During this experiment the velocity and the water height were measured. In this section a description is given of the setup of the experiment and the way the results are measured.

3.3.1 The setup

The experiment was done in the laboratory for Fluid Mechanics of Delft University of Technology (Yossef, 2005). The model has a length of 30 meters and is 5.0 meters wide. In this model five groynes were placed with a spacing of 4.5 meters. The test was done with a typical river Waal groyne. The groyne has a length of two meters, which means the width of the main channel is three meters. This is illustrated in figure (3.4). For this test case the Froude number was small enough to ensure subcritical flow conditions. During the test the Reynolds number was high enough to ensure a fully developed turbulent flow. With the help of separate tests done on the main channel the Nikuradse roughness k_s coefficient of the main channel was estimated to be $6.27 \cdot 10^{-4}$ m. The velocity was measured 2.25 meter upstream of the groyne to ensure that the groyne did not affect the velocity profile. The velocity was measured at 12 lateral points at mid-depth. All test cases were chosen to guarantee submerged flow conditions.

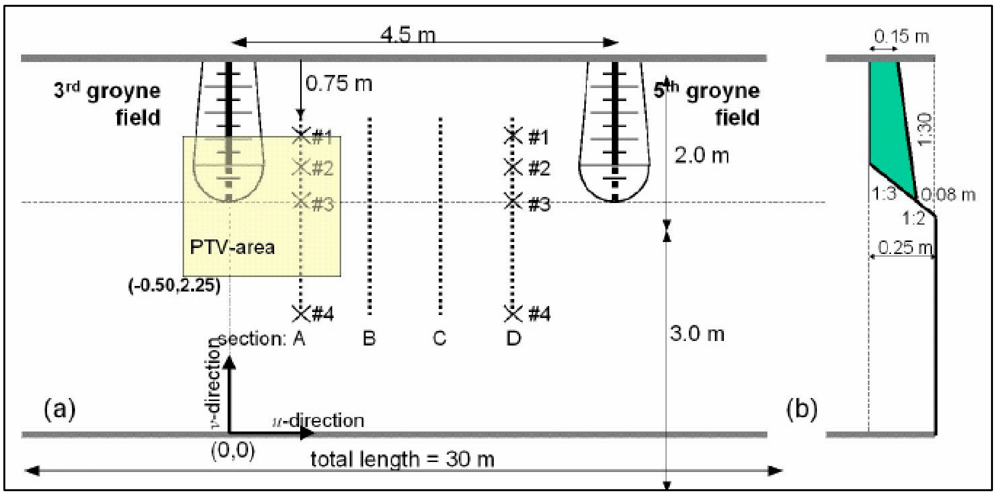

Figure 3.4; set-up experiment (Yossef, 2004)

3.3.2 Test procedure

All tests presented in the article were chosen to guarantee submerged flow conditions. The downstream tailgate was adjusted to a certain level. By keeping the tailgate elevation constant and varying the discharge it was possible to vary the water height and slope thereby creating different hydraulic conditions. To describe the hydraulic conditions the Froude number F_r from the main channel is used:

$$F_r = u_{mc} \sqrt{g \cdot h_{mc}} \qquad \textbf{(41)}$$

With:
g = acceleration due to gravity (m/s^2)
h_{mc} = water depth in the main channel (m)
u_{mc} = water velocity in the main channel (m)

After that the tailgate was set to a different elevation and the process was repeated. This means four sets of measurements are done with the same type of groyne or groynefield.

3.3.3 Groynes as a submerged weir

Although Yossef does describe a weir equation (Mosselman & Struiksma, 1992) briefly he decided to approach the groyne as roughness element. With the weir equation it seemed not possible to have such a high discharge over a weir with the hydraulic conditions as found in the tests. However, in the recommendations of his thesis he does stress he has not investigated possible other weir discharge relations.

3.3.4 Groynes as a roughness element

In Yossef's approach the groyne is seen as roughness element and the resistance of the groyne field consists of the resistance of the bed between the groynes and the resistance due to the groynes. The formulation of the groyne resistance has the form of a drag resistance. This term is the same as F_g **(39)** in the section 3.2, but this time F_g is expressed as force per unit bed area and divided by ρ. This leads to the following force balance:

$$\underbrace{g \cdot h_t \cdot i}_{groynes\ region} = \underbrace{\frac{g}{C_{base}^2} u_{gr}^2}_{bed} + \underbrace{\frac{1}{2} C_D \left(\frac{h_g}{S} \right) u_{gr}^2}_{groyne} \qquad \textbf{(42)}$$

With:

i = water surface slope

h_t = the water depth in the groyne field= $h_1 + h_g$ (m)

C_{base} = base Chézy-coefficient in the main channel ($m^{1/2}/s$)

u_{gr} = velocity in the groynes region away from the mixing layer (m/s)

h_g = the groyne height (m)

S = the spacing between two groynes (m)

C_D = a representative drag coefficient for the groynes

The Chézy coefficient representing the total resistance of the groynes region can be written as:

$$C_{effective} = \sqrt{\frac{1}{\frac{1}{C_{base}^2} + \frac{1}{2g} C_D \left(\frac{h_g}{S} \right)}} \qquad (m^{1/2}/s) \qquad \textbf{(43)}$$

The discharge coefficient can be calculated by using this formula (Yossef, 2005):

$$\frac{C_D}{F_r^2} = a \left(\frac{h_g}{h_t} \right)^b \qquad \textbf{(44)}$$

With:

F_r = Froude number of the main channel

Yossef (2005) based this expression on result of experiments. The assumption is made that the blockage ratio (h_g/h_t) has a relation with the hydraulic conditions of the main channel. The hydraulic conditions of the main channel is expressed in the Froude number. Calibration with the help of the results of the experiments showed that for a good result "a" should have a value of 76.4 and "b" a value of 3.7. In this formula the total water depth h_t and the groyne height h_g are measured relative to the bottom of the groyne field.

3.4 Pre-selection of equations to model groynes

The pre-selection is done using the same criteria as in the chapter 2. These criteria are:

4. The equation must be able to handle submerged situations.
5. The equation must allow changes to the height of the obstacle
6. The equation must be complete. All coefficients must be known, if needed by way of a relation with for example the water depth.

Only two equations, namely formula "the momentum-Balance" **(36)** and Yossef **(42)** came up in this chapter and they both are able to meet the demands.

4. 1D-model for flow in a channel with groynes

The groyne equations that are used in this chapter to represent a groyne will not behave in exactly the same way. In this chapter the groyne equations will be tested on their behavior. The equations have to meet the following requirements:

- The effect of the groynes on the water depth of the equation has to approach zero when the groyne height approaches zero.
- The effect on the water depth of the equation has to reduce when the groyne spacing increases.

The chapter begins in section 4.1 with an overview of the formulas that were selected in chapter two and three and the set-up of the tests in section 4.2. This is followed by three steps to make the effects of the equations visible. This, in turn, makes it possible to decide which groyne equations are able to model a groyne field. The three taken steps are:

1. In section 4.3 a single groyne over the full width of the sloping channel is considered. This means it acts basically as a weir. By varying the discharge and the groyne height it is possible to analyze if the equation responds in the way it is expected to.

2. In section 4.4 the sloping channel is assumed to have infinite length. This channel has series of groynes over the full width of the sloping channel with a constant spacing between those groynes. This is a representation of a groyne field. By varying the groyne spacing it is possible to see the effect of the groyne spacing on the water level. Varying the discharge will give an idea of the water level rise due to the groyne field.

3. In section 4.5 the groyne field from the previous step is combined with a main channel and thus representing a river with groyne field. Yossef also based his groyne equation on the compound channel. This step makes it possible to compare the groyne equation developed by Yossef to the other equations.

More information of the set-up of the 1D hydraulic model can be found in Appendix C in which a flow chart is shown of the model and a calculation example.

4.1 Overview of equations to represent groynes

In the previous chapter equations were selected to represent a groyne or groyne field. Although these equations seem all to be q-h relations, they are actually used the other way around. Based on a discharge, a water depth is calculated. The equations used in this chapter are listed below and categorized by type of groyne equation. More information about the weir equations can be found in chapter two. More information about the obstacle equations is available in chapter three. The code before every groyne equation is used in the tables and graphs in this chapter.

Broad-crested weir:

CAR: $P_2 - P_3 = \rho \cdot u_3^2 \cdot (h_3 + h_g) - \rho \cdot u_2^2 \cdot h_2$ (m^2/s) **(5)**

Sharp-crested weir:

VIL $$q = q_f \left[1 - \left(\frac{h_3}{h_1} \right)^n \right]^{0,385} \text{ (m}^2\text{/s)} \qquad \textbf{(16)}$$

ABOU: $$q = q_f \left[1 + \left(\frac{h_3}{2h_1} \right) \sqrt{1 - \frac{h_3}{h_1}} \right] \text{ (m}^2\text{/s)} \qquad \textbf{(17)}$$

RAJ: $q = 0.90 h_3 \sqrt{g(h_1 - h_3)}$ (m^2/s) **(21)**

General weir:

RYN: $q = m_d h_3 \sqrt{2g} (H_1 - h_3)^{1/2}$ (m^2/s) **(25)**

MOS: $q = m_d \cdot h_3 \cdot \sqrt{2g} (h_1 - h_3)^{1/2}$ (m^2/s) **(27)**

SOB: $q = 0.385 \cdot C_w f \sqrt{2g} (H_1 - h_g)^{3/2}$ (m^2/s) **(28)**

WAQ: $q = 0.58 \cdot m_d \cdot H_1 \sqrt{2g} (h_1 - h_3)^{1/2}$ (m^2/s) **(30)**

Obstacle:

M-B: $$\frac{Q\rho}{g}(u_3 - u_1) = P_1 - P_3 - F_g \text{ (kg)} \qquad \textbf{(36)}$$

YOS: $$ghi = \frac{g}{C_{base}^2} u_{gr}^2 + \frac{1}{2} C_D \left(\frac{h_g}{S} \right) u_{gr}^2 \text{ (m}^2\text{/s}^2\text{)} \qquad \textbf{(42)}$$

The groyne equation Yossef is only tested in step three (section 4.5) as it's working is amongst others based on the Froude number of the main channel.

4.2 Properties of the channel

The channel used in these calculations has the following properties (figure 4.1):

B_{grf} = width of the groyne field, width of the weir, 70 meters.
B_{mc} = width of the main channel, 150 meters
i_b = bottom slope, 10^{-4}
k_s = roughness height, 0.2 meters
dz = elevation difference main channel and groyne field, 2 meters
h_g = groyne height, 1 to 5 meters.

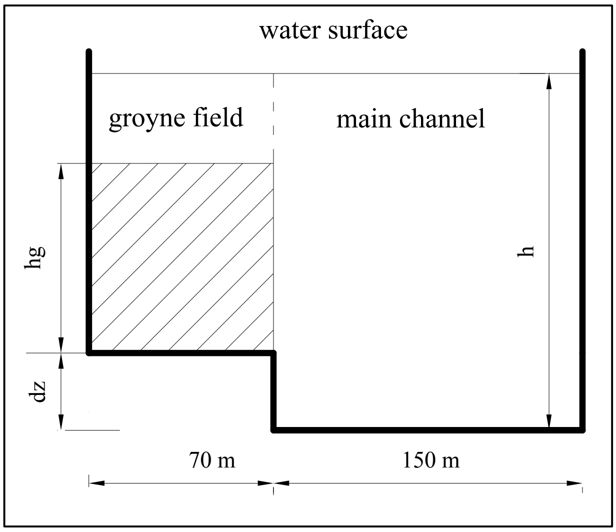

Figure 4.1; cross-section of the compound channel

4.3 A single full width groyne in a channel

For this first step a groyne over the full width (70 m) of a channel is considered. This is basically a weir as shown in figure (4.2). By varying the weir height over a range from 1 to 5 meters the influence of the weir height on the resulting water depth can be seen. This will not be the same as in a groyne field however, because only the effect of one groyne is taken into account for now.

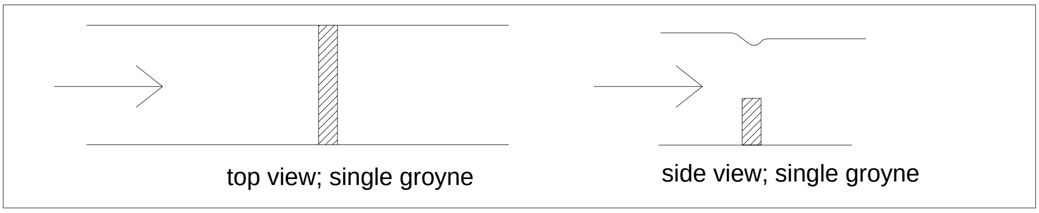

Figure 4.2; schematization full width single groyne, arrow indicate flow direction

4.3.1 Expected effect of a single groyne

The expectation is that with an increasing discharge the effect of the weir on the water depth will get smaller. This means that if the discharge gets high enough, the water depth will not differ much of the water depth from the same channel without the weir. For this reason the same calculation is done with a discharge of 1000 m^3/s and 2000 m^3/s. This should show a decreasing effect on the water level with a higher discharge.

4.3.2 Results of single groyne situation

Figure (4.3) and (4.4) show that increasing the groyne height has an increasing effect on the water depth upstream of the groyne. However this effect is relatively much smaller with a higher discharge. Although most equations stay relatively close to each other MOS falls completely out of range. SOB shows an extreme effect on the water depth and almost immediately goes off the chart. M-B seems to go to a constant value of the ratio

h/h_e which means the effect becomes linear with the water depth. The other equations show an increasing effect on the water depth.

