Escola Tècnica Superior d'Enginyers
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MASTER THESIS

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Civil Engineering

Title

Risk analysis of the Vidaa River System

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Master Thesis Project

Risikoanalyse af Vidå-Systemet

Risk analysis of the Vidaa River system

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Preface

This Master Thesis has been submitted to the Department of Environmental Engineering at the Technical University of Denmark. It has been written by Miquel Vinyals i Patón (s101826) and supervised by the Professor Dan Rosbjerg and Henrik Madsen at DHI Water & Environment. The aim of this Master Thesis is to assess the risk of inland flooding in a tidal sluice regulated catchment using 1D flow simulation model, a stochastic weather generator, and extreme value analysis techniques.

Miquel Vinyals i Patón

(s101826)

14th March 2011

Resum

El principal propòsit d'aquest estudi hidràulic és l'avaluació de la inundabilitat del sistema fluvial del Riu Vidaa. Per tal de poder realitzar una completa avaluació les principals contribucions d'aigua envers el sistema fluvial han estat incloses a la anàlisis d'inundabilitat.

Tres tipus de software han estat utilitzats:

- Simulador de Inundabilitat (MIKE11).
- Generador d'events de precipitació (RainSim).
- Anàlisis de valors extrems (EVA eina procedent del MIKE11).

Mike11 ofereix la possibilitat en base a més de 20 anys de dades observades de precipitació (principals capçaleres de conques) i a dades de nivells d'aigua en la comporta de la desembocadura del Riu Vidaa, crear un model d'autocalibració i avaluar els Coeficients de Manning (M) i els seus nivells d'aigua al llarg del curs del Riu Vidaa.

Per a estimar la inundabilitat produïda, els generadors de temps estocàstic seran emprats. A través de sèries temporals de precipitació, RainSim les analitzarà, les ajustarà i realitzarà una simulació per obtindré sèries temporals sintètiques de precipitació amb diferents períodes de temps. Aquestes sèries temporals tindran les mateixes característiques que les dades de precipitació observades (la precipitació produïda serà exactament la mateixa).

Les sèries temporals sintètiques de precipitació, i l'autocalibració dels valors de Manning seran introduïts en el model d'inundabilitat com a noves condicions de contorn per a simular el nostre riu i extreure una nova sèrie temporal de nivells d'aigua per a cada un dels períodes temporals de precipitació.

Gràcies a aquetes noves sèries temporals de nivells d'aigua, i fent servir l'eina procedent del MIKE11 d'anàlisis de valors extrems (EVA), un enginyer pot obtindré els esdeveniments extrems per a diferents períodes de retorn (10, 25, 50, 100, 200, 500 anys) i avaluar les inundacions amb la finalitat d'obtenir les dades més altes i més perilloses del nostre sistema.

Els períodes de retorn de 50, 100, i 200 anys han estat fets servir per a simular inundacions en tres punts diferents al llarg del Riu Vidaa (WL1 – Aigües amunt, WL4- curs mitjà, i WL5 - Aigües abaix). Els resultats mostren que Tønder (WL1, la població més gran a la zona) estarà fora de perill dels esdeveniments extrems. En el curs mitjà i aigües abaix, la inundació excedirà els marges del riu, inundant les terres agrícoles del voltant.

Paraules Claus: Simulació inundació*, Coeficient de Manning, generadors de temps estocàstics, anàlisis, ajust, simulació, series temporals sintètiques, condicions de contorn, anàlisis de valors extrems, període de retorn, precipitació.*

Abstract

The main goal of this hydraulic study is the asses of flooding in the Vidaa River system. In order to realize a complete assessment, the main water contributions to the river system have been included in the flood analysis.

Three kind of software have been used:

- Flooding simulation (MIKE11).
- Stochastic weather generator (RainSim).
- Extreme value analysis (EVA tool from MIKE11).

Mike11 offers the possibility of based upon twenty years observed rainfall data (main head catchments) and water levels data of the Vidaa River mouth dam, setting up a model to auto calibrate and evaluate the Manning Coefficients (M) and the water levels around the Vidaa course.

To estimate flood, stochastic weather generator is going to be used. Through observed rainfall time series, RainSim will analyse, fit, and simulate to obtain synthetic rainfalls time series with different time periods. These time series will have the same characteristics as observed rainfall data (the precipitation occurrence process will be exactly the same).

The synthetic rainfall time series, and the auto calibrated Manning values will be introduce in the flood model as a new Boundary Conditions to simulate our river and extract a new water level time series for each rainfall time period.

Thanks to these new water levels time series, and using the Extreme Value Analysis (EVA) tool from MIKE11, an engineer can obtain the extreme events for different return periods (10, 25, 50, 100, 200, 500 years) and evaluate if floods in order to get the higher and more dangerous data from our system.

Return periods of 50, 100, and 200 years have been used to simulate floods in three different point along Vidaa River (WL1 – Upstream, WL4-Middle stream, and WL5-Downstream) The results show that Tønder (WL1, the biggest town in the area) will be safe from extreme flood events. In the Middle- and Down- Stream, the flow will exceed Vidaa River banks, flooding surrounding farm lands.

Keywords: *Flood simulation, Manning Coefficient, stochastic weather generator, analyse, fit, simulation, synthetic time series, boundary conditions, extreme value analysis, return period, rainfall.*

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Chapter 1: Location

Vidaa River

This river Vidaa (the German's names *Wiedau*) is located in the Southern part of Denmark, and part of the river is running on the border between Denmark and Germany in a region of salt marshes. Vidaa comes 4 meters above sea level in Jutland's peninsula.

'Salt marshes' is the term used to describe low stretches of clayey coastline formed by the deposition of sludge which is washed along by tidal water and bound by vegetation. When these stretches are no longer washed over by daily high tides, salt meadows are no longer formed and the fertile meadows are then protected by dykes. This type of area, protected by dykes, is called a 'polder'.

The River starts flow from East to West of Jutland. During its course, Vidaa flows beneath the city of Tønder with a different streams providing it discharge from their catchments and ends with the river mouth at North Sea after 28'90 Km close to the German border.

Figure 1– Satellite Image from Vidaa River system

The water level in the river is highly influenced by the water level in the sea, and in order to reduce the risk of flooding, as well as avoiding saltwater intrusion during high tide, the water authorities have installed several structures in the river system during the past 100 years.

Tønder, the capital of the salt marshes, is situated on the southern point of a low bank, 1-2 meters above sea level, surrounded by polders on three sides. During winter these polders used to be flooded with water from the mighty Vidaa river system. This was relieved by a drainage system including pump stations (pump station) in the 1920s. This leads to several smaller branches and tributary streams and a water regulation systems by several control structures. The river is highly controlled with weirs and gates so that the river is protected from tides and surges, and yet can pass floods from upstream.

Figure 2 - Tønder's pump station

In 1947 large parts of Tønder were flooded. The increasing draining of the Tønder marsh has often caused too high water level in Vidaa and during continuous storm periods the low dikes had difficulties to keep the water and ensure the land inside the dikes.

This is an international basin thus Vidaa run by Danish land and by German land. In German land there are two streams, Sonderaa that make as a border between

Denmark and Germany and two other streams that flows through Sonderaa called Geestableiter and Dreiharder-Gotteskoogstrom.

The Vidaa basin has a total area about 1.341’60 Km^2. The biggest part is on Danish land, 1.127’87 Km^2, and the smallest part is on German land, 213’73 Km^2.

The Vidaa River has the next streams with the following lengths:

Country	River	River/Stream Name	Length (Km)
Denmark	Main Course	Vidaa	28.90
	Streams	Gronaa	7.45
		Vidaa-Res	5.90
		Lindskov	4.32
		Margrethe-Kog	3.28
		Galgestrom	2.54
		Rudbol	2.20
		Sejersbek	1.71
Germany	Streams	Sonderaa	9.57
		Dreiharder-Gotteskoogstrom	12.49
		Geestableiter	1.92

Table 1 – Main course and streams lengths

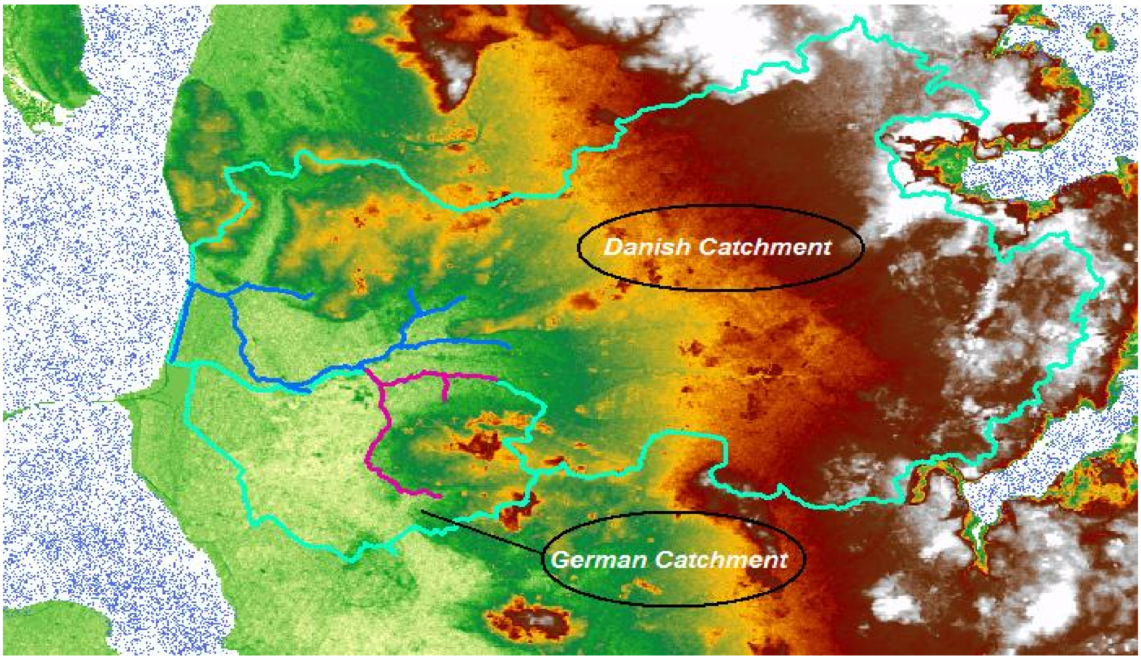


Figure 3 – Vidaa Main Course and streams with the Danish and German Basins

The river mouth of the river Vidaa is nearby Højer to the North Sea such that tides and surges affect the downstream reaches of the river. Storm floods, which broke through the sea dykes and spread death and destruction, were a greater threat than the river water. For a hundred years Tønder and its hinterland were protected by the Højerdiget dyke, built in 1861, but this gradually proved insufficient.

Figure 4 - Højerdiget dyke

The flood on January 3, 1976 clearly showed that the old Højer dike hardly can stand up to the pressure on a long-term basis.