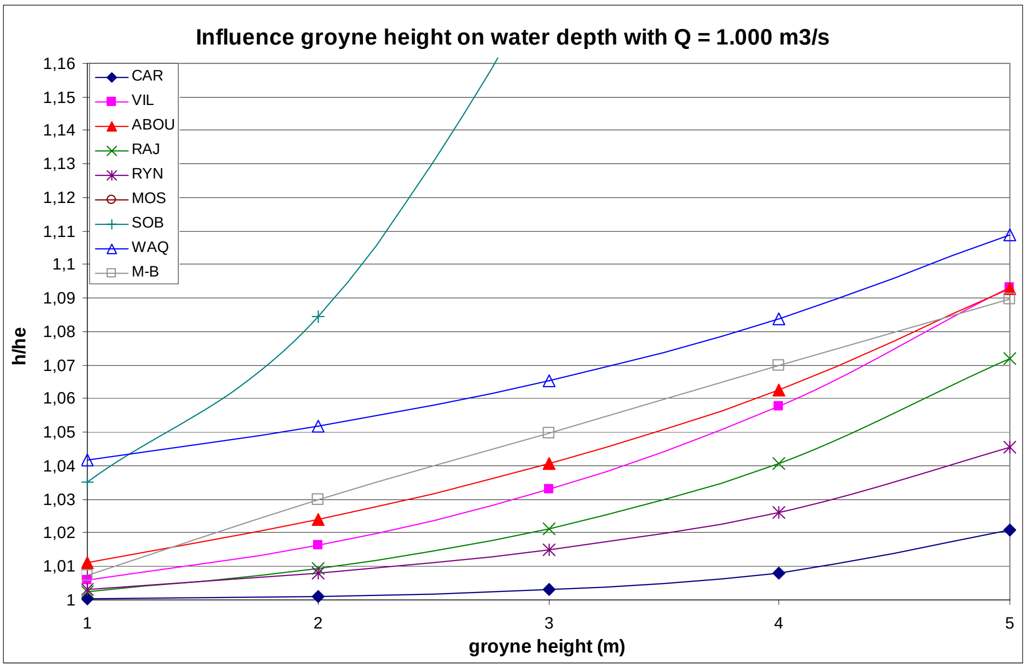

Figure 4.3; influence groyne height on water depth with Q = 1.000 m^3/s
he = equilibrium depth of a channel without groyne, 9.40 meters
h = water height relative to the bottom of the channel upstream of the groyne

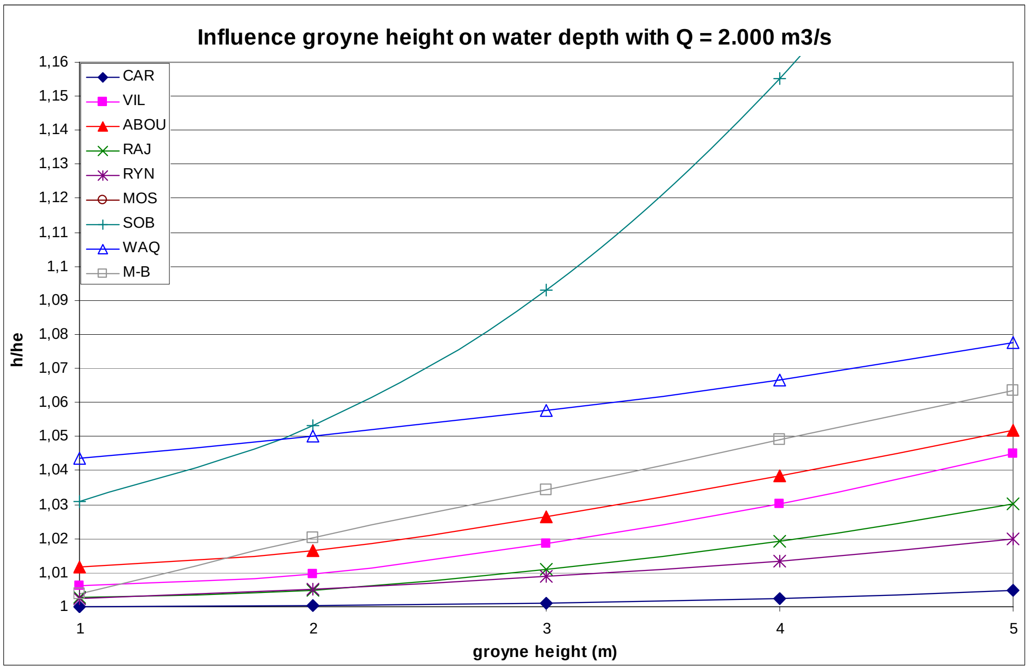

Figure 4.4; influence groyne height on water depth with Q = 2.000 M^3/s
he = equilibrium depth of the channel without groyne, 14.31 meters
h = water height relative to the bottom of the channel upstream of the groyne

Already with the first test, the groyne equations SOB, WAQ and MOS seem to disqualify themselves. SOB shows an unrealistic increase of effect on the water depth as the groyne heightincreases, MOS shows an unrealistic effect on the water level altogether and the effect on the water level from WAQ does not approach zero as the groyne height approaches zero.

4.4 Full width groynes in a channel with infinite length

If the groyne field and the main channel are considered two separate channels, the groyne field can be modeled as a channel with an infinite length and groynes with a constant distance between them (figure 4.5). The infinite channel with a constant cross-section and constant weir spacing will lead to uniform water level. This means that the bottom slope is the same as the water surface slope. Using this slope it is possible to calculate the water depth in the groyne field given a certain discharge through the groyne field. This section starts with an explanation of the way the slope in the groyne field can be used to calculate the water depth. This is followed by tests to see the influence of the groyne height and the groyne spacing on the outcome of the groyne equations. This is done with a groyne field width of 70 meters.

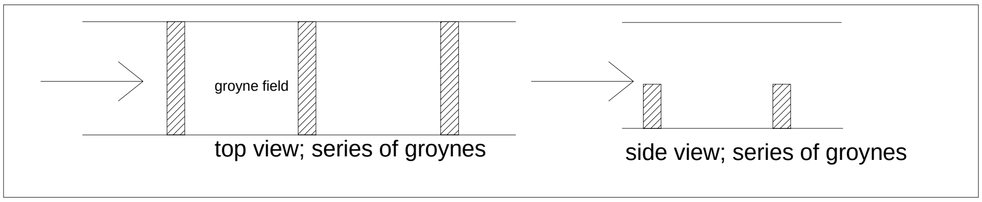

Figure 4.5; schematization series of groynes, arrow indicate flow direction

4.4.1 Using the slope to calculate the water depth

The water surface slope in the groyne field is influenced by two roughness elements:

1. the roughness of the bottom
2. the weir/groyne

The slope caused by the combination of these two roughness elements must be equal to the bottom slope to guarantee uniform flow conditions (see also figure 4.4):

$$i_{water} = i_{br} + i_{gr} = i_{bottom} \quad \textbf{(45)}$$

With:

i_{bottom} = bottom slope
i_{water} = water surface slope
i_{br} = part of the slope caused by the bottom roughness
i_{gr} = part of the slope caused by the groyne

The calculation of the part of the slope caused by the groyne can be calculated realizing:

$$\Delta H = i_{gr} \cdot S \text{ (m)} \quad \textbf{(46)}$$

With:

ΔH = energy loss caused by the groyne (m)
S = spacing between the groynes (m)

This can be rewritten as:

$$\frac{\Delta H}{S} = \frac{u^2}{C_g^2 \cdot h} \qquad \textbf{(47)}$$

With:

C_g = representative Chezy roughness of the groyne ($m^{1/2}/s$)

h = mean water depth in the groyne field (m)

u = flow velocity in the groyne field (m/s)

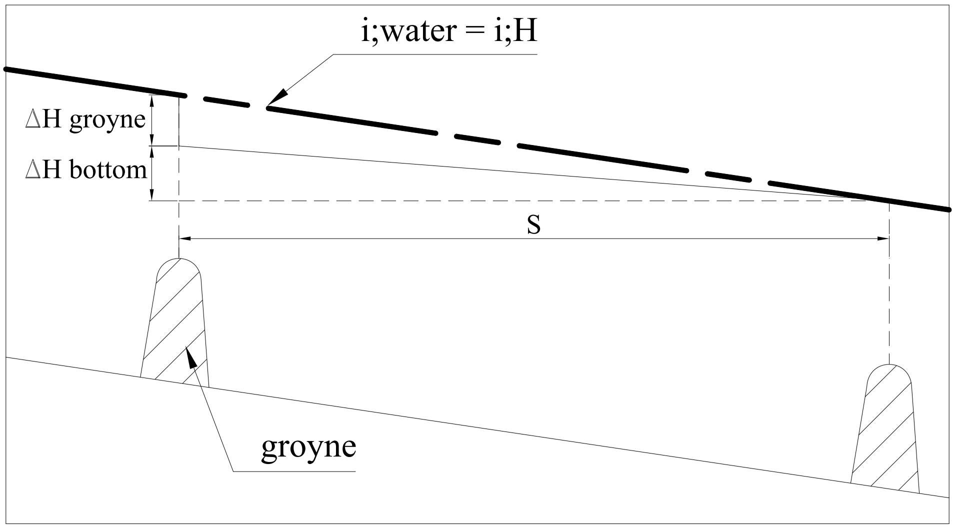

Figure 4.6; slope caused by two roughness elements

The part of the slope caused by the bottom roughness can be calculated using the water depth. This makes it also possible to make an expression for the total roughness of the groyne field expressed as a Chezy coefficient (Appendix A, B). The water surface slope can be calculated using:

$$i = \frac{u^2}{h \cdot C_{tot}^2} \qquad \textbf{(48)}$$

C_{tot} = total Chezy roughness ($m^{1/2}/s$)

If formulas **(47)** and **(48)** are combined, this leads to:

$$i_{water} = i_{gr} + i_{br} = \frac{u^2}{h \cdot C_g^2} + \frac{u^2}{h \cdot C_b^2} = \frac{u^2}{h \cdot C_{tot}^2} \qquad \textbf{(49)}$$

With:

C_b = Chezy roughness of the bottom between the groynes ($m^{1/2}/s$)

With this formula it is now possible to calculate the slope of the water with a certain water height and discharge in the groyne field and vice versa. The energy loss by the groyne can be obtained by using the calculated value for the water depth directly upstream and downstream of the groyne (see Appendix A).

4.4.2 Expected effect of groynes in serie

Just as in section 4.3 the effect of the groynes should decrease as the groyne height decreases. This has to do with the water depth compared to the groyne height and the resulting lesser effect on the top parts of the flow.

The influence of the groyne should decrease as the groyne spacing increases. This is because with an increasing groyne spacing the flow is relatively more influenced by the bottom roughness. This results in a smaller water depth.

4.4.3 Results of groynes in a channel of infinite length

Figure (4.11) shows the increase of water depth due to the groynes (h) compared to the same channel without groynes (h_e). This means that a value of 1.0 stands for a water depth equal to the situation without groynes. The majority of the groyne equations approach a constant relative value of the equilibrium water depth. Strangely enough RAJ and WAQ show a steep increase of water depth and to a smaller extent M-B as well. SOB is not on the chart at all as this groyne equation is not able to calculate a water depth with the given discharges. The behavior of the lines near the 200 m^3/s can be explained by the fact that with this discharge the groyne is on the edge of being perfect/imperfect.

In section 4.3 figure (4.3) and (4.4) showed an effect of the groyne height on the water depth of 0% to 11%. However, this effect on the water depth is nothing compared to the effect of the groyne height on the water depth shown in figure (4.7) and (4.8) of 0% to 300% or more. In both figures the groyne height has a large increasing effect on the water depth for most equations. Especially RAJ has a large effect on the water depth. With a discharge of 2000 m^3/s it is even more than 5 times the equilibrium depth. Also it does not approach the equilibrium depth with a decreasing groyne height. Apart from MOS and RAJ all the other equations do approach the equilibrium depth.

In figure (4.9) and (4.10) the effect of the groyne spacing on the water height is shown. This effect has the same trend for every equation. The trend is dominated by the manner the water depth is calculated based on the slope (47). The only difference is the scale. This scale is decided by the groyne equation. The result is that according to CAR with a groyne spacing of more than 400 meters the groyne has an almost negligible effect on the water depth. However, according to RAJ for a groyne to have no effect on the water depth the groyne spacing must get much larger. With a higher discharge the water depth decreases less with increasing groyne spacing. In the case of MOS and RAJ there is even an increase of the effect of groynes with an increase of the discharge.

Based on the results of this section it has become clear that RAJ, WAQ, MOS and SOB are not able to model the decrease of the groyne height in a groyne field correctly. SOB is not even able to handle most discharges and is impossible to use. Furthermore there are some doubts about the way M-B responds to the changing of the groyne height.

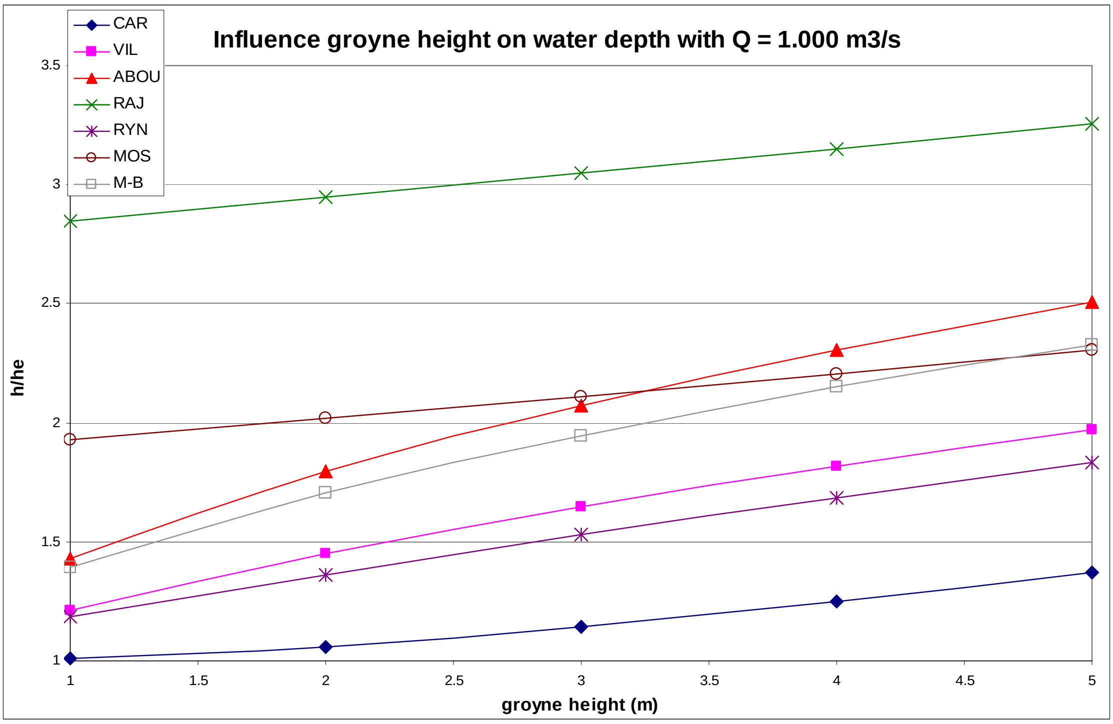

Figure 4.7; the effect of the groyne height on the water depth
S = 400 meters, Q = 1000 m^3/s, h = water depth upstream of the groyne, h_e = 9.40 m

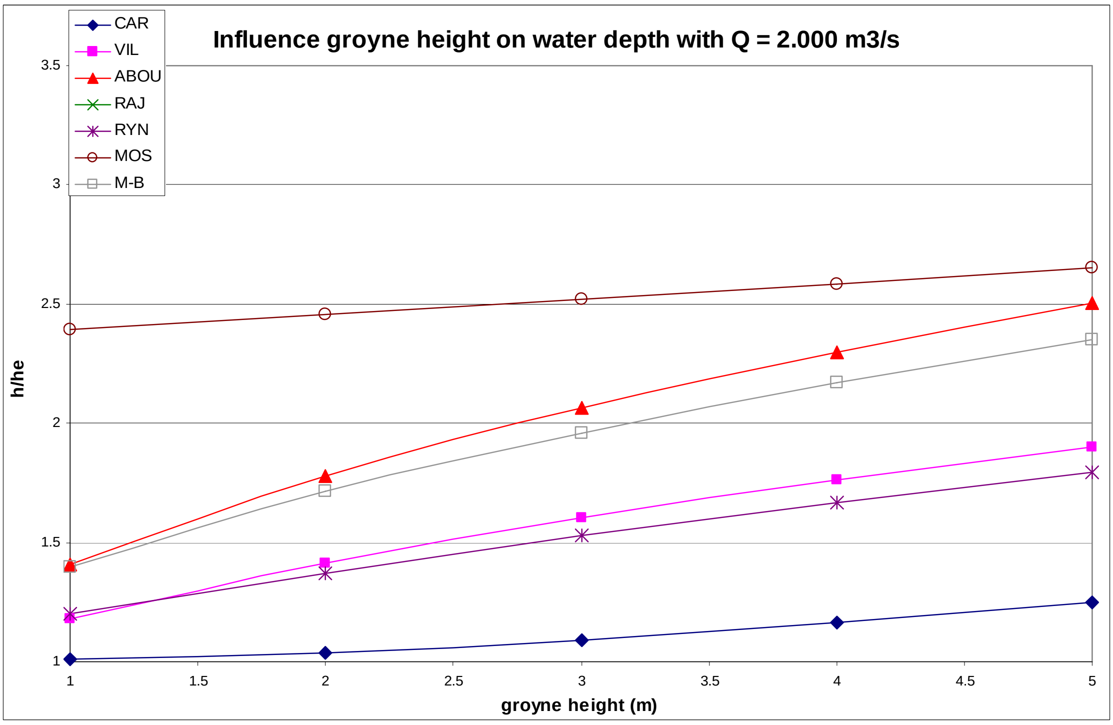

Figure 4.8; effect of the groyne height on the water depth
S = 400 meters, Q = 2000 m^3/s, h = water depth upstream of the groyne, h_e = 14.31 m

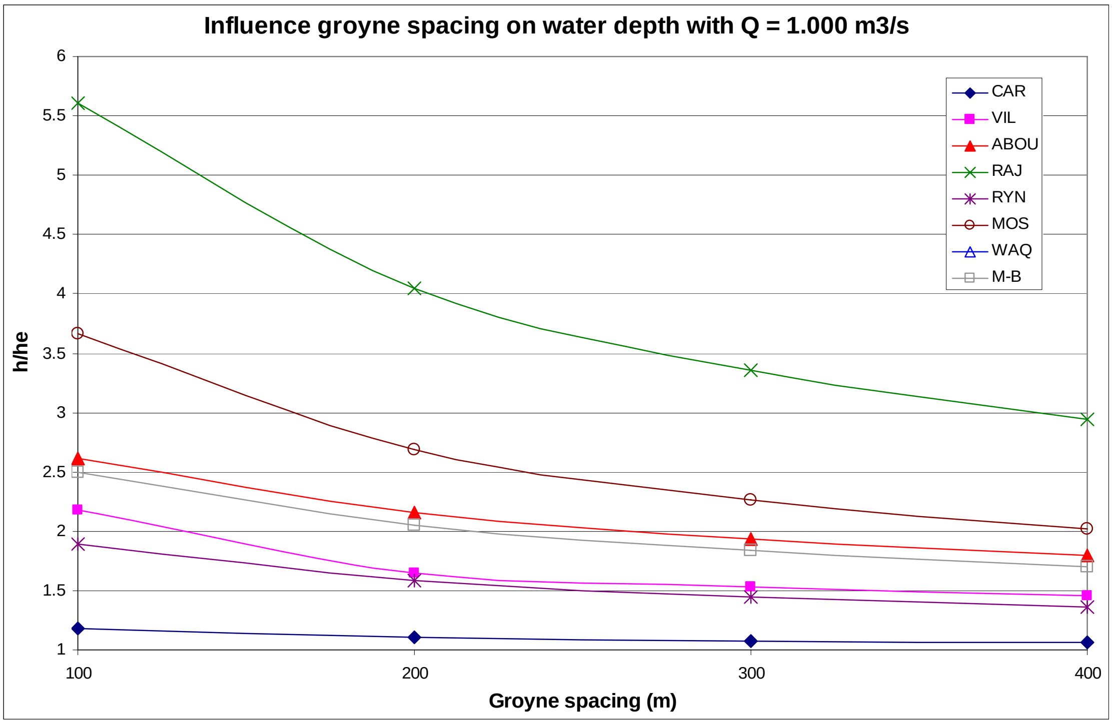

Figure 4.9; water depth with different groyne spacings
Q = 1.000 m3/s, h_g = 2.0 m, h_e = 9.40 m

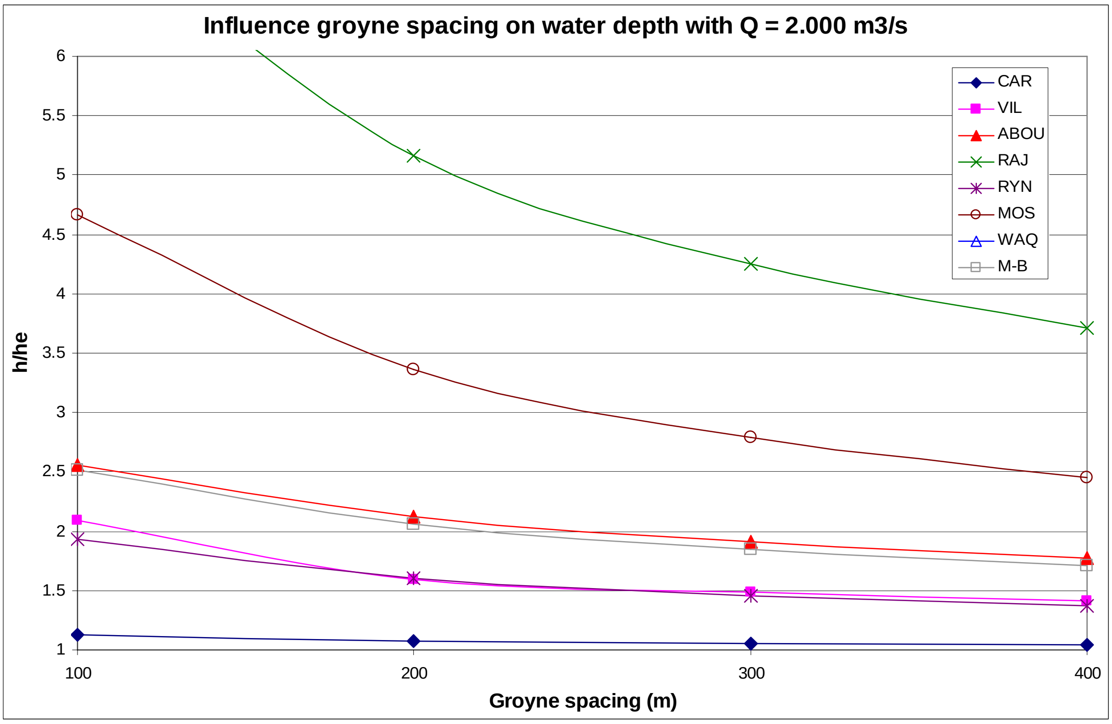

Figure 4.10; water depth with different groyne spacings
Q = 2.000 m3/s, h_g = 2.0 m, h_e = 14.31 m

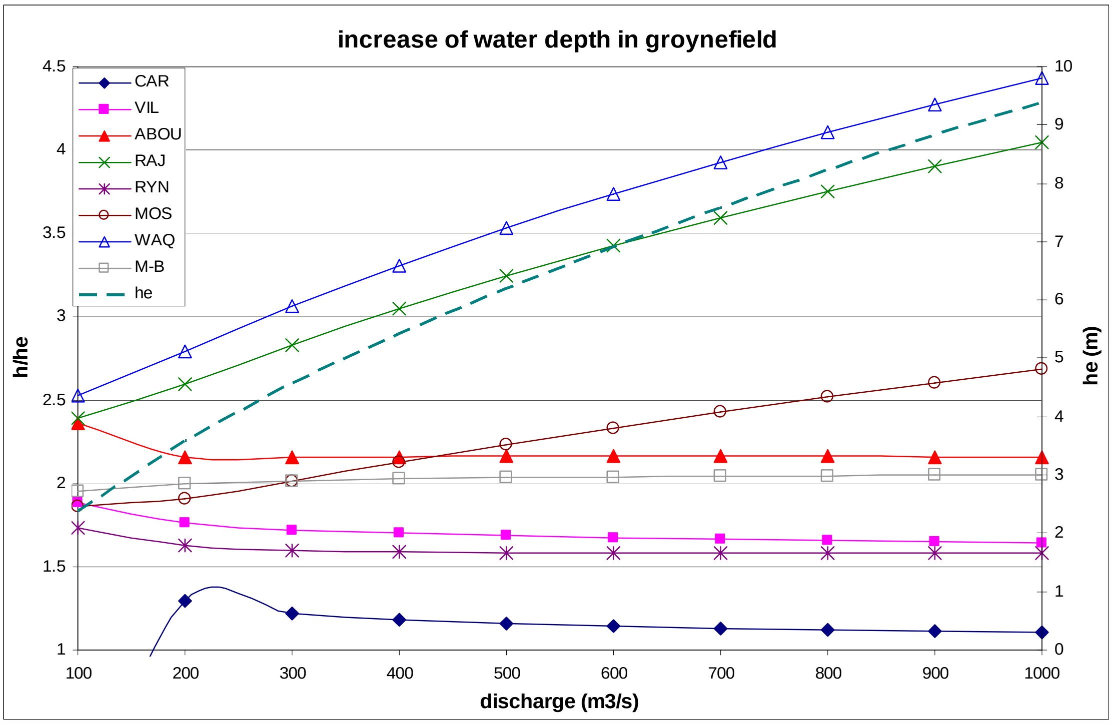

Figure 4.11; discharge through the groyne field, $h_g = 2.0$ m, S = 400 m
h_e = equilibrium depth of the channel without groynes
h = water depth relative to the bottom of the channel

4.5 The compound channel

In order to get a view of the way the groyne equation made by Yossef (YOS) behaves the groyne equations are also tested in a compound channel (figure 4.12). Because the groyne field and the main channel are treated as separate channels a river with groyne fields can be modeled by just adding the discharge of the two channels together:

$$Q_{river} = Q_{mc} + Q_{grf} \quad (\mathrm{m}^3/\mathrm{s}) \qquad \textbf{(50)}$$

With:
Q_{river} = discharge of the total channel (m^3/s)
Q_{mc} = discharge of the main channel (m^3/s)
Q_{grf} = discharge of the groyne field (m^3/s)

This can be done by assuming the same water slope and water level in both channels. Of course this can also be done with multiple channels for instance to model a river with groyne fields and floodplains like the river Waal or Elbe. In order to see if the method of Yossef differs much of the other equations, calculations are done with a compound channel consisting of a groyne field and a main channel (figure 4.1).

To determine a realistic reference situation for the compound channel a Q-h_e relation (figure 4.13) of the cross-section is plotted. This figure represents the relation between the water depth in a situation without groynes and the discharge. Based on this relation a maximum and a minimum discharge are chosen. The water depth of the river Waal is about 16 meters with a maximum discharge (Veen, Pakes and Schutte, 2002). The discharge that corresponds with this water depth will be the maximum discharge. The minimum discharge is based on the top of the groyne crest which is 7 meters above the bottom of the main channel. As a consequence Q_{max} has a value of 7000 m^3/s and Q_{min} of 1800 m^3/s. These discharges will lead to a higher water depth in a situation with groynes then the mentioned 7 and 16 meters, but they will give a good view of the effects of the different groyne equations.

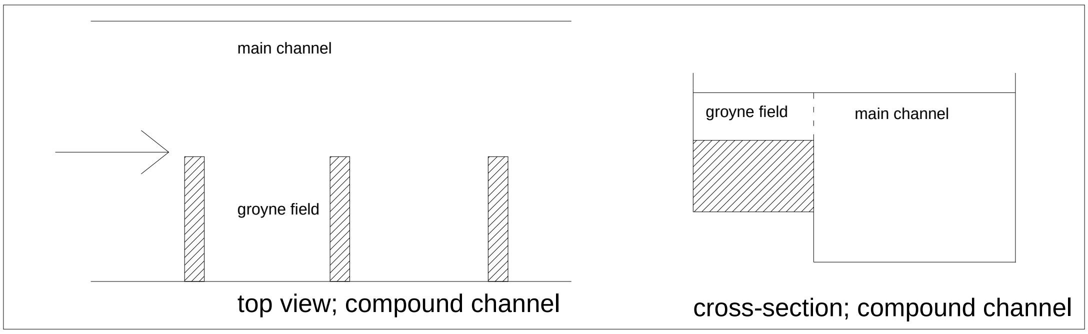

figure 4.12; schematization compound channel, arrow indicates flow direction

4.5.1 Expected effects of the groyne equations in the compound channel

The effect of the groynes on the water depth itself will be smaller overall compared to the previous section when increasing the groyne field width, groyne spacing or groyne height, because the discharge will now be distributed over a wider channel.

4.5.2 Results of the groyne equations in the compound channel

The effect of groynes on the water depth with an increasing discharge as seen in figure (4.11) is the same as seen in figure (4.14). However, the scale is completely different. The resulting water depth increase is dampened by the main channel. Figure (4.11) shows that the groyne field alone leads to a water depth of 1 to 4 times the equilibrium depth. In the compound channel this leads to a water height of only 1 to less than 1.2 times the equilibrium depth. Although it is not exactly the same discharge, the difference is large enough to be sure of a large dampening effect by the main channel on the effect on the water depth by the groynes.

According to the groyne equation YOS the groynes have little to no influence on the water depth. Not even with a relatively small discharge. All groyne equation do seem to approach to a constant relative value of the equilibrium depth. However, the groyne equations (RAJ, WAQ, M-B, RYN, ABOU) have a relative smaller effect on the water depth with low discharges then with high discharges, while the groyne equations (VIL, YOS, CAR) show the opposite effect.

The effect of the groyne spacing on the water depth is smaller as well due to the including of the main channel. This is illustrated in figure (4.15). Although the effect is still visible, it is much smaller than as shown in figure (4.9) and (4.10). According to the groyne equation YOS, changes made to the groyne spacing have a very small effect on the water depth.

The effect on the water depth from the majority of the groyne equations approaches the equilibrium depth as the groyne height approaches zero meters (figure 4.16). The two equations in top of the chart, WAQ and RAJ, stay above the equilibrium depth. This is even more evident with a higher discharge (figure 4.17). Although no limitations with respect to the ratio of the water depth upstream and downstream of the groyne is known, in reality WAQ and RAJ do not seem to respond well when this ratio approaches one. With a high discharge the effect of the groyne height on the water depth is relatively smaller then with a low discharge. With a high discharge YOS shows barely any effect of the groyne on the water depth.

Based on the results presented in this section no more further equations are eliminated. However, there are some doubts about the groyne equation YOS as the groynes seem to barely have an effect on the water depth with high discharges according to this groyne equation.