More than 10,000 people had to be evacuated and there was a great risk that Tønder and the many enterprises in the town would be flooded. The old Højer dike is 6'4 m high above Danish Normal Zero (i.e. mean water level between low and high tide). During the flood the water level at Højer floodgate was measured at 4'92 m to which approximately 2 meters should be added from the wave gathering. The flood causes damages amounting to more than DKK 50 Million.

The rings on a storm flood pillar at the sluice in front of the old Højerdiget dyke show the water level of storm floods through the ages and this still acts as a constant warning that the sea should be taken seriously.

Figure 5 – Rings on a storm flood pillar at the sluice in front of the old Højerdiget dyke

In 1977 a bill was passed to build a new dike from Emmerlev Klev to the dam at Sylt. Since the project crossed the border, the work was to be carried out both by Denmark and Germany. The new dike has a total length of 13.3 km of which 8.6 km are in

Denmark and 3.65 km in Germany. The new dyke can withstand water levels 6 meters higher than normal and 2 meter waves. A gate is built into the dike which takes the out flowing stream water. The gate is divided into 3 lock gates with 3 automatic gates and 3 lock chambers with a total width of 20 m.

The new dike was completed on October 1, 1981 and only one month later the dike was put to the first and severe test when a flood occurred on November 24. The water level reached almost the same height as in 1976. The new dike 'The Margrethe Dike' was inaugurated by Queen Margrethe and the German Federal President Karl Carstens.

Dike in an area totalling 1.400ha was reclaimed – 1.000ha in Denmark. Approximately 650ha are used for agricultural purposes, primarily grazing, since it is not allowed to build in the new polder for safety reasons. The remaining 350ha are used as a reservoir, which during high tide when the flood gates are closed can gather the water until the flood gates are opened again. By doing so the pressure on the stream dike and Rudbøl Sø is removed. Previously during westerly gales the stream dike and Rudbøl Sø were supposed to take the large rain quantity from Vidaa.

Chapter 2: Roughness factor (Manning coefficient value)

One of the weakest points in the rivers hydraulics is the valuation of the resistance to flow. Their quantification is the evaluation of forces exerted by the walls and other elements that come into contact with the flow, moving or not with it, and compensating the gravity action which is the driving force.

A way to evaluate the resistance is using Manning-Strickler formula where Strickler coefficient is 1/n (***Manning, R. 1891***). That formula was obtained experimentally and it expression that best meets channels is:

$$V = M \times R_h{}^{2/3} \times S_o{}^{1/2}$$

Where ***V*** is the mean velocity, ***R_h*** is the hydraulic radius, ***S_o*** is the slope of energy line, and ***M*** is the roughness coefficient, specially known as ***Manning's M***. This formula was developed from seven different formulas, based on Basin's experimental data, and further verified by 170 observations (***Chow, V.T., 1959***).

In applying the Manning formula, the greatest difficulty lies in the determination of the roughness coefficient ***M***. To select a value of ***M*** actually means estimate the resistance to flow in a given channel, which is really a matter of intangibles. To veteran engineers, this means the exercise of sound engineering judgment and experience; for beginners, it can be no more than a guess, and different individuals will obtain different results.

It is not uncommon to think of a channel as having a single value of ***M*** for all occasions. In reality, the value of ***M*** is highly variable and depends on a number of factors. In selecting a proper value of ***M*** for various design conditions, a basic knowledge of these factors should be found very useful.

To estimate the roughness flow coefficient when one has a channel with it geometry, slope and vegetation, many times ones use empirical formulations or by the use of abacas built by photographs and schemes representative about that kind of section and morphology.

The factors that exert the greatest influence upon the coefficient of roughness in natural channels are therefore described below.

Surface Roughness (granulometry)

The surface roughness is represented by the size and shape of the grains of the material forming the wetted perimeter and producing a retarding effect on the flow. The size of the grains is measured according the second axis of an ellipsoid which can assimilate a particle. In the below figure, one can observe that ***b*** is the critical size for a grain pass or be retained by a sieve.

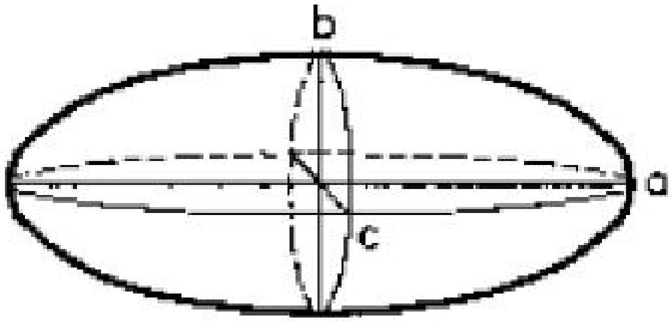


Figure 6 - Imaginary particle axis

The common way to analyse the size's distribution on the channel is to sift a sample and weight the fraction passing for each sieve but is kept in the next sieve. The graphical representation about those fractions in a histogram is an average version, into size classes, a probability density function of the sizes. The cumulative plot where will be represented the fraction (as a percentage) with weightless than a certain size, is obtaining by adding the weights of all the lower types. That curve is an average version from cumulative distribution function of the variable size ***D*** (see the below figure).

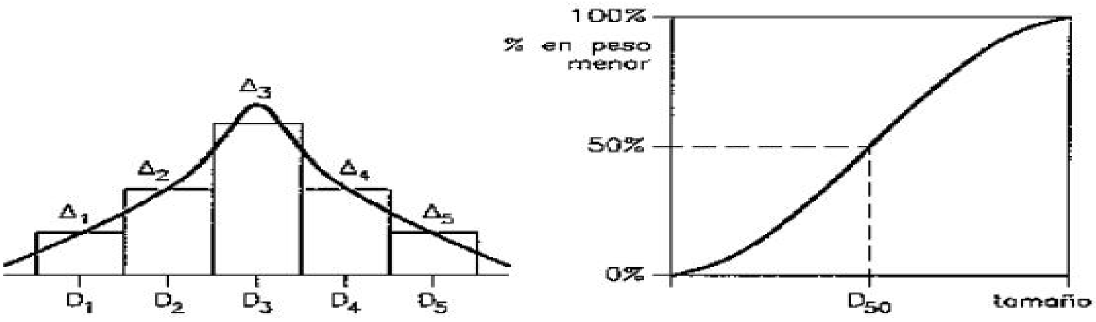


Figure 7 - Discrete or continuous distribution in sizes (left side) and granulometric continue curve

In the last figure, the granulometric curve, the meaning of the nomenclature used to designate size: D_n the size where weight material $n\%$ is less than it. D_{90} means a large size or the material thick part, while D_{10} means small size or the material thin part.

The size and shape are often considered the only factor in selecting a roughness coefficient. Generally speaking, fine grains result in a relatively high value of ***M*** and coarse grains, in a low value of ***M***.

In alluvial streams where the material is fine in grain, such as sand, clay, loam, or silt, the retarding effect is much less than where the material is coarse, such as gravels or boulders. When the material is fine, the value of ***M*** is high and relatively unaffected by change in flow stage. When the material consists of gravels and boulders, the value of ***M*** is generally low particularly at low or high stage. Larger boulders usually collect at the bottom of the stream, making the channel bottom rougher than the banks and decreasing the value of ***M***.

Type of material	Diameter (mm)	Type of material	Diameter (mm)
Clay	< 0’004	Gravels	2’0 < x < 64’0
Slime	0’004 < x < 0’062	Boulders	64’0 < x < 256’0
Sand	0’062 < x < 2’0		

Table 2– Diameters ranges for each type of material

In many cases the Keulegan equation is used to estimate the average speed of open channel flow (***Colosimo, C. et al, 1989***) and obtain the flow resistance. This expression is given by:

$$\frac{U}{u_*} = C_f^{-1/2} = \frac{1}{k} \times \ln\left(\frac{11 \times y}{k_s}\right)$$

$$C_f = \frac{g \times y \times S_o}{U^2}$$

U	Average velocity	k	Universal Von Karman constant (with a value of 0’41)
u_*	Cutting speed	y	Depth
C_f	Friction coefficient	k_s	Roughness height

If one try to link the Manning definition given by the expression with friction coefficient formula:

$$n = \frac{1}{C} \times R_h^{-1/2} = \frac{C_f^{1/2}}{g} \times R_h^{1/6}$$

With Keulegan's formula one can set the following expression:

$$\frac{1}{k} \times \ln\left(\frac{11 \times y}{K_s}\right) = \frac{y^{1/6}}{n \times g}$$

In this relationship has replaced the hydraulic radius value by the depth, ergo, valid to wide channels. On the other hand one can prove that logarithmic function and the exponent (1/6) have almost the same mathematical behaviour so the previous expression can be written as:

$$\frac{1}{k} \times \left(\frac{11 \times y}{k_s}\right)^{1/6} = \frac{y^{1/6}}{n \times g}$$

Where one can simplify in both sides the depth raised to the power of (1/6). Finally, one can express Manning value for streams as:

$$n = \frac{k \times k_s^{1/6}}{g \times 11^{1/6}} = \frac{k_s^{1/6}}{24'4}$$

That expression according Keulegan is made for a rough surface and can be checked experimentally the ***k_s*** value can be replaced by the particle or grain diameter. Thus, according Strickler one can replace by ***D₅₀*** if the factor of proportionality is changed by 21 instead 24'4. If ones use ***D₉₀*** has to change 26 instead 24'4.

$$n = \frac{D_{50}^{1/6}}{21} \qquad \Longleftrightarrow \qquad M = \frac{21}{D_{50}^{1/6}}$$

$$n = \frac{D_{90}^{1/6}}{26} \qquad \Longleftrightarrow \qquad M = \frac{26}{D_{90}^{1/6}}$$

In short, when the material is fine, the value of ***M*** is high and relatively unaffected by change in flow stage and when the material consists of gravels and boulders, the value of ***M*** is generally low particularly at low or high stage.

$$M_{sand\ fine} = {}^{21}/_{0'0001^{1/6}} = 97'47$$

$$M_{sand\ medium} = {}^{21}/_{0'0005^{1/6}} = 74'54$$

$$M_{sand\ coarse} = {}^{21}/_{0'001^{1/6}} = 66'40$$

$$M_{gravel} = {}^{21}/_{0'05^{1/6}} = 34'60$$

$$M_{boulders} = {}^{21}/_{0'26^{1/6}} = 26'29$$

Table 3 – Different Manning values according to Strickler formula for different types of material D50 in meters unit

Vegetation

The morphological role of vegetation is explained by its direct action on the ground. The roots of plants fix the loose material in the riverbed, e.g. Sands. These fix action happens on the banks of main channel, and on flood plains.

The river cross sections are a result of the water interaction, the solid particles and the resistance offered by vegetation, both in the sense of resistance to flow (roughness), and as a drag resistance to flood.

The morphological role of vegetation is more important in short rivers than in larger rivers because vegetation don not keep any proportion with the size of the river.