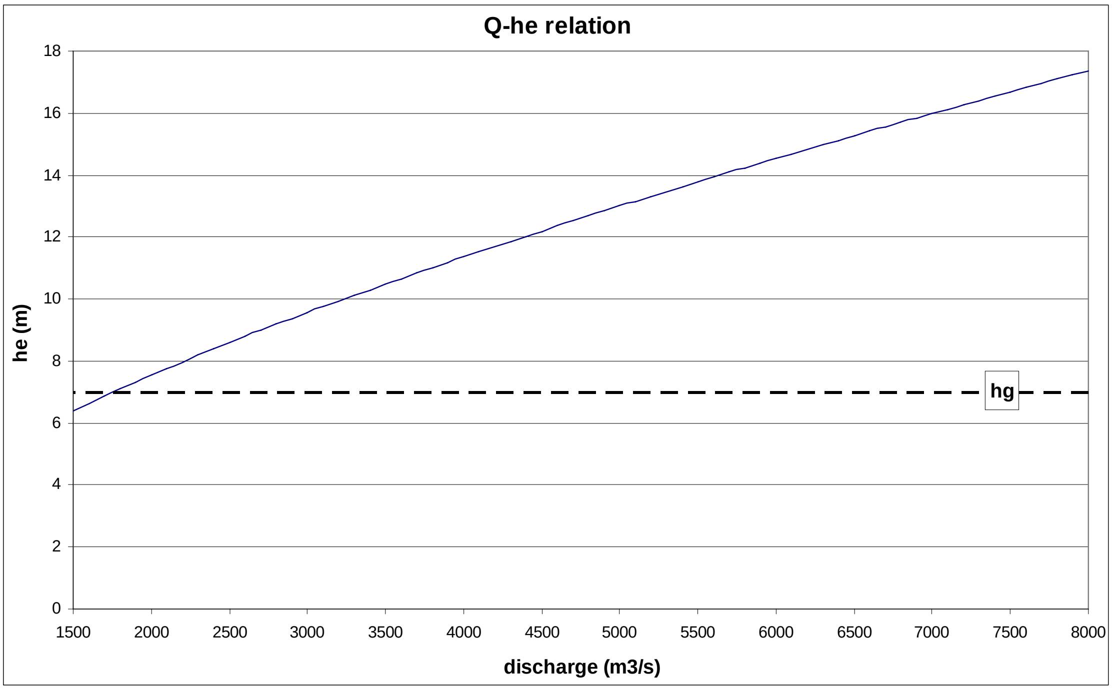

Figure 4.13; equilibrium depth of the compound channel, h_g = 0 m

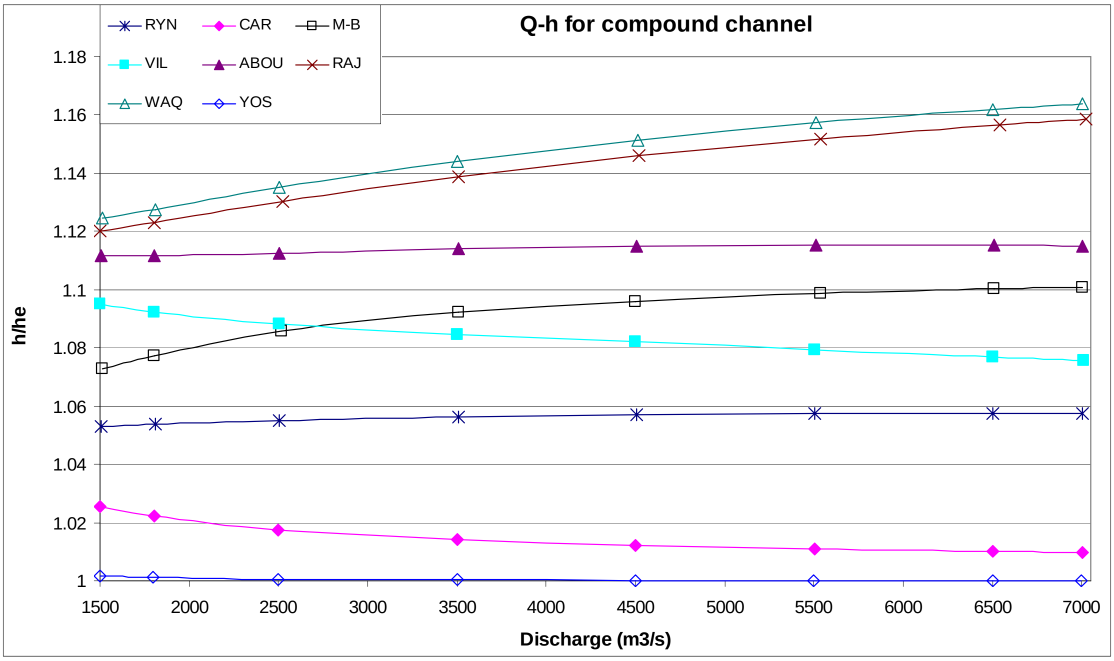

Figure 4.14; Q-h relation for a compound channel, S = 400 m, h_g = 2 m, he = equilibrium depth

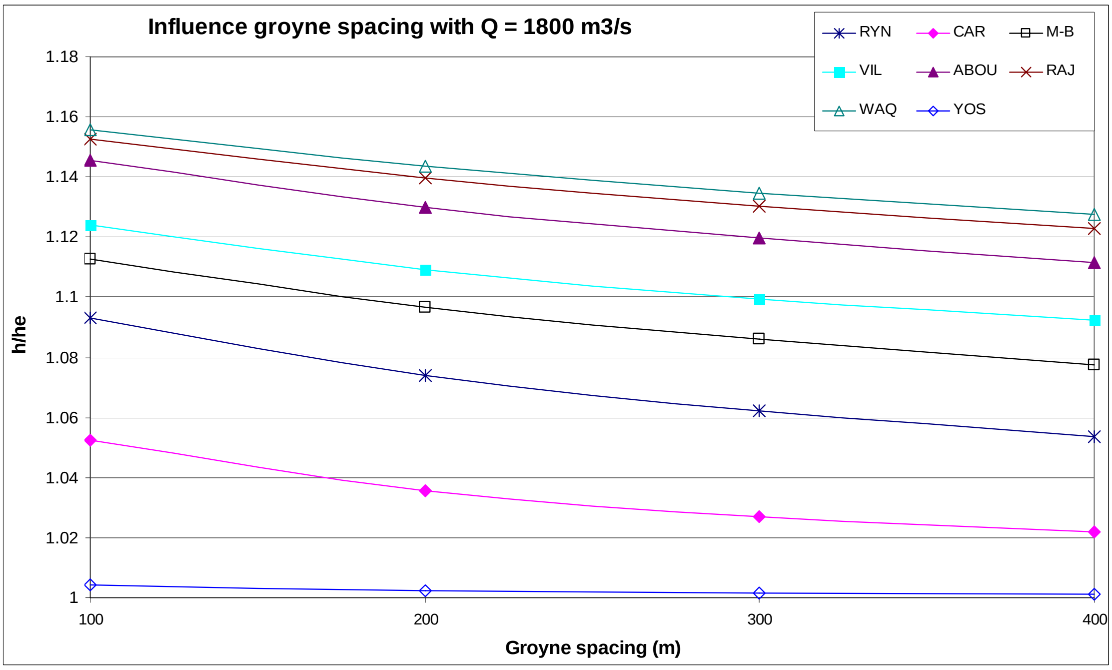

Figure 4.15; Influence groyne spacing on the water depth with a low discharge
h_g = 2 m, h_e = 7.10 m

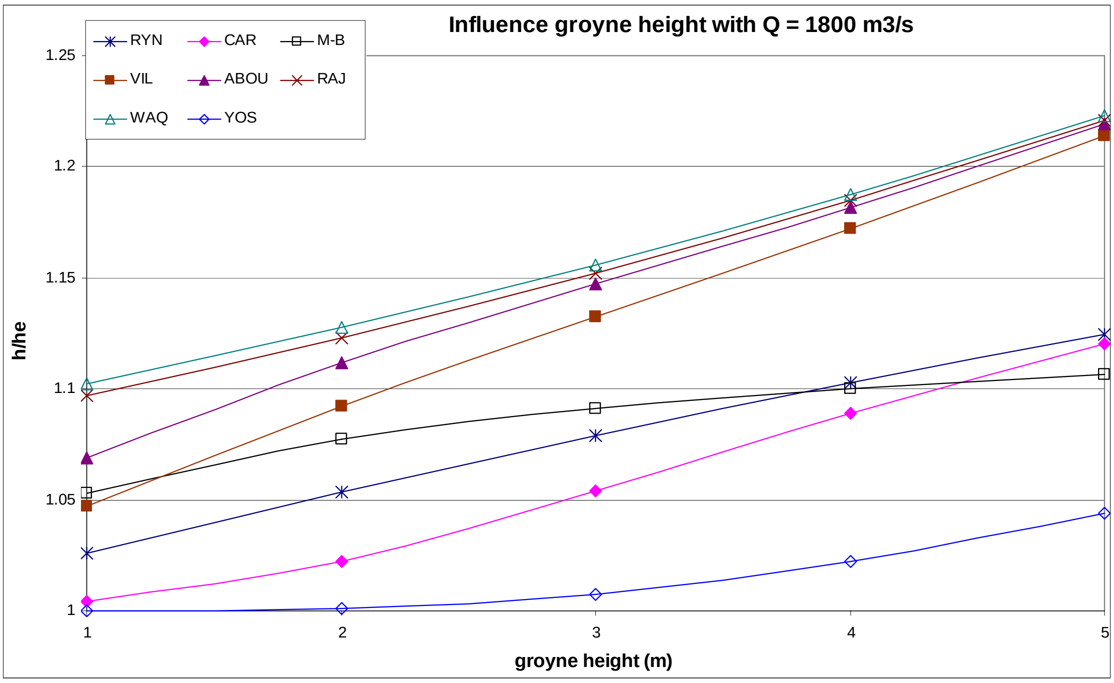

Figure 4.16; influence groyne height on the water depth with a low discharge
S = 400 meters, h_e = 7.10 m

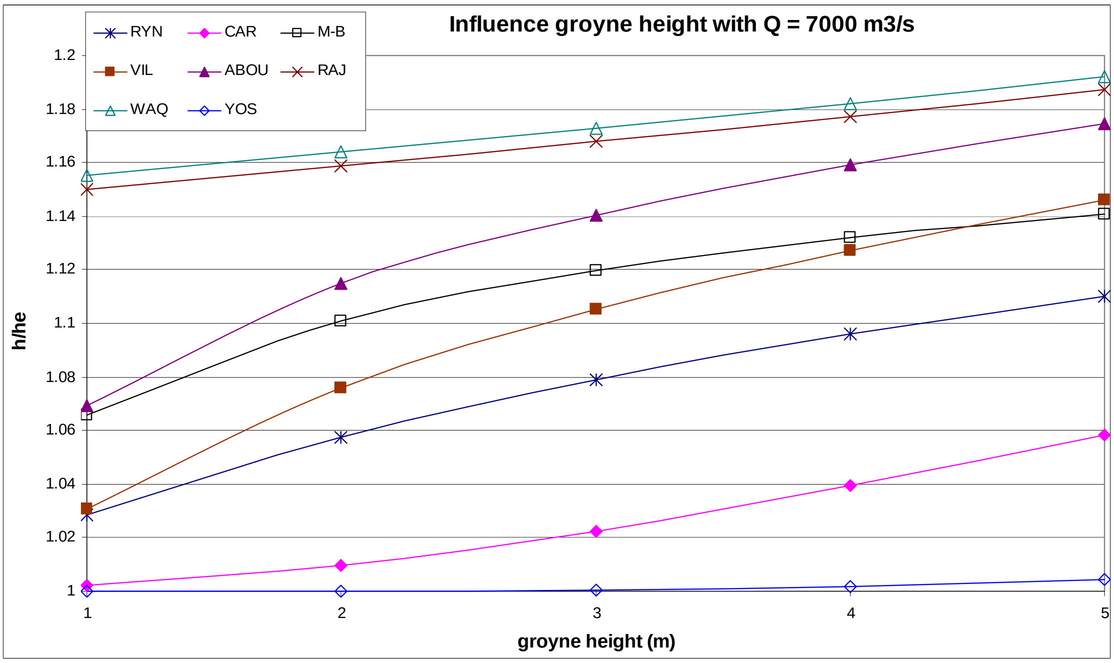

Figure 4.17; influence groyne height on the water depth with a high discharge
S = 400 meters, h_e = 16 m

4.6 Selection for the river test case

In the next chapter the in this chapter tested equations are used to represent groynes in a for the river Waal representative cross-section. In order to have a useful comparison, groyne equations that show illogical behavior are omitted. The groyne equations are judged on the following criteria:

- Groyne height: the increase of the water depth by groynes needs to approach zero when the groyne height approaches zero.
- Groyne spacing: the effect on the water depth by groynes needs to reduce if the groyne spacing increases.

Table 4.1; selecting groyne equations

Name	**Code**	**criteria**	
		1	2
Carnot	CAR	yes	yes
Villemont	VIL	yes	yes
Abou-seida	ABOU	yes	yes
Rajaratnam and Muralidhar	RAJ	no	yes
Van Rijn	RYN	yes	yes
Mosselman and Struiksma	MOS	no	yes
SOBEK	SOB	no	no
WAQUA	WAQ	no	yes
M-balance	M-B	yes	yes
Yossef	YOS	yes	yes

The in **table 4.1** bold printed equations are used in chapter five to asses the effect of adjusting groynes on the water height. The main reason groyne equations are omitted is that they are not able to handle situations properly in which the groyne height goes towards zero.

5. The river test case.

In this chapter the effect of the groynes on the water depth of a river is investigated with the use of the in chapter 4 selected groyne equations. Doing so gives an insight in the effect of the groynes on the water depth of the river Waal and shows the influence of the groyne equation on the water depth. In order to see the effect of the groyne equations on the water depth the following adjustment are made to the groynes:

- Changing the groyne height; the groyne height is varied from zero meters to five meters. With a height of five meters the groyne is at the same level as the floodplain.
- Changing the groyne spacing; the groyne spacing is varied from 100 meters to 400 meters. This is about the same as the variation in groyne spacing that can be found in the river Waal.
- Changing the groyne width; the groyne width is varied from 20 meters to 80 meters. With these values the main channel width has a range from 340 meters to 220 meters. This is close to the range found in the Waal from 412 to 252 meters.

To do a useful test information about a river like design discharge, groyne field layout and a representative cross-section are necessary. This necessary information was only available for the river Waal (Yossef, 2005). Using this information the effect on the water depth of the groynes is investigated.

In section 5.1 the dimensions and other properties of this cross-section are shown. In section 5.2 to 5.4 the effects on the water depth of the adjustments made to the groynes are shown. Other than in chapter 4, this time the results are shown in centimeters because the absolute effect is more important when making a decision with respect to for instance safety.

The most common reason to adjust groynes is to lower the water level at high discharges or make shipping possible at low discharges. Because the focus is on high discharges all the effects on the water depth of the groynes are presented as water depth decreasing measures. This makes it possible to compare the results of the different measures.

5.1 Properties of the river Waal cross-section

Figure 5.1 shows the cross-section that is used for the investigation of the effect on the water depth of the groyne field. This is done with the groyne equations that are selected at the end of chapter 4. The dimensions and the properties of the cross-section are based on the PhD thesis of Yossef (2005). This cross-section is the current situation with a groyne height of 5 meters. With a discharge of 2000 m^3/s the groynes are submerged, albeit only a few centimeters. The design discharge of the river Waal is 10700 m^3/s.

The properties that are not shown in figure 5.1 are:

C_{mc} = Chezy coeffient main channel, 40 $m^{1/2}/s$
C_{fp} = Chezy coefficient floodplain, 25 $m^{1/2}/s$
i = the water surface slope, 10^{-4}
C_b = Chezy coefficient of the bottom between the groynes, 40 $m^{1/2}/s$

The selected groyne equations can be found in section 4.6 and more information about the groyne equations are in chapters 2 and 3.

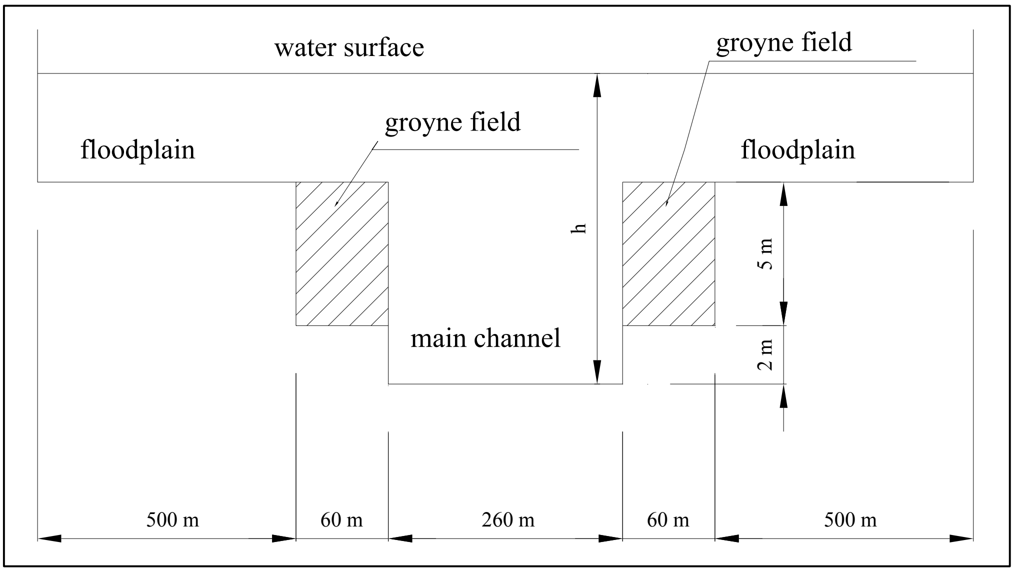

Figure 5.1; representative cross-section of the river Waal (based on Yossef, 2005)

5.2 Adjusting the groyne height

By decreasing the groyne height is it possible to realize a smaller water depth. In this section the effect on the water depth of lowering the groyne height is analyzed. In the current situation (figure 5.1) the groyne spacing is 200 meters and the groyne has a height of 5 meters. This height is decreased with steps of one meter until the groyne height is zero. The results are shown in absolute values, because river management decisions with respect to the safety are based on the amount of centimeters the water depth changes as a result of a measure. The equilibrium depth h_e is the water depth calculated without thhe presence of groynes.

With a relatively low discharge of 2000 m^3/s the difference between the groyne equations can go to a maximum of almost 0.60 meters. This is a very large difference considering the maximum decrease of water depth near 1.00 meters. This large difference is partly due to the difference in reaction to the decrease of the groyne height. Where Carnot and Yossef show a decreasing effect on the water depth with a decreasing groyne height, all the other groyne equations react in an opposite manner. One of the reasons for that could be that the groyne equation YOS is made by fitting a line through results of laboratory measurements. This line was based on the blockage ratio $h_g/(h_l+h_g)$. The measured blockage ratio had a range of 0.59 to 0.97, but in the Waal the blockage ratio can have values of 0.20 or even less with high discharges.

With the design discharge of 10700 m^3/s the same effect shows up as on the lower discharge of 2000 m^3/s. Only this time the difference is even a bit larger. This time it leads to a difference of over 0.70 meters. The maximum decrease of the water depth is 0.90 meters. Yossef still has a concave form as does Carnot.

Although it seems strange that the effect of the groynes on the water depth for the majority of groyne equations is almost the same with high and low discharges, there is a logical explanation for this. At a discharge of 2000 m^3/s and a groyne height of five meters the groynes are just a few centimeters submerged. As the groynes are lowered, the water level decreases and as a result the floodplain will not convey any water at all. The effect of the groyne is now divided over 380 meters, instead of over 1380 meters.

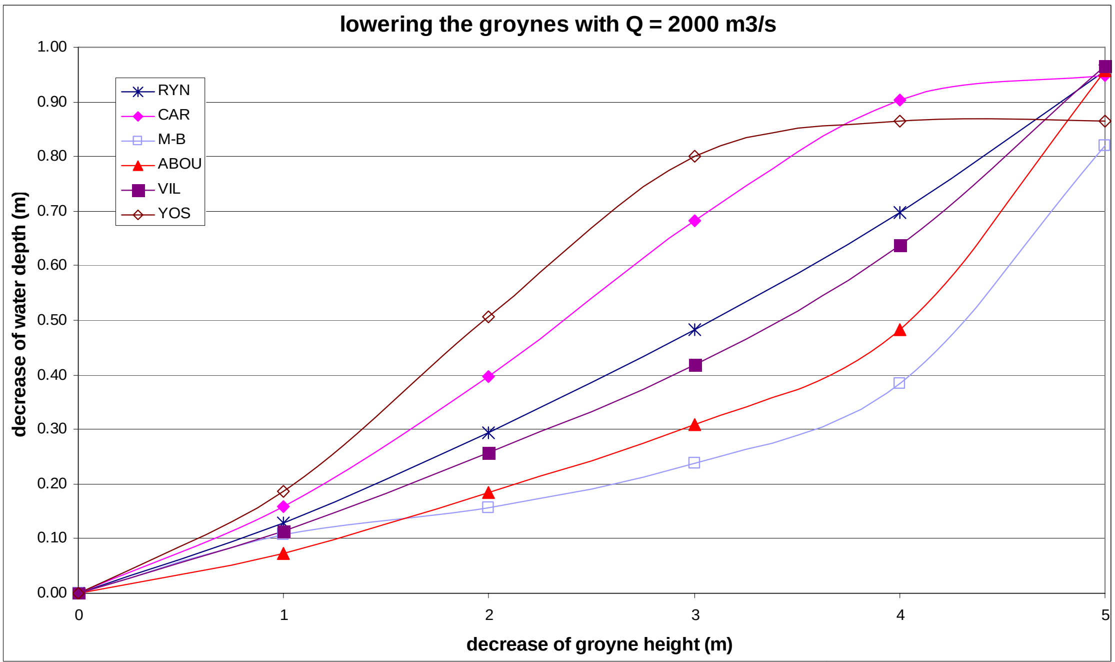

Figure 5.2; effect of the groyne height on the water depth, Q = 2000 m^3/s, h_e = 6.21 m

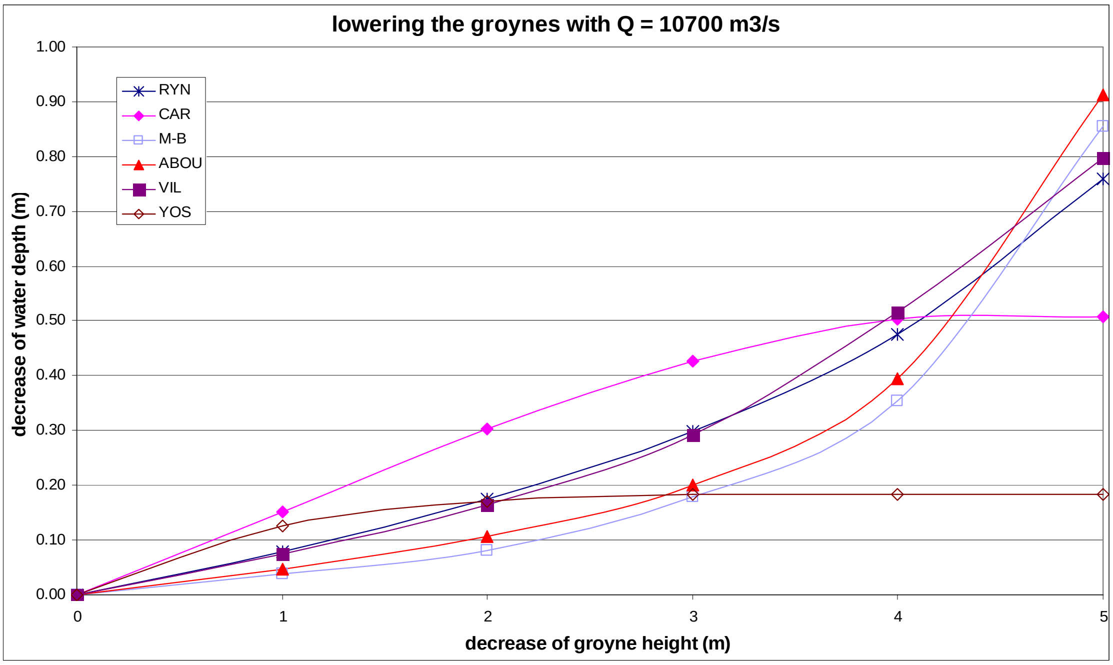

Figure 5.3; effect of the groyne height on the water depth, Q = 10700 m^3/s, h_e = 13.27 m

5.3 Adjusting the groyne spacing

By adjusting the groyne spacing the water depth can be influenced. With an increasing groyne spacing the water depth decreases. A too large increase of the groyne spacing can also lead to an unstable flow pattern. This means that the flow accelerates at the groynes. For this reason the effect of changing the groyne spacing is only investigated over a range from 100 to 400 meters. This range of groyne spacing does not differ much of the range actually found in the river Waal, which is 50 to 420 meters (Yossef, 2005). Adjusting the groyne spacing does not have to mean removing and rebuilding the groynes, but can also mean that intermediate groynes are removed. To study the lowering effect of increasing the groyne spacing in the reference situation is 100 meters, the groyne height is 5 meters..

With a low discharge of 2000 m^3/s the maximum difference between the groyne equations is 0.07 meters on a maximum decrease of the water depth of 0.07 meters. In contrast to section 5.2 the development of the water depth decrease is now convex for all groyne equations but one. M-B shows no decrease of the water depth on low discharges. This has to do with the fact that this groyne equation, with the water level only a few centimeters above the groyne, conveys enough water to reach a total discharge of 2000 m^3/s. Overall the effect with low discharges is not much.

With the design discharge of 10700 m^3/s the largest difference between the groyne equations is 0.12 meters on a maximum water depth decrease of 0.28 meters. All of the groyne equations show similar behavior. It is also clear that YOS goes towards the equilibrium depth much faster then al the other groyne equations. With an increase of the groyne spacing of 300 meters the development of YOS is already almost linear. CAR seems to need the longest groyne spacing to reach the equilibrium depth, but that is a little deceiving. CAR only needs to have a water depth decrease of 0.50 meters to reach the equilibrium depth (figure 5.3). The majority of the groyne equations need a much larger distance than 300 meters to reach the equilibrium depth.

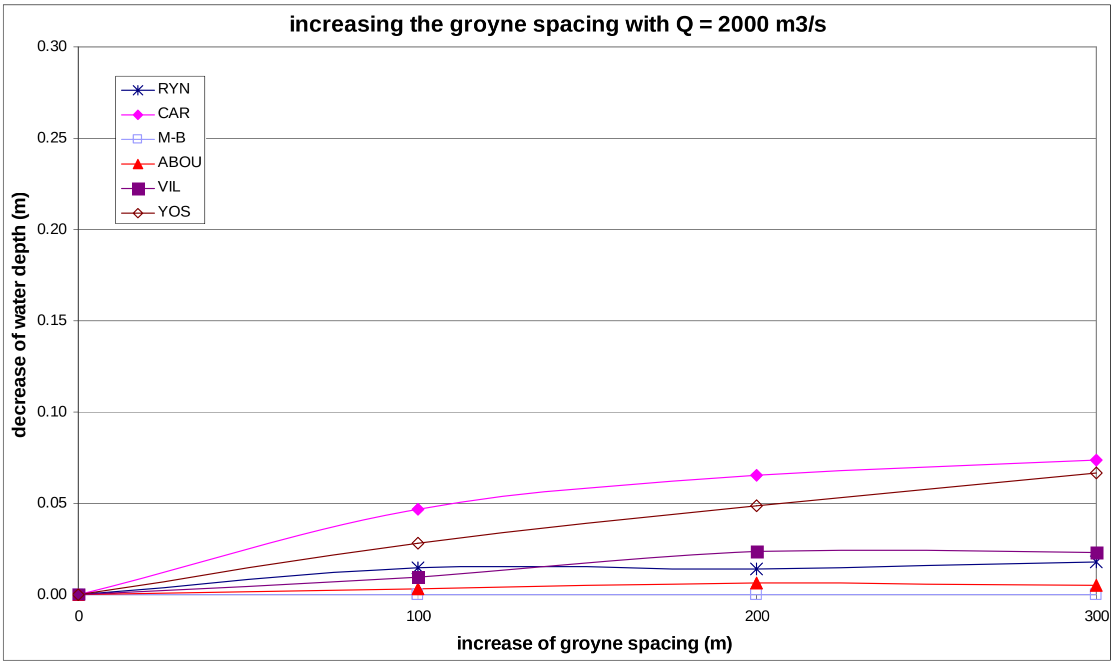

Figure 5.4; effect of the groyne spacing on the water depth with Q = 2000 m^3/s

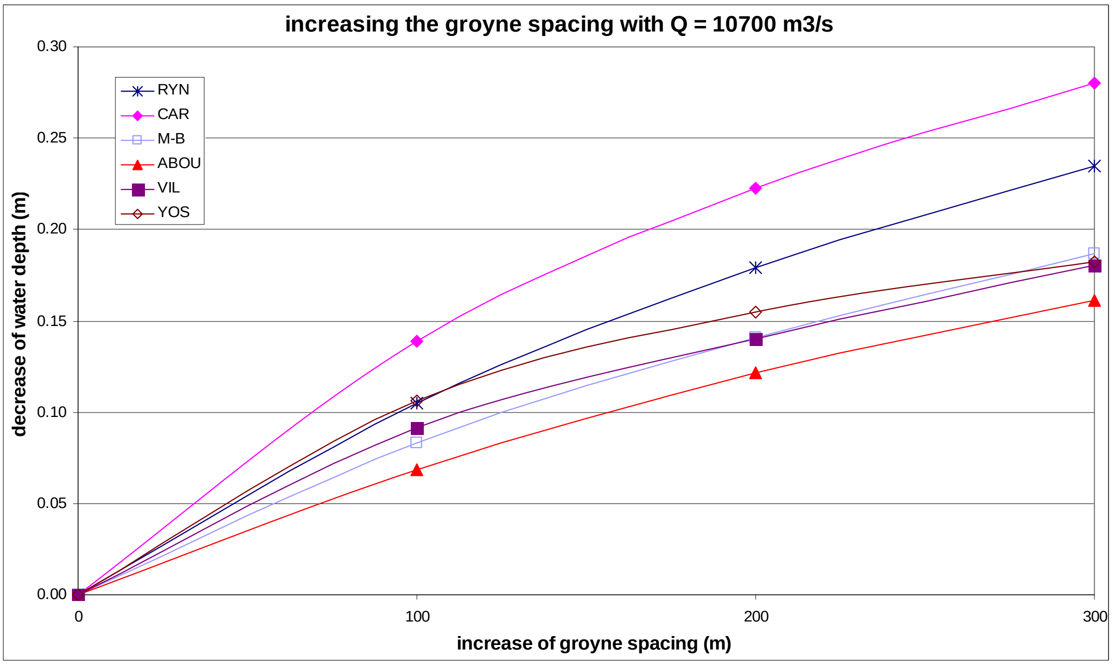

Figure 5.5; effect of the groyne spacing on the water depth with Q = 10700 m^3/s

5.4 Adjusting the groyne length

By adjusting the groyne length the water depth can be influenced as well. A decrease of the groyne length results in the decrease of the water depth. However in contrast to the decrease of the groyne height and the increase of the groyne spacing this will lead to a decrease of the water depth during low discharges as well. As this research is done with a focus on mainly high discharges the effect of decreasing the groyne length is investigated. This is done by varying the groyne length from 80 to 20 meters. This means the main channel will vary from 220 to 340 meters. The decreasing of the groyne length also has the effect that the length of the bottom elevation decreases. During this test the groyne spacing is 200 meters and the groyne height is 5 meters.