Vegetation develops as a function of physical factors, climate and water (***Martín Vide, J.P., 2002***). From the last factors, the most important of them are:

- Moisture in the root zone determined by the ordinary levels of the river
- Mechanical action from high water and floods
- Water quality (or inversely pollution)

Changes in those hydric conditions cause "normal" developmental disorders of population, for instance:

- Wilting vegetation due a low water table
- Replacement of species to lose the water quality
- Drag loss frequency and grown plants in floods

Those changes affect the shape and dimension of the channel (***Hemphill, R.W. et al, 1989***). Resistance features values are 4 m/s if flood action lasts less than an hour, but only 1.5 m/s if lasts two days.

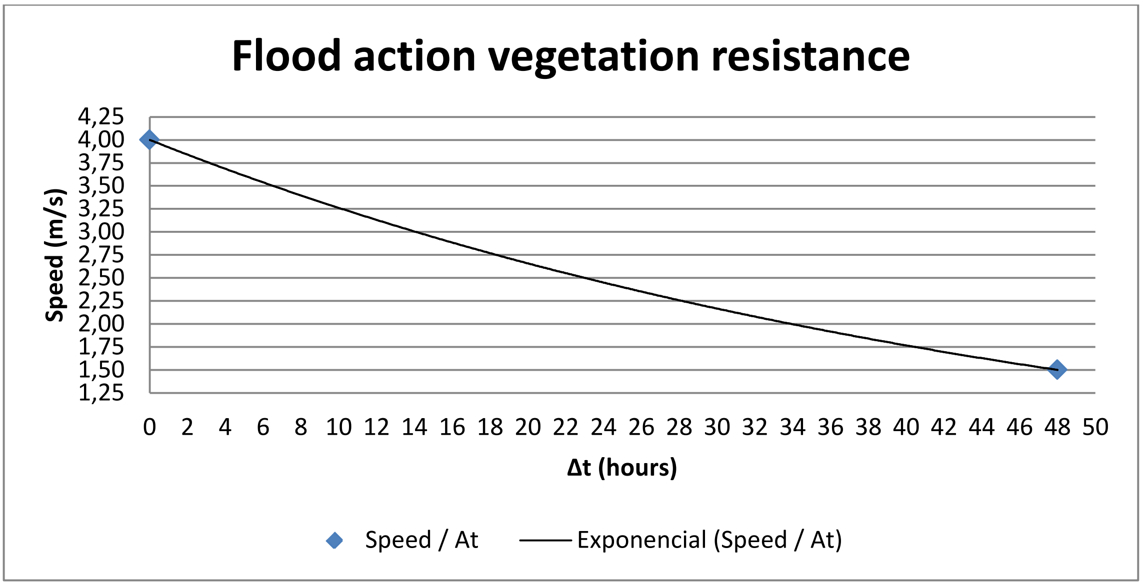


Figure 8 - Evolution vegetation resistance graphic with flood action

A vegetated course presents the difficulty associated with the natural variability in the roughness coefficients.

The reactions of drag strength make it from the plant, is the resistance that makes the plant over the flow.

The drag strength can be expressed as:

$$F_D = \frac{1}{2} \times \rho \times C_D \times A \times U^2$$

A	Frontal vegetation area against the flow	**U**	Average speed of approximation to the obstacle
C_D	Drag coefficient	**ρ**	Water density (1000 Kg/m^3)

This equation together with the vegetation reaction to the flow (flexion when the flow is great) considering the branch structure and distribution areas (channel density vegetation) determine the average flow resistance from the vegetation system.

All these things make the evaluation of the resistance coefficient difficult because it is variable with flow. This happens because; if one talk about flexible vegetation, plants is flexed as it passes over water and therefore increasingly have less opposition to the flow. However, with rigid vegetation, the law is incremental and resistance factors increase with the flow.

Increasing power flow, represented by ***UxR_h*** (where ***U*** is the velocity and ***R_h*** is the hydraulic radius), causes important decreases in the coefficients of flows resistance in vegetated streams. ***Ree & Palmer, (1949),*** from US Soil Conservation Service, (USSCS) created “Delay curves” as a function of type and grass species to the stabilization of vegetated irrigation canals (see below figure).

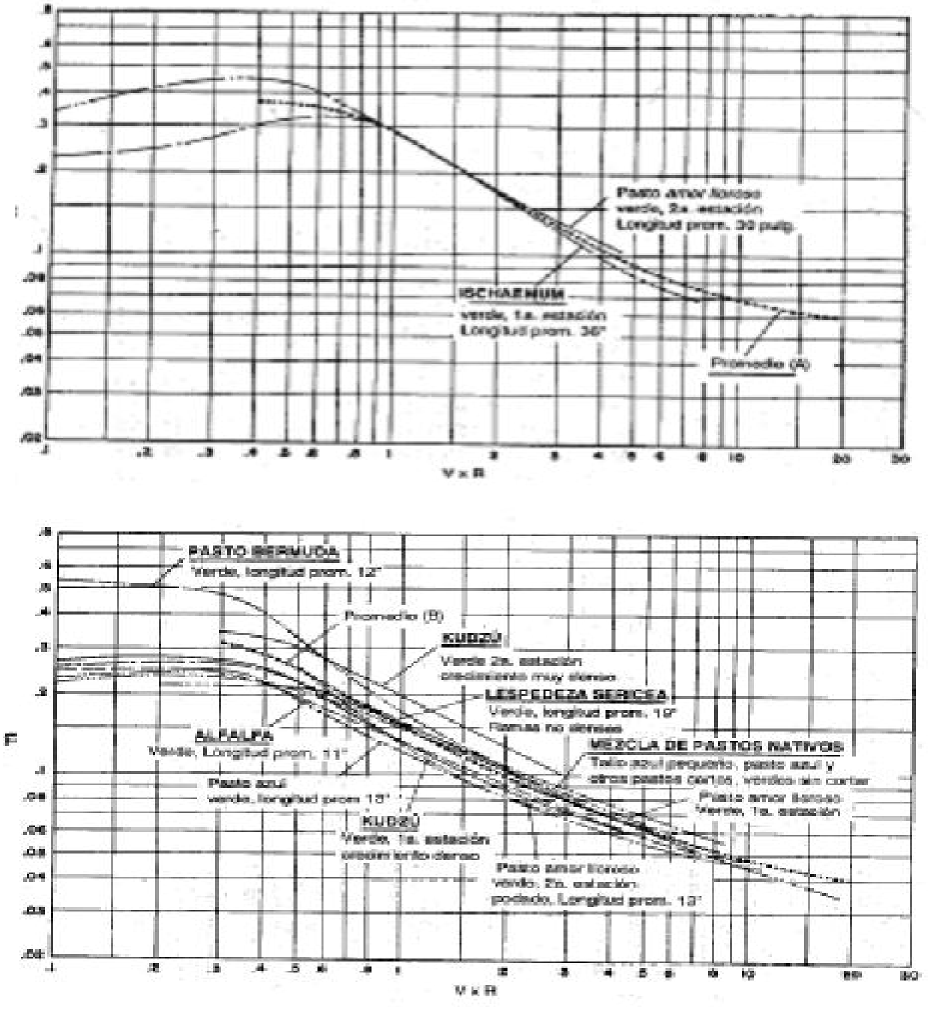


Figure 9 - Curves for very high (A) and high (B) plant delay (n – VxR)

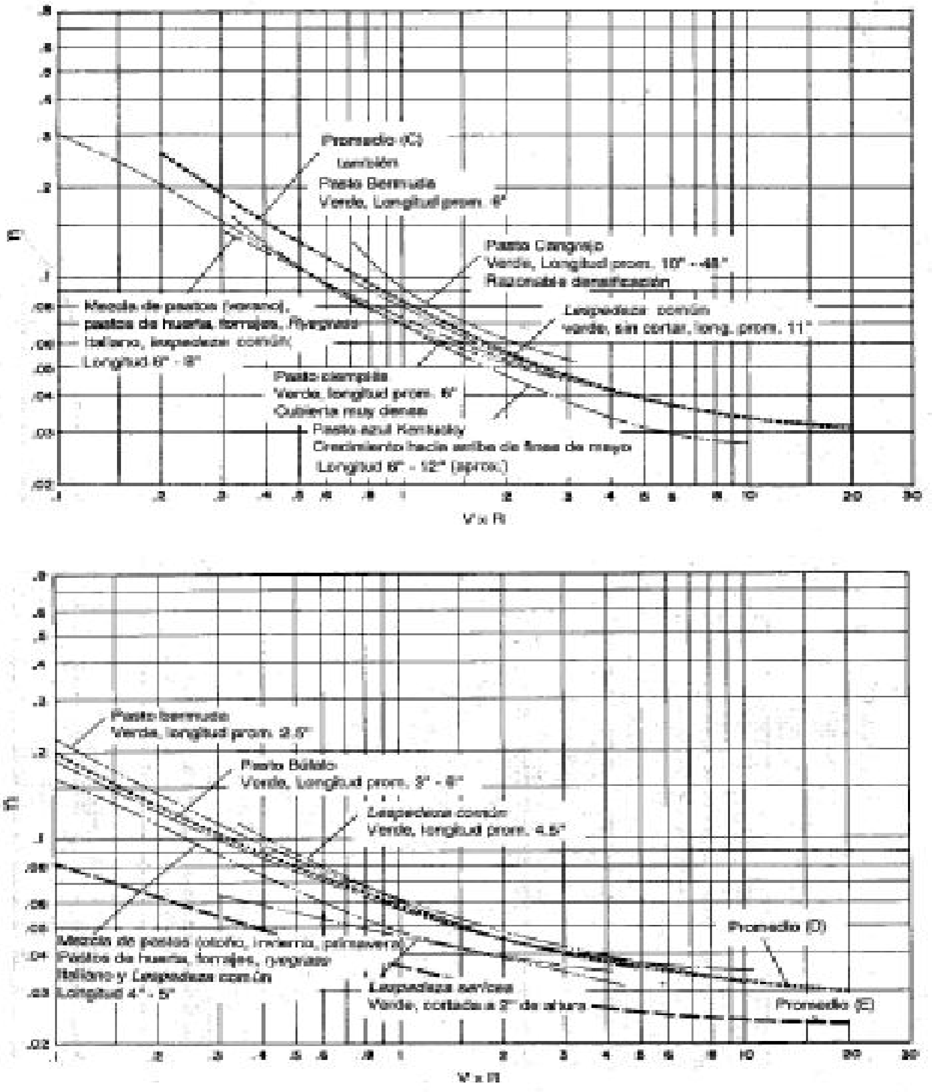


Figure 10 - Curves for moderate (C), low (D) and very low (E) plant delay (n – VxR)

Kouwen, N. (1969, 1973, and 1980) is the first researcher who recreates those kinds of problems and formulates for the first time a relationship that is used to determine the Darcy Weissback friction factor:

$$\frac{1}{\sqrt{f}} = a + b \times log_{10} \times \left(\frac{h}{k}\right)$$

f	Flow resistance factor	**h**	Depth
a - b	Constant that depend on the flow characteristics (submerged and emerged plants	**k**	Deformed or flexed plant height

for the flow resistance model and the next dimensionless connection to the flexion influence model on the plant

$$\frac{k}{h'} = 0'14 \times \left[\frac{\left(\frac{M \times E \times I}{\gamma \times h \times S_o} \right)^{0'25}}{h'} \right]^{1'59}$$

M	Plan density per unit area	**γ**	Water specific weight
E	Vegetation elasticity module	**h'**	Undeformed plant height
I	Inertia of the cross section	**S_o**	Channel slope

Velasco (2006) proposed to use the next formula that improves the ***Kouwen*** formula. ***Kouwen*** used plastic plants and ***Velasco*** used real vegetation.

$$\frac{k}{h'} = 0'434 \times \left[\frac{\left(\frac{M \times E \times I}{\rho \times V^{*2}} \right)^{1/4}}{h'} \right]^{0'568}$$

There exist later formulations with higher precision on the calculation that could be used for to estimate flow resistance.

Rahmeyer, M., Werth, D., and Freeman, G. (1999) proposed two kinds of formulas:

- Submerged Plant (see Figure 11)

$$\sqrt{\frac{f}{8}} = 0'183 \times \left(\frac{E_s \times A_s}{\rho \times A_i \times V^{*2}} \right)^{0'183} \times \left(\frac{H}{Y_o} \right)^{0'243} \times (M \times A_i)^{0'273} \times \left(\frac{v}{V^* \times R_h} \right)^{0'115}$$

A_i	Wet front obstruction area	**A_s**	Plant projection plan area

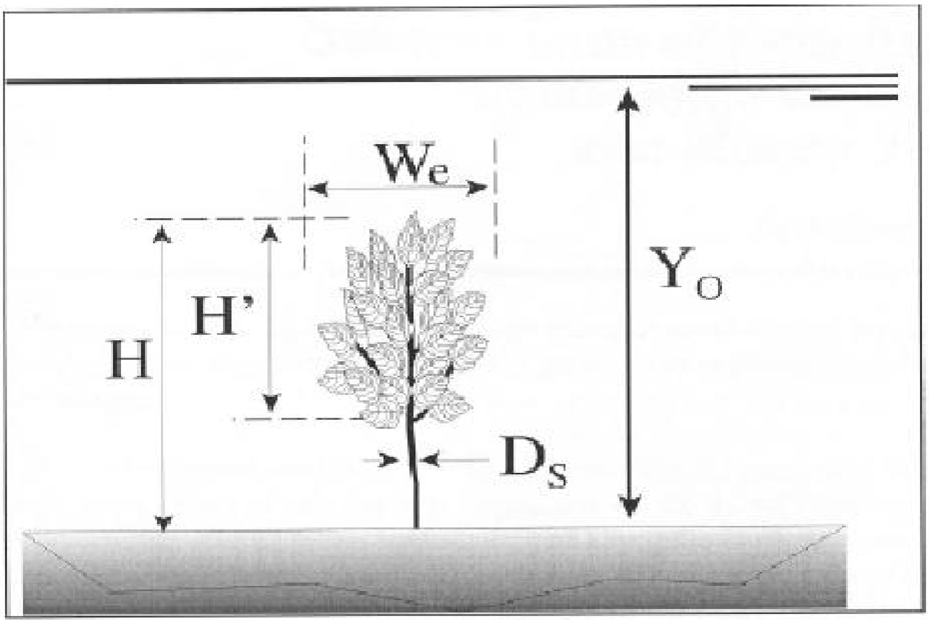


Figure 11 – Plant dimension definitions for submerged plants

- Emergent Plant (see Figure 12)

$$\sqrt{\frac{f}{8}} = 9'159E - 5 \times \left(\frac{E_s \times A_s}{\rho \times A_i \times V^{*2}}\right)^{0'207} \times (M \times A_i)^{0'0547} \times \left(\frac{V^* \times R_h}{v}\right)^{0'490}$$

A_i	Wet front obstruction area	**A_s**	Plant projection plan area

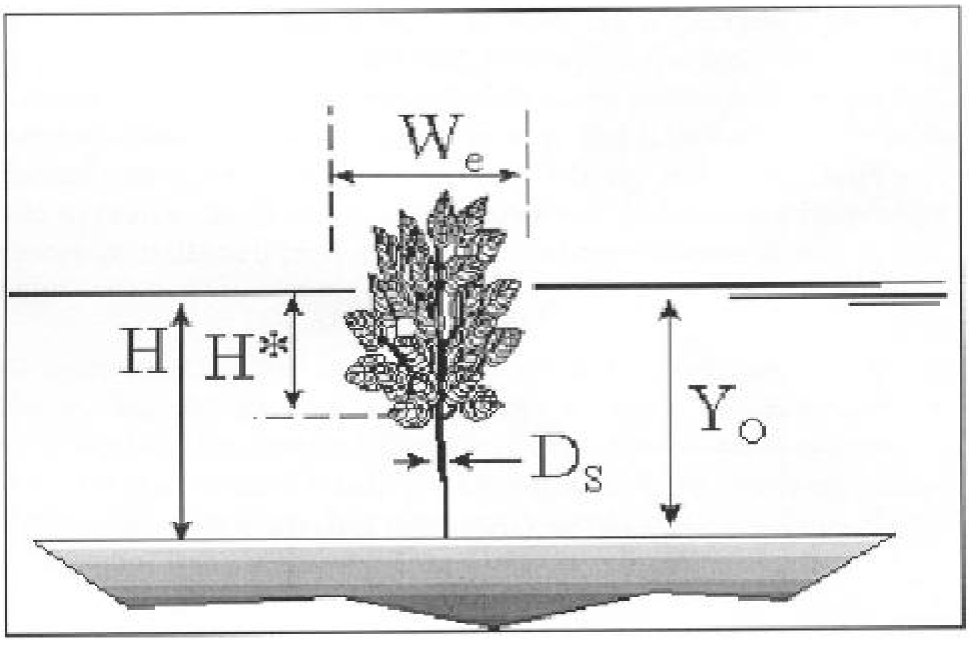


Figure 12 – Plant dimension definitions for partially submerged plants

One has to accept vegetation has a physic limit; it cannot withstand the stresses to a certain value, above which the vegetation as structure fails and break. On the other hand the vegetative system may fail as a group yield the floor that supports.

The distribution of absorbed strength by vegetation is the unknown parameter that one has to solve. The equation which permits evaluate this strength is the Drag strength. One can observe that Drag strength varies with altitude.

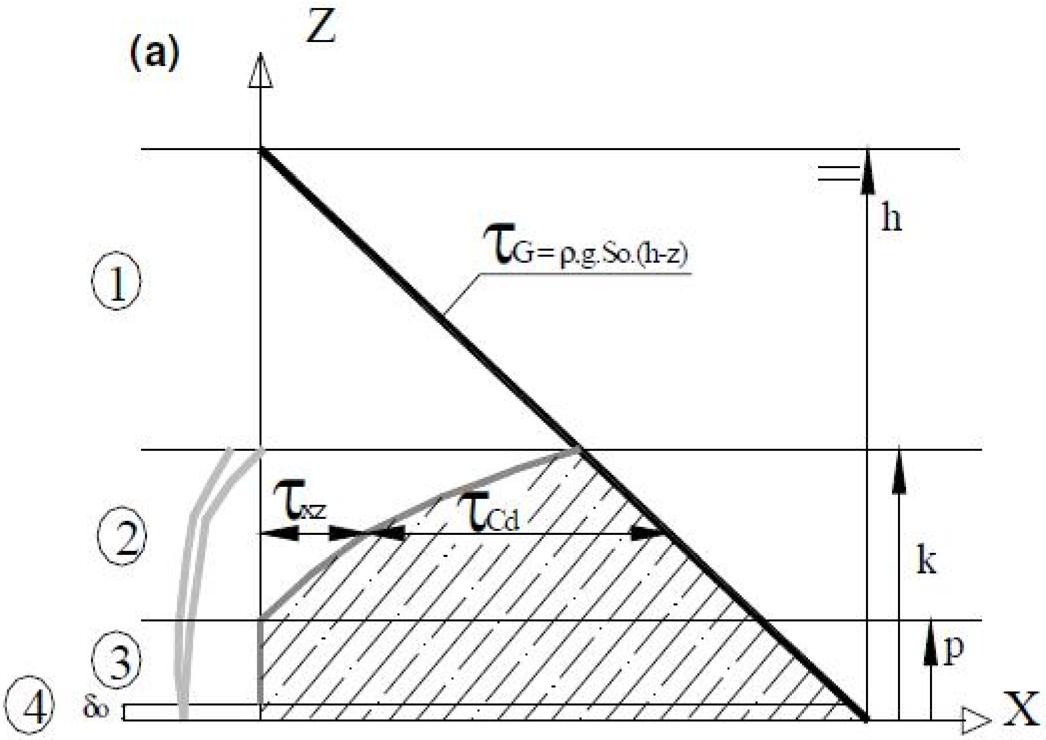


Figure 13 – Distribution of the stresses of weight and Drag along water depth

The vegetation absorbs Reynolds strength and through the stem these strength are transmitted to the bottom channel. Reynolds stresses decrease rapidly until almost cancelled.

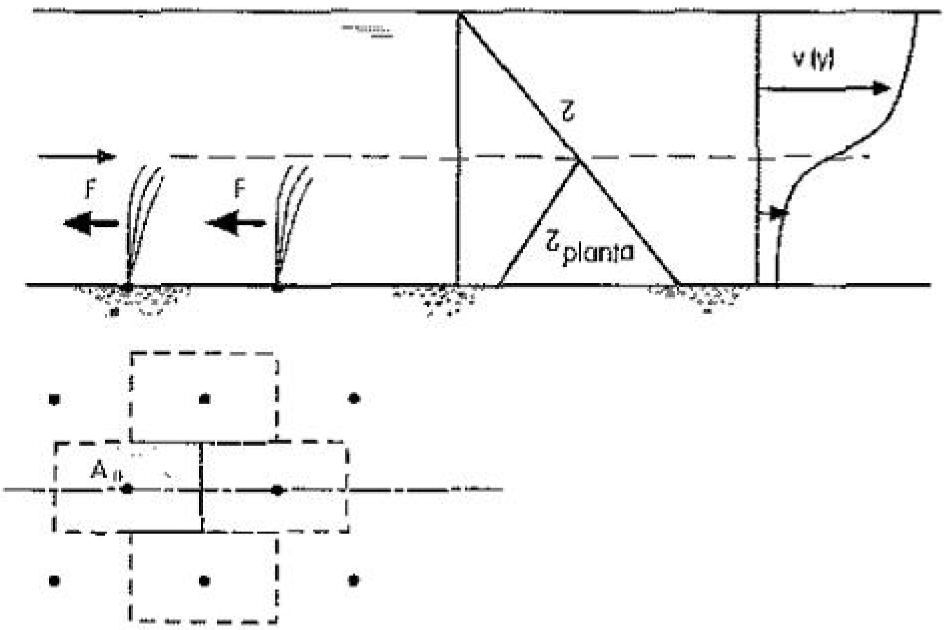


Figure 14– Effect of vegetation of the speed distribution and strains, and plant deformation

The Figure 14 shows the effect of vegetation of the speed distribution and strains as a result of uptakes of vegetation stress.