With a low discharge of 2000 m^3/s the difference between the groyne equations is almost nothing as the groyne length is decreased. The biggest difference of 0.23 meters is with a groyne length decrease of 60 meters. At that time the groyne equations all show exactly the same linear behavior. This is caused by the fact that as the groyne length decreases, the water depth decreases until the groynes are no longer submerged. This also explains the large effect on the water depth as only the main channel conveys water. The groyne equation does have an impact on the water depth, because else all lines would be the same. The difference is made in the beginning when the groynes are submerged.

With a high discharge of 10700 m^3/s the effect on the water depth is constantly linear. This suggests that the groyne equation itself is not the dominant factor, but the width of the channel. The differences between the groyne equations are smaller, but still large. With a decrease of the groyne length of 60 meters this leads to a difference between the groyne equations of the water depth of 0.70 meters. As the maximum water depth decrease is close to 1.30 meters this is a very large difference. However this difference is mainly caused by the low values of YOS and to a lesser extent CAR.

Figure 5.6; effect of the groyne length on the water depth with Q = 2000 m^3/s

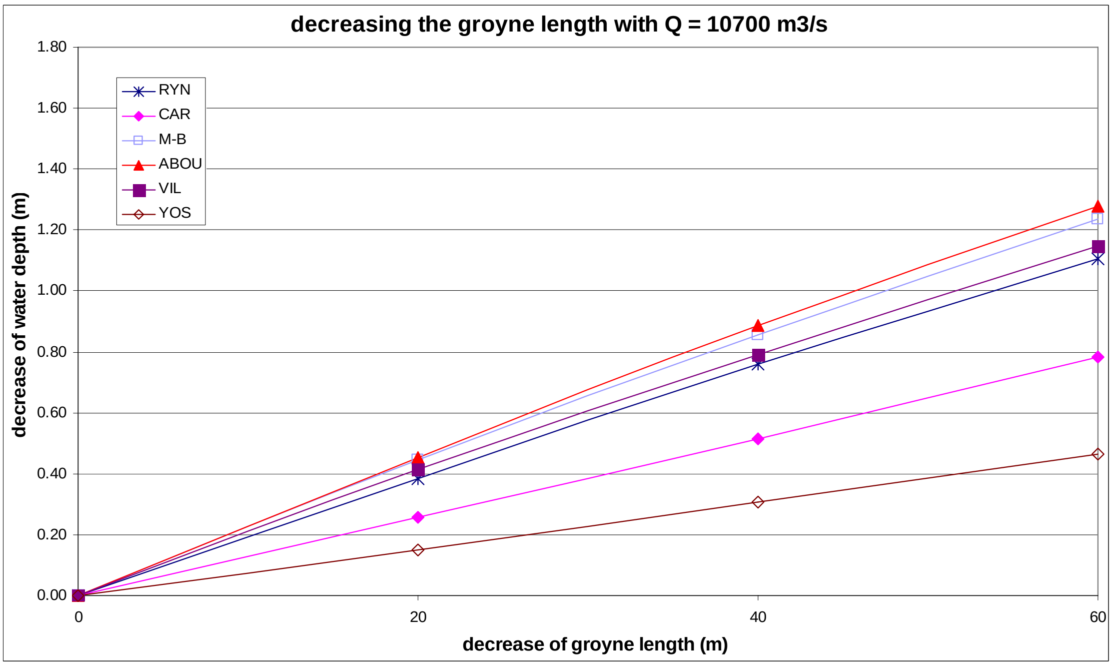

Figure 5.7; effect of the groyne length on the water depth with Q = 10700 m^3/s

6. Synthesis: Roughness coefficient of the channel

In the Elbe DSS the roughness of the floodplains and main channel is expressed as the Manning value. The cross-section of the river is divided into three parts: two floodplains and the channel (groyne field and main channel). The roughness of the channel implicitly includes the roughness of the groyne field. The roughness in the 1D hydraulic model is expressed as Chezy coefficient and not calculated for the channel as a whole. The Chezy coefficient can be rewritten as a Manning coefficient *n* using (Ribberink et al., 2003):

$$C = \frac{1}{n} R^{1/6} \quad (\mathrm{m}^{1/2}/\mathrm{s}) \tag{51}$$

With:
C = Chezy coefficient ($\mathrm{m}^{1/2}$/s)
n = Manning's coefficient ($\mathrm{s/m}^{1/3}$)
R = hydraulic radius (m)

The best way to illustrate the roughness of the groyne as Manning value would be to make a plot with the water depth on the x-axis and the roughness expressed as Chezy or Manning or any other roughness coefficient on the y-axis. This is possible as the water depth can be calculated over a range of discharges for a river consisting of a main channel, groyne field and floodplains. The calculated water depths can be plotted against the Chezy roughness using Chezy's law:

$$Q = u \cdot A = A \cdot C \cdot \sqrt{R \cdot i} \quad (\mathrm{m}^{1/2}/\mathrm{s})$$

With:
Q = discharge of the main channel and groyne field(m^3/s)
A = total wet area of the main chanel and groyne field (m^2)
i = water surface slope
R = hydraulic radius of the main channel and groyne field (m)

When the groyne properties are changed the roughness must be calculated over a range of discharges again, resulting in another relation between the water depth and the Manning coefficient. By basing the value of the channel roughness on a cross-section of the channel without groynes, there is no longer a need to include the groyne explicitly in the cross-section to obtain the discharge-roughness relationship. The groyne can be adjusted by changing the roughness value of the channel. The roughness value can be calculated using the 1D model and the dimensions of the channel, the water surface slope, a groyne equation, the groyne field layout, and the bottom roughness of the river. This is illustrated in figure (6.1) which is based on calculations using the Waal cross-section with a groyne height of five meters and the groyne equation YOS. At a water depth of seven meters the flood plain starts to transport water.

In the Elbe-DSS the roughness of the channel is estimated through linear interpolation. The relation between the roughness and the number of groynes per km is assumed to be constant. In figure (6.2) this same relation is shown, but this time using the results acquired by calculations with the 1D hydraulic model with a discharge of 2000 m^3/s and 10700 m^3/s, the groyne equation YOS and the for the Waal river representative cross-section. The groyne height is five meters. Figure (6.2) shows that the relation between the roughness of the channel and the amount of groynes per km is not linear.

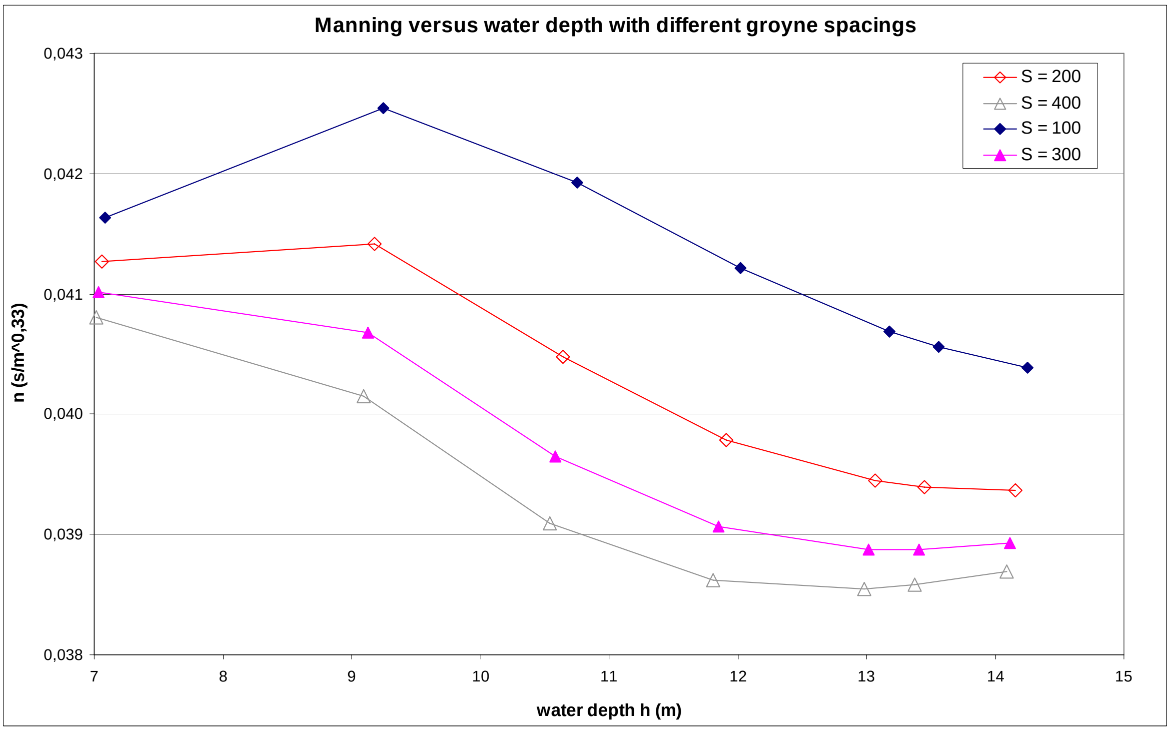

Figure 6.1; roughness of the channel with different water depths.

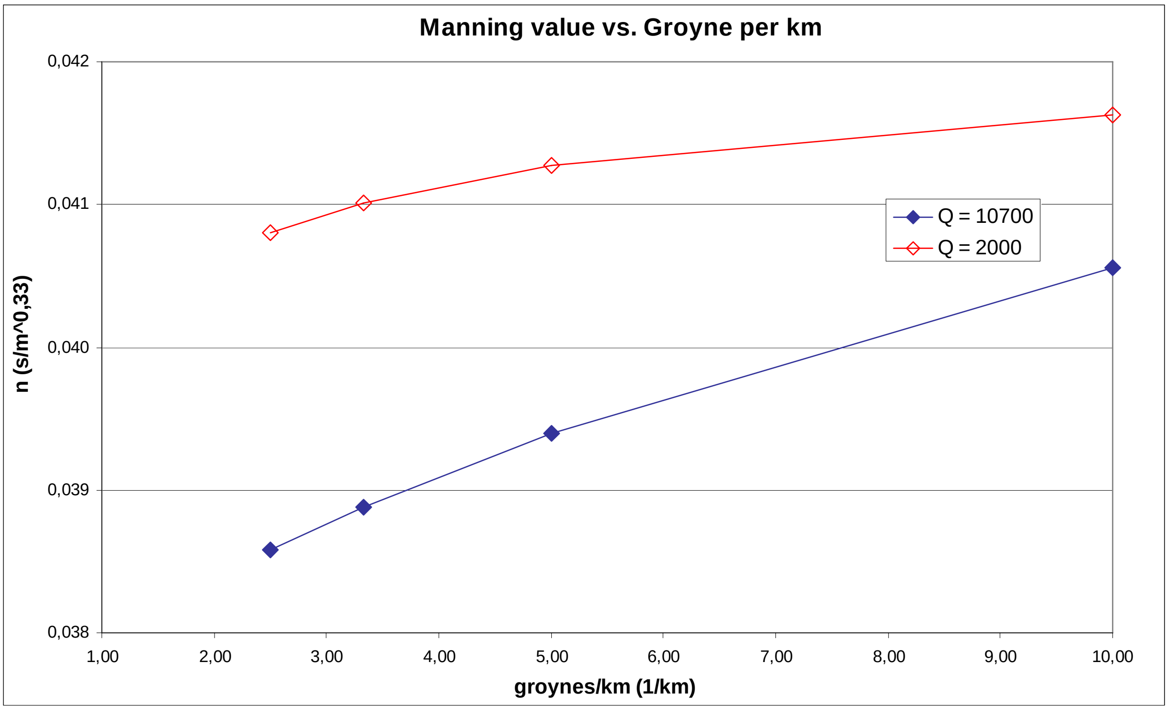

Figure 6.2; Manning value vs. groynes/km

7. Discussion

In this chapter attention is paid to the effect of the assumptions that were made while making the 1D hydraulic model and the reason for these assumptions. This is followed by an explanation why certain groyne equations were not suitable to represent a groyne. Also some surprising results are discussed.

7.1 Model assumptions

Backwater curve

When calculating the water level profile between groynes the effect or rather the forming of a backwater curve was neglected. A typical value for the adaptation length for Dutch rivers (h_e = 4 meters, $i = 10^{-4}$) is 40 kilometers (Ribberink et al., 2003). As the distance between the groynes has a maximum of 400 meters the influence of the backwater curve would be minimal, thus unnecessarily making calculations more complicated. Therefore it was decided to not include the backwater curve in the hydraulic1D-model.

Flow friction

The friction between the flows of the different channels was neglected. This friction is caused by the difference of flow velocity in the groyne field and the main channel. Apart from the fact that is it not possible to estimate the energy loss accurately due to the friction between flows with different velocities, it complicates the model as well.

2D flow

The interchange of flow between the groyne field and the main channel was neglected as well. However, it does have an impact on the resistance a groyne field poses to the flow according to Yossef (2005). In the 1D hydraulic model the water that is transported by the groyne field has to flow over the groyne. In reality water can also flow around the groyne thus poses less resistance to the flow.

7.2 Elimination of groyne equations

Mosselman

The groyne equation Mosselman (MOS, 27) was found to be inadequate in the first test in the 1D hydraulic model. This is surprising, because it is a widely used weir equation. Nevertheless the water level increase is not realistic with increase of the discharge. This made it impossible to calculate the desired water surface slope using MOS as a groyne equation with high discharges.

WAQUA

The equation used in WAQUA (WAQ, #) to describe the effect of a barrier on the water level did not work to satisfaction. This particularly has to do with the behavior of the equation when the groyne height or the height of the barrier would approach zero value. The effect of the barrier would not approach zero when the height of the barrier approaches zero. Although there is a possibility that in the model this is partly compensated by adjusting a coefficient, this meant he could not be used in the 1D hydraulic model.

SOBEK

The SOBEK weir equation could not be used in the 1D hydraulic model because the energy loss over the weir was too large. As a result small discharges over the weir lead to a very large increase of the water levels when trying to get to a certain water surface slope. This does not mean that the weir equation is wrong, but it is most likely that the weir equation is used differently in the SOBEK software. Another reason can be that a weir in SOBEK is used to describe a local effect, and although according to the manual it is possible to work with a ratio near 1.00 of the downstream and upstream water depth, in reality it is not possible or it will never happen in SOBEK. Unfortunately, the manual gives no clues regarding to other aspects that influence the outcome of this equation or the way it is used.

7.3 Unexpected results

Momentum balance

Chapter 3 saw the introduction of a “new” groyne equation which was called “Momentum Balance”(M-B, **36**). Just like in the groyne equation Yossef (YOS, **42**) the effect of the groyne on the water level is represented as a drag force. This time the groyne equation is based on a momentum balance over a section of a channel with a obstacle in it. No earlier examples to represent a groyne or a weir this way were found in literature. Although this groyne equation is, in contrast to most other used equations, based solely on theory, it showed a remarkable similarity to the other equations. The drag coefficient C_D has a fixed value which leaves room for improvement.