One can specify when vegetation in a river exists, the river has higher roughness and the water level will increase, so Manning value will change with that parameter. Also, Manning value depends on the plant flexibility, height, density, distribution and type of vegetation, therefore the Manning value will decrease if the plant flexibility increase and vice versa, Manning will increase if height, density and distribution plant decrease. In the below table one can check different Manning values for different kind of plants.

Grass	n = 0’035	M = 28’6
Orchard	n = 0’040	M = 25’0
Fruit trees	n = 0’050	M = 20’0
Hurdle	n = 0’075	M = 13’3

Table 4 – Different vegetation Manning values

Channel Irregularity

Channel irregularity comprises irregularities in wetted perimeter and variations in cross section, size, and shape along the channel length. In natural channels, such irregularities are usually introduced by the presence of sand bars, sand waves, ridges and depressions, and holes and humps on the channel bed. These irregularities definitely introduce roughness in addition to that caused by surface roughness and other factors. Generally speaking, a gradual and uniform change in cross section, size, and shape will not appreciably affect the value of ***M***, but abrupt changes or alternation of small and large sections necessitates the use of a short value of ***M***. In this case, the decrease in ***M*** may be 0.005 or more. Changes that cause sinuous flow from side to side of the channel will produce the same effect.

The river bottom with sediment transport can present a configuration no flat but wavy, following the bed forms calls. Bed forms are pretty important because they take part on the sediment transport and decisively involved in the flow resistance (roughness). Bed forms happens in sand beds while are not happen (not easy to happen) in grave beds.

When the movement starts in a sand bed and the velocity is increasing ones can observe following bed forms: ripples, dunes, flatbed, antidunes and rapids and deep pools.

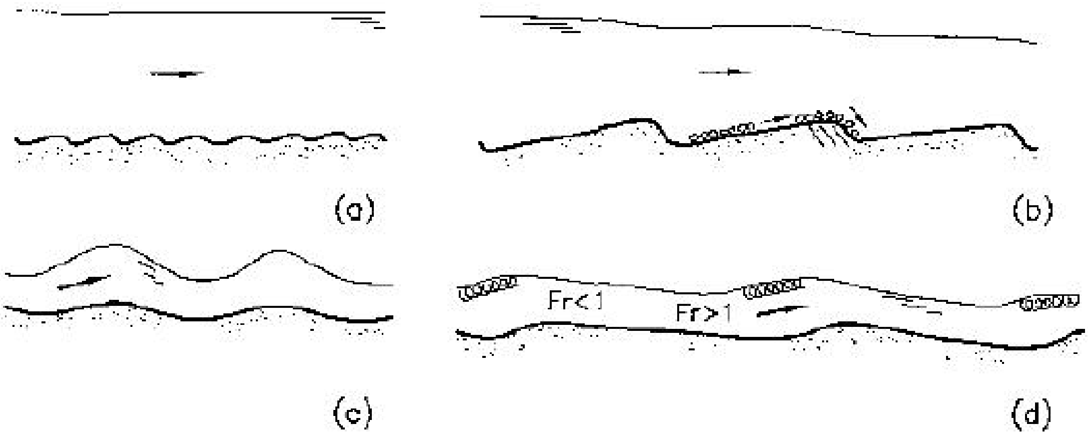


Figure 15 - Bed forms: ripples (a), dunes (b), antidunes (c), rapids and deep pools (d)

Channel Alignment

Smooth curvature with large radius will give a relatively high value of ***M***, whereas sharp curvature with severe meandering will decrease ***M***. On the basis of flume tests, ***Scobey, Frederick C. (1933)*** suggested that the value of ***M*** be decreased 0.001 for each 20 degrees of curvature ever decreases ***M*** more than 0.002 or 0.003, its effect should not be ignored, for curvature may induce the accumulations of drift and thus indirectly decrease the value of ***M***. Generally speaking, the increase of roughness in unlined channels carrying water at low velocities is negligible. The meandering of natural streams may decrease the ***M*** value as high 30%.

Silting and Scouring

Generally speaking, silting may change a very irregular channel into a comparatively uniform one and increase ***M***, whereas scouring may do the reverse and decrease ***M***. However, the dominant effect of silting will depend on the nature of the material deposited. Uneven deposits such as sand bars and sands waves are channel irregularities and will increase the roughness. The amount and uniformity of scouring will depend on the material forming the wetted perimeter. Thus, a sandy or gravelly bed will be eroded more uniformly than a clay bed. The deposition of silt eroded from the uplands will tend to even out the irregularities in a channel dredged through clay. The energy used eroding and carrying the material in suspension or scouring is not significant as long as the erosion on channel bed caused by high velocities is progressing evenly and uniformly.

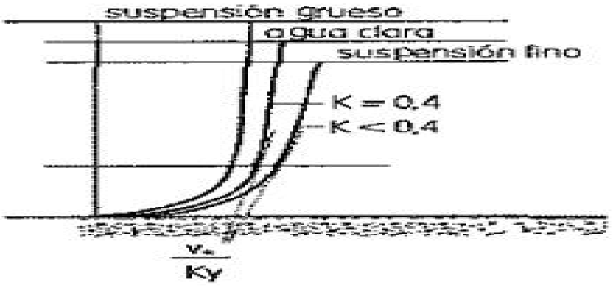


Figure 16 - Effect of a suspension of fine material and coarse material on the velocity profile

Stage and Discharge

The ***M*** value in most streams increase with increase in stage and in discharge. When the water is shallow, the irregularities of the channel bottom are exposed and their effects become pronounced. However, the ***M*** value may be short at high stages if the banks are rough and grassy.

When the discharge is too high, the stream may overflow its banks and a portion of the flow will be along the flood plain. The ***M*** value of the flood plains is generally shorter than that of the channel proper, and its magnitude depends on the surface condition or vegetation. If the bed and banks of a channel are equally smooth and regular and the bottom slope is uniform, the value of ***M*** may remain almost the same at all stages; so a constant ***M*** is usually assumed in the flow computation. On flood plains the value of ***M*** usually varies with the stage of submergence of the vegetation at low stages. This can be seen, for example, from Table 5, which shows the ***M*** values for various flood stages according to the type of cover and depth of inundation, as observed in the Nishnabotna River, Iowa (***Chow, V.T. (1959)***), for the average growing season.

Depth of water (ft)	**Channel section**	**Flood-plain cover**				
		Corn	**Pasture**	**Meadow**	**Small grains**	**Brush and waste**
Under 1	33.33	16.67	20.00	10.00	10.00	8.33
1 to 2	33.33	16.67	20.00	12.50	11.11	9.09
2 to 3	33.33	14.29	25.00	14.29	12.50	10.00
3 to 4	33.33	14.29	25.00	16.67	14.29	11.11
Over 4	33.33	16.67	25.00	20.00	16.67	12.50

Table 5 - Values of M for various stages in the Nishnabotna River, Iowa, for the average growing season

Curves of *n* (*n* = 1/M) value versus stage in streams have been given by ***Lane, E.W. (1951)***, showing how value of *n* varies with stage in three large river channel (see the figure below).

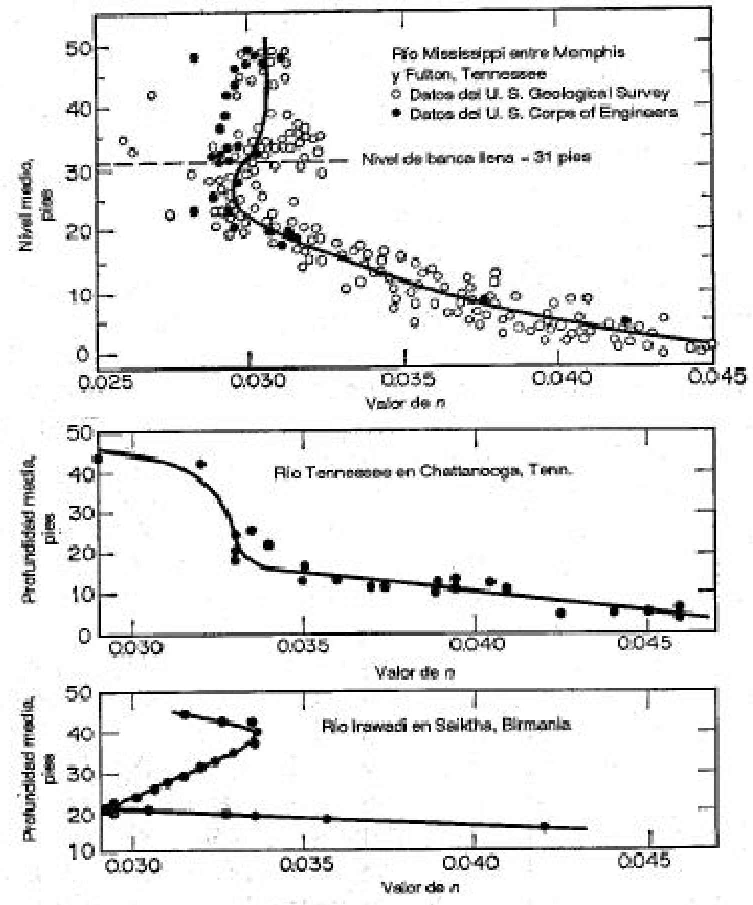


Figure 17 - Variations of the n (n = 1/M) value with the mean stage or depth

The two most important conclusions reached from this study were:

- The *n* value for a river channel is least (higher for ***M*** value) when the stage is at or somewhat above normal bank full stage, and tends to increase for both higher and lower stages.
- The bank full *n* (or ***M***) values do not vary greatly for rivers and canals in different kinds of material and in widely separated locations.

Seasonal Change

Owing to the seasonal growth of aquatic plants, grass, weeds, willow, and trees in the channel or on the banks, the value of ***M*** may decrease in the growing season and increase in the dormant season.

Suspended Material and Bed Load

The suspended material and bed load, whether moving or not moving, would consume energy and cause head loss or increase the apparent channel roughness.

That kind of material will silt following the Stokes Law.

$$v = \frac{\gamma_s - \gamma_w}{18 \times \eta} \times D^2$$

v	Silt velocity	η	Fluid viscosity
γ_s	Soil specific weight	D^2	Grain diameter
γ_w	Water specific weight		

If flow velocity is lower than ***v***, the grains will start to silt, and vice versa, if flow velocity is higher than ***v***, the grains will continue suspended and moving with the river flow.

All above the factors should be studied and evaluated with respect to conditions regarding type of channel, state of flow, degree of maintenance, and other related considerations. As a general guide to judgment, it may be accepted that conditions tending to induce turbulence and cause retardation will decrease ***M*** value and that those tending to reduce turbulence and retardation will increase M value.

Recognizing several primary factors affecting the roughness coefficient, ***Cowan, W.L. (1956)*** developed a procedure for estimating the value of n (n = 1/M). By this procedure, the value of n may be computed by:

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m_5$$

Where:

n_0	Value for straight, uniform, smooth channel in the naturals materials involved
n_1	Value to correct for the effect of surfaces irregularities
n_2	Value for variations in shape and size of the channel cross section
n_3	Value for obstructions
n_4	Value for vegetation and flow conditions
m_5	Correction factor for meandering of channel

Proper values of n_0 to n_4 and $m_5$may be selected from the below table according to the give conditions:

Channel conditions		**Values n**	
Material involved	Earth	n0	0.020
	Rock cut		0.025
	Fine gravel		0.024
	Coarse gravel		0.028
Degree of irregularity	Smooth	n1	0.000
	Minor		0.005
	Moderate		0.010
	Severe		0.020
Variations of channel cross section	Gradual	n2	0.000
	Alternating occasionally		0.005
	Alternating frequently		0.010-0.015
Relative effect of obstructions	Negligible	n3	0.000
	Minor		0.010-0.015
	Appreciable		0.020-0.030
	Severe		0.040-0.060
Vegetation	Low	n4	0.005-0.010
	Medium		0.010-0.025
	High		0.025-0.050
	Very high		0.050-0.100
Degree of meandering	Minor	m5	1.000
	Appreciable		1.150
	Severe		1.300

Table 6 - Values for the computation of the roughness coefficient

Chapter 3: Weather Generators

Introduction

Weather generators (WG) are statistical models used to produce realistic synthetic time series of weather variables (***Kilsby C.G. et al, 2007***) of unlimited length for a location based on the statistical characteristics of observed weather at that location. Usually have a similar structure, with precipitation considered to be the primary variable (***Wilks and Wilby, 1999***). Models for generating stochastic weather data are conventionally developed in two steps (***Hutchinson 1987***). The first step is to model daily precipitation and the second step is to model the remaining variables of interest, such as daily maximum and minimum temperature, solar radiation, humidity and windspeed conditional on precipitation occurrence, depending on whether the day is wet or dry.

The most common types of WGs are usually single-location or point-process models, meaning that only data at a single-point, or independently at multiple points, can be generated (single & spatial analysis). So thanks to WGs the user can exclude the use of synthetic data for further climate change impact studies, where information about basin scale is needed.

Different model parameters are usually required for each month, to reflect seasonal variations both in the values of the variables themselves and in their cross-correlations.

Perhaps the best known approach for developing weather generators was reviewed by ***Richardson, C. W., 1981***, and WGs based on the approach are often referred to as the "Richardson-type". At the first step, the estimation of precipitation involves first modeling the occurrence of wet and dry days using a Markov procedure, and then modeling the amount of precipitation falling on wet days using a functional estimate of the precipitation frequency distribution. The remaining variables are then computed based on their correlations with each other and with the wet or dry status of each day. The Richardson-type of generator has been used very successfully in a range of applications in hydrology, agriculture and environmental management.

The decision to apply a weather generator in an impact assessment may be determined by one or more of the following requirements:

- Long time series of daily weather, which are not available from observational records
- Daily weather data in a region of data shortage
- Gridded daily weather data for spatial analysis (e.g. of risk)

Weather Generators are a group of methods than can either provide alternative weather sequences, compensating for the inadequate length, completeness and spatial coverage of climate records, or be a mean of in-filling missing data.

The results consist of meteorological time series data with similar statistical properties as those of observed data.

Synthetic produced time series are of an infinite length, thus it allow impact studies of exceptional meteorological variables. With that kind of synthetic time series, the user only will have a time period with the similar statistics as the period observed, I mean, WG's cannot forecast the rainfall that will be produce in the future, but even so will be a good approximation. Therefore WGs are not weather forecast algorithms. WGs are stochastic models for day-to-day (or longer periods) variations in the weather. Stochastic model outputs only simulate key statistical properties of observed meteorological records, therefore "it is not expected that any particular simulated weather sequence will be duplicated in weather observations at a given time in either the past or the future" (***Wilks and Wilby, 1999***).

The basic idea in statistical downscaling is to define a relationship between the large-scale model and the local climate. The basic assumption is that the relationship between large and local scale will remain constant in the future. This is the main drawback in statistical downscaling since the basic assumption cannot be verified (***Fowler et al., 2007***).

There are currently many weather generators in existence, but they can be divided in three main types:

- Parametric WGs
- Semi-parametric/empirical WG’s
- Non-parametric WG’s

The precipitation process is the most important to develop a WG. Rainfall represents the most critical variable and shows correlation between values at successive time-periods and, due to the fact that its value is often exactly zero (dry day), a discontinuity in the probability distribution between zero and the non-zero observations comes out.

The user can divide the precipitation process into two separate processes:

- Precipitation occurrence process
- Precipitation amount process

The occurrence process will be characterized by the wet and dry state. The tendency of wet and dry day’s exhibit persistence, or positive serial correlation, is a key feature of stochastic weather models. On the one hand, the precipitation amount process models and simulates the non-zero precipitations amounts (wet days) according to a specific distribution. The typical presence of many small values and few, but important, large values confirms that non-zero precipitation amounts are strongly skewed to the right.

Neyman-Scott Rectangular Pulses Weather Generator

The Neyman-Scott Rectangular Pulses (NSRP) WG is based on a clustering approach, where rainfall is associated with clusters or rain cells making up storm events. The model rain cells may be thought of as loosely representing small-scale rain-bearing meteorological structures. For example, a short intense rain cell could be a thunderstorm while a longer less intense cell could be associated with a warm front. It represents the observed clustered nature of rainfall and differs from the weather generators introduced above by handling occurrence and amounts in one process (***Kilsby et al., 2007***). The positions of the rain cells are determined by a set of independent and identically distributed random variables representing the time intervals between the storm origin and the birth of the individual cells. The model structure is shown below.

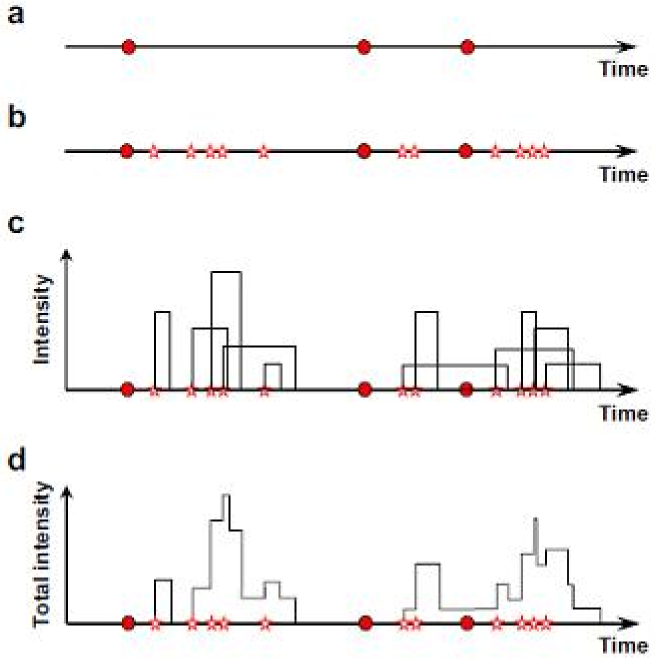


Figure 18 –Schematic of the Neyman-Scott Rectangular Pulses model

In NSRP a storm is defined through 4 different steps:

- A storm origin arrives according to a Poisson process with the arrival rate represented by a parameter λ.
- Each storm origin generates a (Poisson) random number C, with a mean value ν, of rain cells separated from the storm origin by time intervals that are each exponentially distributed with parameter β.
- The duration (*X*) of each rain cell is independent random parameters and is exponentially distributed with parameter η.
- The intensity (*X*) of each rain cell is independent random parameters and is exponentially distributed with parameter ε.
- The total rainfall intensity is the sum of the intensities of all the active cells at that time step.

In the spatial–temporal version of the model (STNSRP) (***Cowpertwait, 1995***) the raincell generation process of the single site model, the first part of second step, is replaced by a uniform Poisson process in space with density ρ to generate the centers of spatially circular raincells. Additionally, the radius of each raincell is exponentially distributed with parameter γ. During each cell's lifetime rainfall occurs with a uniform intensity across its spatial extent and throughout its duration. This process is spatially stationary and so a necessary final step is to account of orography by non-uniform scaling of the rainfall field. Time series sampled at each site m are scaled by a factor, φm, proportional to each sites mean rainfall. Sampling the simulated rainfall field at locations without observed records therefore requires interpolation of these factors.

The parameters of the model can be summarized as follows:

Parameters	Descriptions	Units
λ^{-1}	Mean waiting time between adjacent storm origins	(h)
β^{-1}	Mean waiting time for raincell origins after storm origin	(h)
η^{-1}	Mean duration of raincell	(h)
ν	Mean number of raincells per storm	(-)
ε^{-1}	Mean intensity of a raincell	(mm/h)
γ^{-1}	Mean radius of raincells	(km)
ρ	Spatial density of raincell centres	(km^{-2})
ϕ	A vector of scale factors, ϕ_m, one for each rain gauge, *m*	(-)

Table 7 – Parameters of NSRP/STNSRP simulators

The five first are used for single site, NSRP, applications and seven for spatial applications, STNSRP.

A large number of statistics can be used in the model fitting. These are: mean, variance and skewness of rainfall amount, lag-correlation, dry period probability, probability of a dry-dry sequence, and probability of a wet-wet sequence. The model fitting is carried out using a numerical optimization routine to minimize an objective function, which is a function depending on the set of statistics selected.

Change factors are calculated for the set of statistics selected, in this case: mean, variance and skewness of rainfall amount, dry day probability, and lag-correlation.