Yossef

The groyne equation by Yossef was also introduced in *chapter three*. This groyne equation represents the effect of the groyne on the water level as a drag force. The river test case in chapter 5 shows that YOS has little effect on the water level with high discharges compared to other groyne equations. This consequently leads to little effect on the water level when adjusting the groyne height, width or spacing. Interestingly enough YOS shows more effect on the water level with low discharges then with high discharges. With low discharges the effect on the water level is about as large as other groyne equations. What was also remarkable is that the calculated water level decrease of 19 centimeters when removing the groynes (figure 5.3) is substantially larger then the 6 centimeters Yossef calculated in his PhD thesis, while the circumstances were virtually the same. A reason for this difference can be the use of the hydraulic radius in calculations, while Yossef used the water depth, although that should not lead to such a large difference.

Roughness of the summer bed

The wide range of effects on the water depth of the groyne equations has to do with the different reactions to larger discharges of the groyne equations. YOS for instance shows that groynes have less effect on the water depth with a higher discharge as does Carnot (CAR, 5). With a groyne equation like YOS or CAR this means that eventually the water depth will be independent of the presence of groynes if the discharge is high enough.

However, the majority of the groyne equations show an increasing effect of groynes on the water depth with larger discharges and go towards a constant relative value of the water depth of a situation without groynes (figure 7.1). This means that even with very high discharges the roughness of the summer bed with groynes will not get nearer to the roughness of a summer bed without groynes. This seems incorrect, as the bottom roughness in the calculations has a constant value, but the groyne field roughness is not constant and should be getting smaller with a higher water depth. This should lead to a situation that the roughness of the summer bed with groynes is approaching the roughness of a situation without groynes.

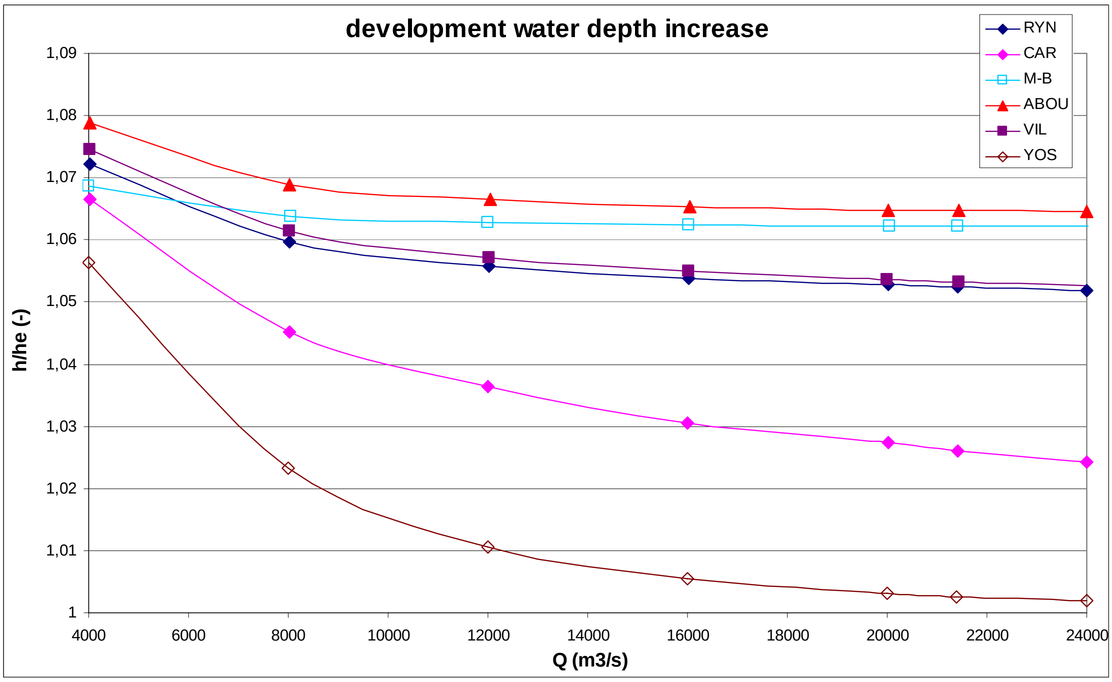

Figure 7.1; relative water depth increase

8. Conclusions and recommendations

8.1 conclusions

This section begins with the answering of the research questions formulated in the introduction of this report. This is followed by conclusions about the influence of adjustments to groynes on the water level, the possibilities to use this method to estimate the roughness of groynes in general and the accuracy of the used groyne equations.

1. **Which equations are available to represent groynes in a 1D hydraulic model?**

It is possible to divide these formulas into two groups:

- Groynes represented as weir
- Groynes represented as an obstacle in the flow

From these groyne equations the ones that are able to function as submerged groyne and those that allow the groyne to be changed in height are selected and are tested in a 1D hydraulic model.

2. **Can the groyne equations be used to model a groyne field in a hydraulic 1D-model?**

By assuming the water level and the water surface slope to be the same in the groyne field and the main channel a groyne field was modeled. However, not all the groyne equations were able to respond to the change of the groyne height correctly in tests done in the 1D hydraulic model. A channel with groynes of zero meters high did not always result in the same water depth as that of a channel without groynes. For that reason some groyne equations are omitted.

3. **What are the effects of the groynes on the water level?**

The effect on the water level of the groynes was investigated for a cross-section that can be considered representative for the river Waal using the 1D hydraulic model. The analysis showed different effects on the water level of the different adjustments that can be made to groynes (height, width, spacing). This leads to the conclusion that the effect on the water level of an adjustment made to a groyne can not be estimated by linear interpolation as done in the current Elbe-DSS. A distinction should be made per type of adjustment.

4. **Can a groyne and adjustments made to a groyne be expressed via the roughness only?**

To represent the channel (main channel and groyne field) as a roughness coefficient it is necessary to first calculate the water depth in the main channel over a range of discharges per groyne field layout using the 1D hydraulic model. Using the calculated relation between the discharge and the water depth it is possible to derive the roughness of the channel without explicitly including the groyne in the cross-section. The groyne is implicitly included in the roughness of the channel.

The different groyne adjustments and their effects on the water level

The range in the effects on the water level is due to the use of different groyne equations and differs per measure:

- Decreasing the groyne width; the largest effect on the water depth is seen with a decrease of the groyne length. With the design discharge of 10700 m^3/s this can lead to a decrease of the water depth of 45 to 125 centimeters if the groyne field width is decreased from 80 meters to 20 meters. Although this decrease of the water depth is desirable with high discharges, it also happens with a low discharge of 2000 m^3/s (1.40-1.65 m). This can cause problems for shipping, making this measure only suited for rivers where shipping has no problems with the water depth, even with low discharges.
- Decreasing the groyne height; with a design discharge of 10700 m^3/s the lowering of the groynes from five to zero meters has a decrease of the water depth of 19 to 90 centimeters as result. With a low discharge of 2000 m^3/s the water depth decrease has a range from 80 centimeters to 95 centimeters. Although this is a good result for high discharges, lowering the groynes is only an option if the groynes are too high in the current situation as the water depth also decreases considerably with low discharges.
- Increasing the groyne spacing (removal of groynes); with a low discharge of 2000 m^3/s the decrease of the water level is 0 to 7 centimeters if the groyne spacing is increased from 100 to 400 meters. With the design discharge of 10700 m^3/s the effect on the water level is 16 to 28 centimeters.

Increasing the groyne spacing has the most positive effect on the water depth as with high discharges the water level decreases whereas with low discharge the water level decrease is very small. Also the range of the results is smaller. The only drawback is that the effect on the water level is a lot smaller as well.

The accuracy of the predicted water level changes

In practice, the required accuracy of predicted water levels is variable, depending of the stakeholder’s interest, and ranging from 1 centimeter to 10 centimeters. Water depths and vertical clearance (bridges) for shipping on the Elbe are monitored with an accuracy of 1 centimeter (www.elwis.de). On the other hand development of vegetation is predicted using an accuracy of 10 to 15 centimeters (Berlekamp et al., 2005) to calculate the days flood plains are inundated in a year. The 1D hydraulic model predicts a much wider range when using the various groyne equations. This has to do with the fact that it is not known which groyne equation comes closest to reality.

Groynes as roughness in a 1D hydraulic model

Chapter 6 shows how, using the 1D hydraulic model of this research, it is possible to represent the groynes as roughness in the channel like it is done in the Elbe-DSS. The method used to express groynes as roughness can also be used in different 1D models. It is also possible to include the roughness of the groyne field in the total roughness of the cross-section of a river or to express the roughness of the groyne field separately. It is even possible to express the roughness of the groyne field per unit width. That leaves the groyne height and the groyne spacing as the only adjustable parameters of the groyne field. There are two options to estimate the roughness of a unit width groyne field:

- Calculate the roughness of the groyne per situation using the 1D hydraulic model.
- Use a contour plot like figure 6.1 in which the roughness of the channel is plotted against the water depth for a certain amount of groyne field configurations to estimate the groyne field roughness.

8.2 Recommendations

In the Elbe-DSS the roughness of the channel is estimated by linear interpolation based on the amount of groynes per kilometer. As the relation between the roughness of the channel and the amount of groynes per kilometer is not linear, the way the roughness of the channel is estimated should be changed, for example by using the 1D hydraulic model of this research.

In the 1D hydraulic model the friction between the flows of the different channels was neglected. Including this “interface shear” can lead to an additional energy loss and subsequently a larger roughness of the cross-section of a river. At present it is not known how much effect the inclusion of the interface shear has and this should be further investigated.

The morphology was neglected in the 1D hydraulic model as well. Although the effect on the water level, specifically with high discharges, will not be much it can have an impact on for instance shipping with low discharges. Adjustments made to the groyne field will also lead to morphological effects. This makes it important to take morphology into account, when shipping is relevant.

The effect of the groyne spacing on the water level is also worth investigating as the conclusion also showed that the increasing of the groyne spacing can be a valid option to decrease the water depth with high discharges. Until now no literature was found that shows the effect of the groyne spacing on the water level at high discharges At the moment the effect on the water level of the groyne spacing is dominated by the roughness of the bottom and the energy loss over the groyne.

The 1Dhydrailic model was set-up assuming uniform flow conditions. It should be investigated how the model can work under non-uniform flow conditions.

In Yossef (2005) an investigation was done with a ratio of the groyne height and the water depth from 0.5 to almost 1.0, but this ratio can reach a value as low as 0.2 in the river Waal. This makes it interesting to investigate ratio’s lower than 0.5 as this was not done in Yossef’s study. It is also very likely that other groyne equations are not tested at such circumstances as well.

Also the groyne equation Momentum Balance (M-B, 37) can be optimized further. This for instance can be done by relating the value of the drag coefficient to the water depth above the groyne. However, it is recommended to validate this new method with the help of for example measurements done in the field or a summer bed set-up in a laboratory.

Finally, it would be interesting to find out why the groyne equations SOB, WAQ and MOS were not able to meet the expectations or what would be necessary to make them meet the expectations in the 1D hydraulic model

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Appendix A - Open channel flow.

In this chapter basic formulas to describe open channel flow are collected in order to be able to better understand the way weir discharge equations are constructed. First formulas to for uniform steady flow are described. These are followed by the basics of the energy line and the momentum balance.

A.1 Steady uniform flow

In an open channel the discharge can be described as:

$$Q = uA \text{ (m}^3\text{/s)} \tag{52}$$

The velocity of the steady, uniform flow can be written as relation between the bed slope, the roughness expressed as Chézy coefficient, the water depth and the wetted perimeter:

$$u = C\sqrt{R \cdot i_b} \text{ (m/s)} \tag{53}$$

With:

R = the hydraulic radius = A/P (m)
A = cross section area of flow (m^2)
P = wetted perimeter (m)
C = Chézy coefficient ($m^{1/2}/s$)

This leads to the discharge per unit width:

$$q = u \cdot h = C\sqrt{R \cdot i_b} \cdot h \text{ (m}^2\text{/s)} \tag{54}$$

With:

i_b = bed slope (m/m)
h = water height (m)

In the case of a rectangular channel and b >> h, then R = h:

$$q = C\sqrt{h \cdot i_b} \cdot h = C\sqrt{i_b}\,h^{3/2} \text{ (m}^2\text{/s)} \tag{55}$$

Then h equals:

$$h = \left[\frac{q}{C\sqrt{i_b}}\right]^{2/3} \text{ (m)} \tag{56}$$

The discharge can be described in two different ways:

1. By way of the momentum principle;
2. By way of the energy principle.

These are described in the next two sections.

A.2 Energy principle

With help of the energy principle it is possible to calculate the energy height of the flow in a certain cross-section. More important is that it also makes it possible to calculate the energy loss between two sections.

The general energy equation states that energy is neither created nor destroyed. If the energy principle is applied to open flow, the total energy consists of three different types of energy:

1. Kinetic energy, expressed as $u^2/2g$ (m).
2. Potential energy, expressed as z (m).
3. Pressure, expressed as h (m).

The amount of energy of the flow will decrease as flow goes downstream. This is represented by head loss h_f. The energy of flow can be expressed as:

$$\left(z_1 + h_1 + \frac{u_1^2}{2g}\right) = \left(z_2 + h_2 + \frac{u_2^2}{2g}\right) + h_f \text{ (m)} \quad \textbf{(57)}$$

This represents the difference in energy between two different cross sections. The part in parentheses is the total head H (m) of the flow. With the total head of multiple cross sections it is possible to construct an energy grade line.

Rapidly varied flow occurs over a short distance. Over a short distance the bed elevation will not change much. As a result the h_f will be negligible small. In this situation the total head can be expressed as:

$$h_1 + \frac{u_1^2}{2g} = h_2 + \frac{u_2^2}{2g} = \text{constant} = H \textbf{ (m)} \quad \textbf{(58)}$$

This can also be written as:

$$h + \frac{q}{2gh^2} = H \textbf{ (m)} \quad \textbf{(59)}$$

For larger distances H is not constant and can be expressed as friction slope S_f. The friction slope represents the energy loss per unit distance. S_f is defined as:

$$S_f = \frac{h_f}{\Delta x} \textbf{ (-)} \quad \textbf{(60)}$$

This leads to:

$$\left(z_2 + h_2 + \frac{u_2^2}{2g}\right) - \left(z_1 + h_1 + \frac{u_1^2}{2g}\right) = -h_f = -S_f \Delta x \textbf{ (m)} \quad \textbf{(61)}$$

This can also be written as:

$$\frac{\left(z_2 + h_2 + \frac{u_2^2}{2g}\right) - \left(z_1 + h_1 + \frac{u_1^2}{2g}\right)}{x_2 - x_1} = \frac{\Delta H}{\Delta x} = -S_f \text{ (-)} \tag{62}$$

To make things simpler the bed slope is defined as:

$$\frac{z_2 - z_1}{x_2 - x_1} = -S_0 \text{ (-)} \tag{63}$$

This leads to:

$$\frac{\left(h_2 + \frac{u_2^2}{2g}\right) - \left(h_1 + \frac{u_1^2}{2g}\right)}{x_2 - x_1} = S_0 - S_f \text{ (-)} \tag{64}$$

The friction slope can also be expressed as a Chézy based formula:

$$\sqrt{S_f} = \frac{q}{C} h^{3/2} \text{ (-)} \tag{65}$$

This is only true in steady flow and wide channels (B >> h).