The model is calibrated separately for each calendar month in turn. A numerical optimization scheme is used to find the best choice of parameters to minimize an objective function, D(λ, β, …, ε), which describes the degree to which a simulation is expected to correspond to a selected set of observed rainfall statistics, with possibly varying aggregation periods, where the parameters are {λ, β, ν, η, ε} for single site and {λ, β, ρ, γ, φ, η, ε} for spatial applications. Analytical expressions are available for expected statistics of arbitrary period (e.g. 1 day or 2 h) accumulations of the STNSRP process at any site for the mean, variance, lag-auto covariance, lag-autocorrelation, dry period probability, probability of dry–dry (or wet–wet) transition probabilities and the third order central moment (e.g. ***Cowpertwait, 1995,1998***). Inter-site properties can be estimated as cross-covariance and correlations (***Cowpertwait, 1995***). The third order moment property (***Cowpertwait, 1998***) is particularly important for applications where extreme rainfall events are important, such as flood risk assessment. This is implemented in RainSim V3 as the skewness coefficient, Eq. (1), where E ( ) indicates statistical expectation, Y_h is an *h* hour accumulation and σ^3_{Yh} its variance.

$$E\left[\left(Y_h - E(Y_h)\right)^3\right] / \sigma^3_{Y_h}$$

RainSim V3

RainSim V3 is a robust and well tested stochastic rainfall field generator used successfully in a broad range of climates and end-user applications. RainSim generates stochastic rainfall fields using a Spatial Temporal Neyman-Scott Rectangular Pulses process. Synthetic rainfall fields or synthetic multi-site time series can be sampled from this process for use in the evaluation of hydrological or hydraulic systems. Single site time series may also be generated by use of the simpler Neyman-Scott Rectangular Pulses process. The software includes tools to calculate statistics from time series, to calibrate the model and to generate simulations. RainSim uses a single cell type with an exponential intensity distribution, includes skewness statistics and can operate either in single site or in spatial mode.

RainSim operates in three modes: analysis, fitting and simulation (for an alternative description see ***Burton et al., 2008***).

First the one obtains a set of observed time series, prepares a file defining the rainfall statistics of interest (statistics template) and a file defining the location(s) of the rain gauges and the properties of the observed time series (catchment definition). Analysis then calculates the required statistics from the observed time series (observed statistics or target statistics).

The Analysis capabilities of the RainSim V3 software allow the user to quickly evaluate rainfall statistics from a set of rainfall time series, whether observed or simulated. The statistics are selected by the user and may be either single site statistics such as the aggregation moments, or dual-site statistics such as the correlation or covariance between sites. Each selected statistic is evaluated separately for each month of the year for each time series. During an application, time series analysis is typically used both to characterize the observed data sets and to analyze the synthetic time series. Comparison of these two sets of statistics provides assurance that the synthetic data sets are indeed a good representation of observed rainfall data sets.

Fitting then identifies the parameter set that, according to analytical expectation, best matches the observed statistics. It can also specify the corresponding expected statistics (fitted statistics). The common idea is to adopt a flexible fitting procedure which assumes that it is more desirable to fit a larger set of sample moments approximately rather than a smaller set exactly. Hence, an objective function (*D*) depending on the set of statistics selected (*G*) is defined. D is then minimized using a numerical optimizing routine (e.g. simplex algorithm) subject to fixed upper and lower bound parameters. In RainSim the objective function (***Burton et al., 2008***) is defined as:

$$D = \sum_{h \in G} \frac{W_h^2}{h_s^2} \left(f_h - \widehat{f_h}(\lambda, \beta, \eta, \nu, \varepsilon) \right)^2$$

W_h	Statistic weight	f_h	Observed statistic
h	Statistic with a specific aggregation level	$\widehat{f_h}$	Expected mean value of the statistic *h* arising from NSRP
h_s	Scaling term		

h_s takes the value of 1 for probability of dry period or correlation and the value of annual mean of f_h for the other statistics (***Burton et al., 2008***).

Here is when one need to compare observed and fitted statistic and check if the fitted results are close to the observed results.

Simulation generates synthetic time series using these parameters. Since the simulated time series are likely to start at different times, have different file names and different time steps than the observed time series, a file is also output detailing the properties of the simulated time series (simulated catchment definition). The simulated catchment definition may then be used with RainSim in the analysis mode to evaluate the rainfall statistics of the simulated time series.

In summary, synthetic time series may be generated and the properties of the observed data, the fit and the synthetic series may be compared in terms of their statistics.

Figure 19 provides a schematic of how RainSim is used for an application.

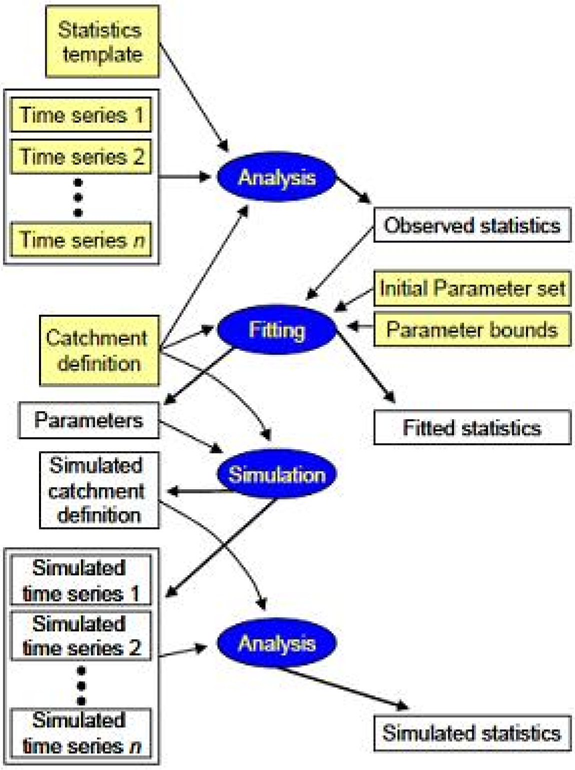


Figure 19 – Simplified schematic of the input and output files of RainSim during a typical application

Chapter 4: Extreme Value Analysis

The EVA toolbox, part of MIKE Zero (DHI software), is a powerful tool to analyze Extreme Value Series. It uses a parametric frequency analysis approach, i.e. the extreme value model is formulated fitting theoretical probability distribution to the observed data.

The EVA editor includes a large number of routines to perform the extreme value analysis, the main ones used in this study are: tool for extraction of the extreme value series from the observed data, large number of probability distributions functions, three different parameters estimation methods, validation tests for independence and homogeneity of the extreme value series, different goodness-of-fit statistics tests and probability plots. The different steps in the analysis of extreme events values are:

- Extraction of extreme values series from the record of observations.
- Select different probability distribution functions suitable to fit the observed sample.
- Select different estimator methods to be tested for each probability distribution.
- Carry out homogeneity and independency tests and goodness-of-fit tests for the EVS and the probability density function respectively.
- Analyze results from EVA toolbox from steps 1-4 and the probability plot for the fitted distributions.

The main steps in the analysis carried out with EVA Editor are explained in detail in the following sections.

Extraction of extreme values series

For evaluating the risk of extreme events a parametric frequency analysis approach is adopted in EVA. This implies that an extreme value model is formulated based on fitting a theoretical probability distribution to the observed extreme value series. Two different extreme value models are provided in EVA:

- Annual Maximum Series (AMS) method.
- Partial Durations Series (PDS) method, also known as the Peak Over Threshold (POT) method.

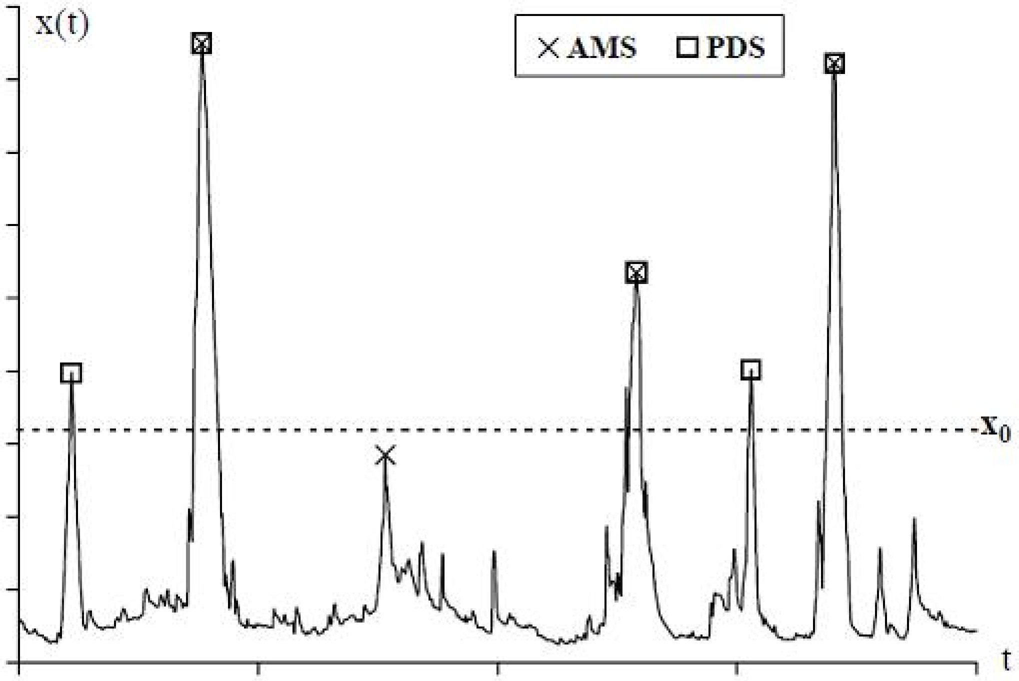


Figure 20 – Extraction of AMS and PDS from the recorded time series

In the annual maximum series (AMS) method the maximum value in each year of the record are extracted for the extreme value analysis. The analysis year should preferably be defined from a period of the year where extreme events never occur in order to ensure that a season with extreme events is not split in two.

In the partial duration series (PDS) method all events above a threshold are extracted from the time series.

The PDS can be defined according to two different approaches. In the first one, all the values over the threshold are extracted from the observed data; this implies that the number of events per year is not a constant value. In the second approach, the number of events per year is defined as a constant, then; the threshold level becomes a random variable (***Madsen, H. et al, 2005***).

Probability distributions and estimation methods

EVA Editor contents a large number of probability distribution functions which can be tested in order to fit the observed data sample. In hydrology, the most typical distributions used for AMS analysis is the Generalized Extreme Values distribution (GEV). AMS have been chosen in that study.

In the threshold exceedances approach (PDS), the Generalized Pareto (GP) distribution is the analogous to the GEV distribution for annual maxima

The number of parameters to be estimated in order to define a probability distribution depends on the distribution. In the GEV and GP distributions the parameters to be estimated are: the location parameter (ε), the scale parameter (α) and the shape parameter (k).

The parameters of the marginal distributions can be estimated using three different estimation methods: method of moments (MOM), L-moment estimators (LMOM) which is equivalent to the probability weighted moments (PWM) and maximum likelihood (ML). The three methods are available in EVA toolbox. It is important to notice that for a specific distribution the three methods cannot always be applied. Table 8 shows the estimation methods that can be applied for each distribution. In this study, all the methods available for each of the distributions tested (GEV) have been applied.