A.3 Momentum balance

The flow in an open channel can be described by way of a momentum balance. The momentum balance is an application of the Newton's second law of motion. This says that: "The change of momentum per unit of time in the body of water in a flowing channel is equal to the resultant of all the external forces that are acting on the body." This means that on a part of a steady uniform flow the momentum change per unit time is equal to zero. The momentum balance is shown in figure (1.1).
The momentum change per unit time between two sections can be expressed as:

$$\frac{Q\rho}{g}\left(u_2 - u_1\right) = P_1 - P_2 + W \cdot \sin\theta - F_f \qquad \text{(kg)} \tag{66}$$

$$m \quad \cdot \quad a \quad = \quad F$$

With:

$$P_1 = \frac{1}{2}\rho b h_1^2 \quad \text{(kg)} \tag{67}$$

$$P_2 = \frac{1}{2}\rho b h_2^2 \quad \text{(kg)} \tag{68}$$

$$F_f = \rho h_f^{'} b \bar{h} \quad \text{(kg)} \tag{69}$$

$$W = \rho b \bar{h} L \quad \text{(kg)} \tag{70}$$

$$\bar{h} = (h_1 + h_2)/2 \qquad \text{(m)} \tag{71}$$

$h_f' = friction\,head$ (m)

$\theta = bedslope\,in\,\deg rees$

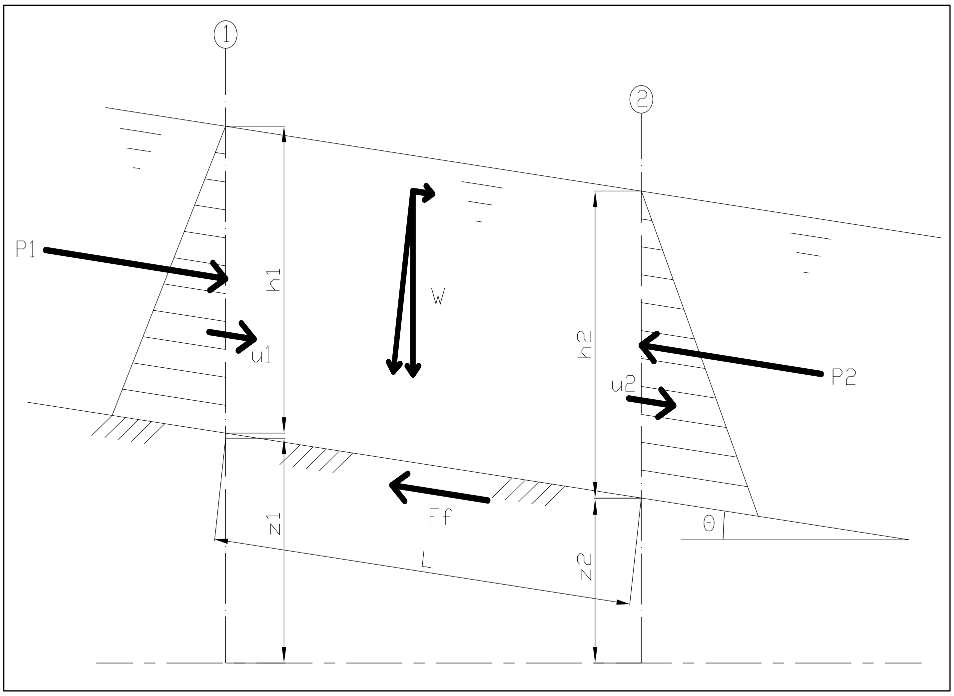

figure 1.1; Momentum balance in a channel

After substituting and simplifying:

$$z_1 + h_1 + \frac{u_1^2}{2g} = z_2 + h_2 + \frac{u_2^2}{2g} + h_f' \qquad \text{(m)} \tag{72}$$

This equation seems to be the same as the one of the energy principle but it is not. The velocity distributions coefficients are different and the friction losses have a different meaning as well. In the energy principle the friction consist of the dissipation of internal energy whereas in the momentum principle the friction losses are caused by external forces acted out on the water by

Appendix B - Energy loss as roughness

Most equations used to describe the discharge over a weir present the possibility to calculate the energy loss caused by that weir. The water height in a river however is mostly calculated by way of the roughness of the river. The most commonly roughness coefficient used in the Netherlands is the Chézy coefficient. Thus to make things easier it would be useful to divert the energy loss into a value of the Chézy coefficient.

The Chézy coefficient can be expressed as a relation of the water depth, bed slope and flow velocity:

$$C = \frac{u}{\sqrt{R \cdot i}} \tag{73}$$

The energy loss caused by the weir can be expressed as:

$$\Delta H = i_{zw} \cdot S \tag{74}$$

With:

i_{zw} = slope of the water level.
S =spacing between groynes.

With formula **(62)** and **(63)** this can be rewritten to an expression for C_g are rewritten as expressions for i_{zw}:

$$\frac{\Delta H}{S} = \frac{u^2}{C_g^2 \cdot R} \rightarrow C_g = \frac{q}{h}\sqrt{\frac{S}{R \cdot \Delta H}} \tag{75}$$

With:

C_g = roughness caused by the groyne.
u = velocity of flow in the groynefield.
R = hydraulic radius of the groynefield

The roughness of the groyne field C_{tot} is equal to the combined roughness of the groyne C_{gr} and the bed C_{bed}. The groyne field roughness C_{tot} can be calculated by considering the water surface gradient:

$$i_{tot} = \frac{u^2}{R \cdot C_{tot}^2}$$

i_{tot} = total water surface slope in groyne field
C_{tot} = total roughness of groyne field

In this case the water surface slope is influenced by two roughness factors:

$$i_{tot} = i_{gr} + i_{bed} = \frac{u^2}{R \cdot C_{gr}^2} + \frac{u^2}{R \cdot C_{bed}^2} = \frac{u^2}{R \cdot C_{tot}^2}$$

i_{gr} = slope caused by groyne roughness
i_{bed} = slope caused by bed roughness

Because the velocity and water height are the same on both sides of the equation this formula can be rewritten to the following expression for the total roughness of the groyne field C_{tot}:

$$C_{tot} = \sqrt{\frac{1}{\frac{1}{C_b^2} + \frac{1}{C_g^2}}} \ (\mathrm{m}^{1/2}/\mathrm{s})$$

Appendix C - Calculation water depth in compound channel

In this appendix first a flow chart of the 1D hydraulic model is shown with a list of symbols. This is followed by an calculation example of the 1D hydraulic model. The numbers right of the flow chart refer to the calculation steps in the example.

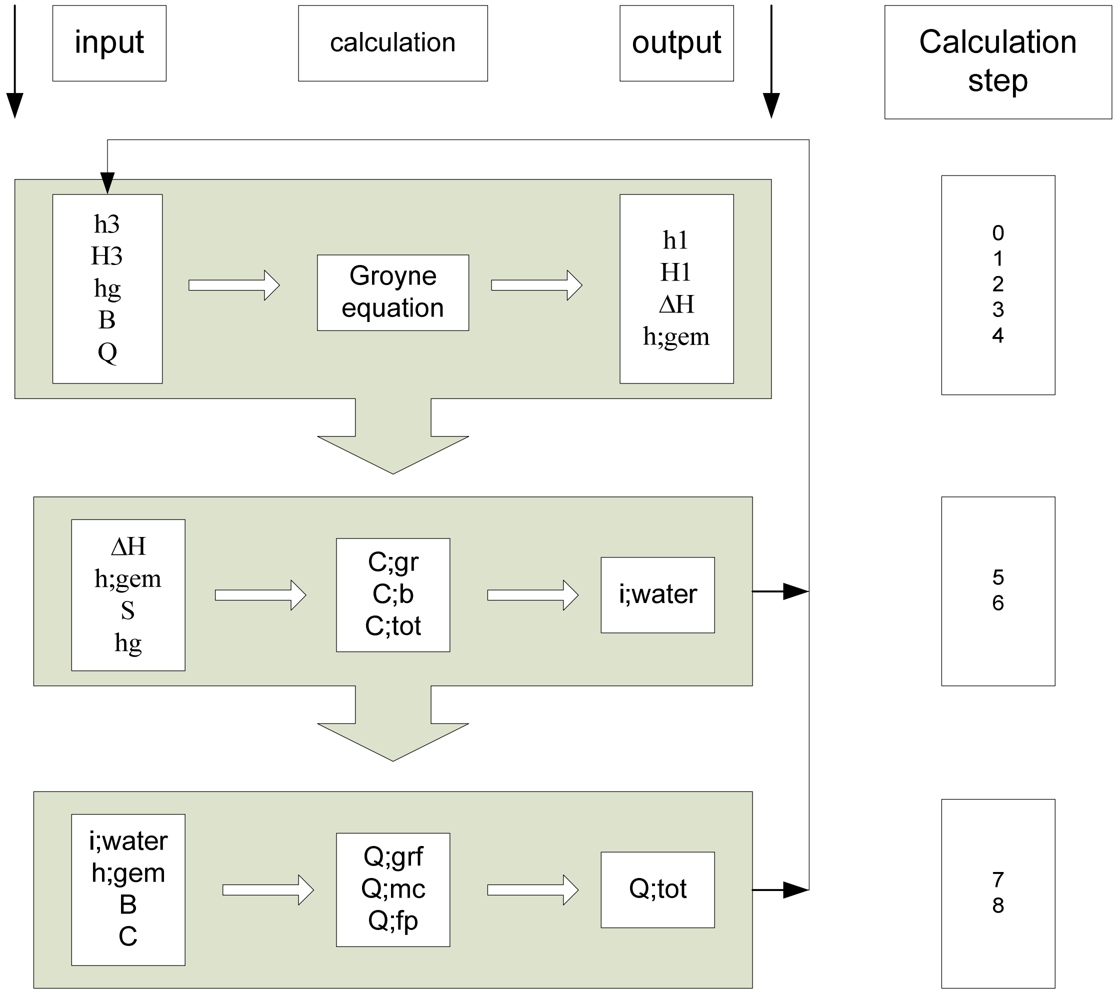

Figure A.1; flow chart of the 1D hydraulic model

h1 , h3 = water depth relative to the crest of the groyne upstream, downstream
H1, H3 = energy height upstream, downstream
ΔH = H1 – H3
B = width (groyne field, main channel)
hg = groyne height
h; gem = water depth in the groyne field
S = groyne spacing
C;gr, C;b, C; tot = representative chezy roughness of the groyne, bottom, groyne field
i;water = water surface slope
Q;grf, Q;mc, Q;fp, Q;tot = discharge of the groyne field, main channel, floodplain, river

Compound channel with Carnot

color index
known
unknown
determined by goalseek

	Q;gr	559	$m^3/m/s$	
known	ib	1,00E-04	-	
	k;s1	0,2	m	groynefield
	k;s2	0,2	m	main channel
	hg	2	m	
	g	9,81	m/s^2	
	S	400	m	
	Qtot	2000	m3/s	total discharge of river
	B;gr	70	m	width of groynefield
	B;mc	150	m	width of main channel
	Δz	0,2	m	difference in bottomlevel groynefield and main channel
wanted	Δh = (h1-h3))	0,01	m	
	ΔH = (H1-H3)	0,01	m	
	h;gem	7,21	m	water depth in groynefield
	h;gem-he	0,18	m	water level rise due to groynefield

0 Calculate h3 (downstream)

h3=	5,20	m
C=	47,44	$m^{1/2}/s$
h3+hg=	7,20	m
Q;gr	642,14	m^3/s

$$C = 18\log\left(\frac{12(h_3 + h_g)}{k_{s1}}\right)$$

$$Q_{gr} = B_{gr} \cdot C \cdot (h_3 + h_g)^{3/2}\sqrt{i}$$

1 Calculate H3 (downstream)

H3=	5,29	m

$$H_3 = h_3 + \frac{q^2}{2g(h_3 + h_g)^2}$$

with:

$$q = \frac{Q}{B}$$

2 Calculate h2 and H2 (on weir)

h2=	5,15	m
h2+hg=	7,15	m
H2=	5,28	m

impulse balans:

$$\frac{1}{2}g(h_2+h_g)^2-\frac{1}{2}g(h_3+h_g)^2=\frac{q^2}{h_3+h_g}-\frac{q^2}{h_2}$$

$$\frac{1}{2}g(h_2+h_g)^2+\frac{q^2}{h_2}=\frac{q^2}{h_3+h_g}+\frac{1}{2}g(h_3+h_g)^2$$

$$H_2=h_2+\frac{q^2}{2g\cdot h_2^2}$$

3 Calculate h1 and H1 (upstream)

h1=	5,21	m
h1+hg=	7,21	m
H1=	5,30	m

$$h_1+\frac{u_1^2}{2g}=h_2+\frac{u_2^2}{2g}=H1$$

$$q=u_1.(h_1+h_g)=u_2.h_2$$

$$h_1+\frac{q^2}{2g(h_1+h_g)^2}=h_2+\frac{q^2}{2g.h_2^2}$$

$$H1=h_1+\frac{q^2}{2g(h_1+h_g)^2}$$

4 Calculate Δh en ΔH

Δh =	0,010	m	$\Delta h = h_1 - h_3$
ΔH =	0,010	m	$\Delta H = H1 - H3$

5 Calculate h and C in groynefield

h;gem=	7,21	m	$h_{gem} = (h_1 + h_3)/2 + h_g$
C;gft=	41,25	$m^{1/2}/s$	$\frac{1}{C_{gft}^2} = \frac{1}{C_g^2} + \frac{1}{C^2}$
C=	47,4	$m^{1/2}/s$	
C;g=	83,48	$m^{1/2}/s$	$C_g = \sqrt{\frac{u_{gr}^2}{h_{gem}} \frac{S}{\Delta H}} = \sqrt{\frac{q^2}{h_{gem}^3} \frac{S}{\Delta H}}$ with: $u = \frac{q}{h}$

6 Calculate the water slope in the groynefield

i;gr=	0,000100034	m/m

$$i_{gr} = \frac{q^2}{h_{gem}^3 \; C_{gft}^2}$$

under uniform conditions the slope of the water is equal to the slope of the bed
to achieve this the water depth must be larger than that of a normal channel
let h3 rise until water slope = bed slope
this results in a difference between Q in step 0 and the Q at the top of the page

7 Calculate the discharge in the groynefield with a given discharge of the channel

Q;tot	2000,71	m^3/s
Q;gr	558,91	m^3/s
Q;mc	1441,80	m^3/s

$$Q_{tot} = Q_{gr} + Q_{mc}$$

$$Q_{gr} = B_{gr} \cdot C_{gft} \cdot h_{gem}^{3/2} \sqrt{i}$$

Q;mc	1441,80	m^3/s
C;mc	47,66	$m^{1/2}/s$

$$Q_{mc} = B_{mc} C_{mc} (h_{gem} + \Delta z)^{3/2} \sqrt{i}$$

$$C_{mc} = 18 \log\left(\frac{12(h_{gem} + \Delta z)}{k_{s2}}\right)$$

start with a low value of Q;gr and let this rise until Q;gr + Q;mc is the desired Q;tot
with every increase of Q;gr a new h;gem must be calculated

8 Calculate the water level rise caused by the groynefield

h;gem - he=	0,18	m
Qtot=	2000,82	m^3/s
he=	7,03	m
Q;mc=	1384,30	m^3/s
C;mc	47,47	
Q;gr=	616,52	m^3/s
C=	47,25	

he is water depth relative to bottom of groynefield in case of river without groynes

$$C_{mc} = 18 \log\left(\frac{12(h_e + \Delta z)}{k_{s2}}\right)$$

$$C = 18 \log\left(\frac{12 \cdot h_e}{k_{s1}}\right)$$