Distribution	**Nº of param.**	**Estimation methods**			**Probability density function**	**Cumulative distribution function**	**Quantile function**
		MOM	**LMOM**	**ML**			
GEV	3	x	x	x	$f(x)=\frac{1}{\alpha}\left[1-\frac{k(x-\varepsilon)}{\alpha}\right]^{1/k-1} exp\left(-\left[1-\frac{k(x-\varepsilon)}{\alpha}\right]^{1/k}\right)$	$F(x)=exp\left(-\left[1-\frac{k(x-\varepsilon)}{\alpha}\right]^{1/k}\right)$	$x_p=\varepsilon+\frac{\alpha}{k}\left(1-[-\ln p]^k\right)$
GP	3	x	x	-	$f(x)=\frac{1}{\alpha}\left[1-\frac{k(x-\varepsilon)}{\alpha}\right]^{1/k-1}$	$F(x)=1-\left[1-\frac{k(x-\varepsilon)}{\alpha}\right]^{1/k}$	$x_p=\varepsilon+\frac{\alpha}{k}[1-(1-p)^k]$

Table 8 – Combinations of probability distributions and estimation methods, and probability density, cumulative and quantile function

Parameters: ε (location), α (scale), k (shape)

Homogeneity and independency tests and goodness-of-fit tests

The basic requirement for the extreme value models outlined above is that the stochastic variables Xi are independent and identically distributed. For testing independence and homogeneity of the observed extreme value series, three different tests are available in EVA:

- Run test
- Mann-Kendall test
- Mann-Whitney test

The results obtained from these tests are the test statistic value and the level of significance. The test statistic is asymptotically normally distributed.

The run test is used for general testing of independence and homogeneity of a time series, while the Mann-Kendall test and Mann-Withney test analyse respectively the monotonic trend and the shift in mean between two sub-samples.

In any statistical analysis is necessary to ensure that the population of data being handled is homogeneous from the statistical viewpoint. This verification or goodness-of-fit is analysed with the most common statistics tests as Chi-Squared or Kolmogorov-Smirnov (both tools from EVA tools).

- ***Chi-squared*** – The X^2-test statistic is based on a comparison of the number of observed events and the number of expected events (according to the specified probability distribution) in class intervals covering the range of the variable. The test statistic reads:

  $$z = \sum_{i=1}^{k} \frac{(n_i - np_i)^2}{np_i}$$

  Where k is the number of classes, n_i is the number of observed events in class *i*, n is the sample size, and p_i is the probability corresponding to class *i*, implying that the number of expected events in class *i* is equal to np_i.

- ***Kolmogorov-Smirnov*** – The Kolmogorov-Smirnov test is based on the deviation between the empirical and the theoretical distribution function. The test statistic is given by:

  $$z = Max|F_n(x) - F(x)|$$

  Where $F(x)$ is the theoretical cumulative distribution function, and $F_n(x)$ is the empirical distribution function defined as:

  $$F_n(x) = \begin{cases} 0 & ,x < x_{(1)} \\ \frac{i}{n} & ,\ x_{(i)} \leq x < x_{(i+1)} \\ 1 & ,x \geq x_{(n)} \end{cases}$$

Extreme value series analysis

In this section, the analysis of the EVS obtained using AMS approaches is carried out for the Water Level in different point along the main stream. For each point and the different periods calculated (10, 25, 50, 100, 200 and 500), the marginal distributions selected are tested and the parameters of the most suitable one are given.

Frequency and probability plots

Plot of histogram and probability density function

A histogram is a plot of the empirical probability density function. The histogram is constructed by dividing the range of the variable in class intervals and counting the number of observations in each class. Denoting by n_i the number of observations in class i, and Δx the size of the interval, the histogram value of class i is given by:

$$f_i = \frac{n_i}{n\Delta x}$$

Where n is the total number of observations. For evaluating the goodness-of-fit of an estimated probability distribution, the probability density function is compared to the histogram.

Probability plots

A probability plot is a plot of the ordered observations $\{x_{(1)} \geq x_{(2)} \geq \ldots \geq x_{(n)}\}$ versus an approximation of their expected values $F^{-1}(p_i)$, where p_i is the probability of the i'th largest observation in a sample of n variables. The probability is determined by using a plotting position formula.

The plotting position formulae available in EVA are shown in Table 9. These formulae can be written in a general form:

$$p_i = \frac{i - a}{n + 1 - 2a}$$

Name	Formula	a
Weibull	$p_i = \frac{i}{n+1}$	0.000
Hazen	$p_i = \frac{i-0.5}{n}$	0.500
Gringorten	$p_i = \frac{i-0.44}{n+0.12}$	0.440
Blom	$p_i = \frac{i-0.375}{n+0.25}$	0.375
Cunnane	$p_i = \frac{i-0.40}{n+0.20}$	0.400

Table 9 – Plotting position formulae

For plotting, three different probability papers are available: Gumbel, lognormal, and semi-log papers. Gumbel will be used in that study.

Probability plots are used for evaluating the goodness-of-fit of the estimated probability distributions. In a Gumbel probability paper, the Gumbel distribution is a straight line, whereas the 2-parameter log-normal and the exponential distributions are straight lines in the log-normal and semi-log probability papers, respectively.

Chapter 5: Hydrolocical study

Introduction

In the present study I'm going to develop a Risk Analysis from Vidaa River System using MIKE 11 software and a Stochastic Weather Generator to forecast different flood period returns.

Different kind of data has been given to use in that analysis. These data are Topography, Catchment Areas, Network & Cross Sections, and different Time Series as:

- Rainfall Precipitation
- Potential Evapotranspiration
- Boundary Conditions (water levels in the downstream and discharges at upstream)
- Control Stations, where I will can check my results with it values (pump stations or weirs)

As I have explained before, MIKE 11 is 1D model software where a user can use it for flood forecasting, flood control, sediment transport calculations, transport dispersion and water quality model. From all these possibilities I'm going to focus on flood forecasting comparing and discussing the results obtained as better as possible to be close to the real situation. Ones should never forgets than the calculus done in any forecast model will not be exactly the same that happens in the nature, but could be an enough improve to make oneself a close idea with the reality.

Thanks to MIKE software and different Stochastic Weather Generator that is possible.

Starting to set up Vidaa River system

As I say before, different kinds of data have been given. These data are necessary to develop that current study. Topography, Catchment Areas, Network (***.NWK11*** file), Cross Sections (***.XNS11*** file) and Structures (like dikes, weirs or pump stations) are the physical and graphical part of that initial data where the user can make himself a first idea about Vidaa River and it different branches and catchments. But all that kind of information that influences the flow will not give any information on the river runoff.

This is why the user needs to input boundary conditions on the model. Manny different types of boundary conditions can be used, but the most common are discharge and water level boundaries (also known as ***Q*** and ***h*** boundaries). ***Q*** boundaries are most common at the upstream end of a river branch (head catchments), typically measured in m^3/s. An ***h*** boundary specifies the water level at a boundary, typically at the river mouth.

Figure 21 – Vidaa River Control Station

Figure 22 – Extreme measures witness at the Vidaa River mouth

The task of MIKE 11 is to simulate how the water specified at the boundaries is moving through the river network towards the sea. In order to run a simulation, boundary conditions must be specified at all upstream and downstream ends of the river network.

Water can be added to the river network in other places than the upstream and downstream boundaries as inflow from point's sources along the river or inflow from the sub-catchments contributing to the river.

Catchment inflow is distributed along the part of the river that belongs to a given catchment. The catchment inflow is usually calculated using a rainfall-runoff model (***.RR11*** editor file) that simulates the runoff based on the time series precipitation and potential evapotranspiration.

Rainfall-Runoff model editor

After that short explanation, we begin to modeling our river. First step will be starts with the Rainfall-Runoff model to evaluate the inflows from the sub-catchments of Vidaa River.

The period studied is from 2nd January 1972 to 1st January 2007. During this period the following data are available:

- Daily rainfall, stored in the files Q4210010_Rainfall.dfs0 (from Vidaa OVR catchment) and Q4240080_Rainfall.dfs0 (from Gronaa_TM catchment).
- Daily potential evapotranspiration, stored in the file EvaPot-SJA1961-2009.dfs0.

The main contribution of water comes from the catchments located along the river network, both as groundwater inflow and inflow from small tributaries, drains and ditches that are not included in the model.

One can choose between different kinds of catchment models: ***NAM, UHM, SMAP, Urban, and Combined***. The NAM model is a deterministic, lumped and conceptual Rainfall-Runoff model accounting for the water content in up to 4 different storages. NAM can be prepared in a number of different modes depending on the requirement, As default, NAM is prepared with 9 parameters representing the Surface Zone, Root Zone and the Ground Water Storages.

Twenty-nine sub-catchments have been defined in the Vidaa catchment. These catchments generate a lateral inflow to the river network. These water contributions, in general, are relevant compared with the runoff from the main branches of the river (Gronaa_TM and Vidaa-OVR). The best solutions would be to have gauges measuring the runoff from each of the twenty-nine sub-catchments and then use these observations in your model. This kind of observation is, however, almost never available, and even if ones has a very dense network of discharge gauges, such observations would have to cover the period that one wants to simulate. In many cases, they do not, and one will have to rely on simulated discharge from rainfall runoff models such as the NAM model. The rainfall-runoff model serves two purposes:

- For a number of sub-catchments contributing to Vidaa River the NAM model has been used to fill gaps in or extend the time series of observed discharge so that they cover the period of interest.
- For others, no observations are available at all, and the NAM model has been used to estimate the runoff from these catchments. Observations from nearby climate stations have been used as input to NAM.

When no observations are available at all, the split-sample calibration is useless. In this case, the only applicable strategy is the proxy-basin calibration. The proxy basin calibration is based on the assumption that runoff from two catchments with similar hydrological properties is the same except for scale, the scaling factor being the area. This implies that the parameters from one (calibrated) catchment can be applied in another (ungauged) catchment to simulate runoff, if the hydrological properties of the two catchments are similar.

After give names, areas and choose what kind of catchment is everyone (see Table 13 in Appendix 1), the user need to input and edit of rainfall runoff and compute the parameters required for the rainfall-runoff modeling.

NAM model is performed by difference kind of storages modules: ***Surface zone, Root zone, Ground Water, Snow Melt, and Irrigation***. Only the three firsts have been studied.

I take into account that no exist snow accumulation or it is not too important as take into account.

Minor irrigation schemes within a catchment will normally have negligible influence on the catchment hydrology, unless transfer of water over the catchment boundary is involved. That subject doesn't happen in Vidaa River System and for that reason I don't take into account Irrigation module.

About the three first storages modules, the kind and values parameters, are explaining on "*The NAM Rainfall-Runoff model*".

I need to define also the initial parameters before start the simulation of rainfall-runoff model. These parameters are showed also on Table 14 from Appendix 1.

As a last step before NAM simulation, I have to link the time series files (***.dfs0***) about rainfall and potential evapotranspiration to each sub-catchment weighting it if is necessary from rain gauges.

After all that steps, I start with the simulation from 2nd January 1972 to 1st January 2007, and I obtain the result for Rainfall-Runoff model that will be used later when I will have to simulate the Hydrodynamic parameters.

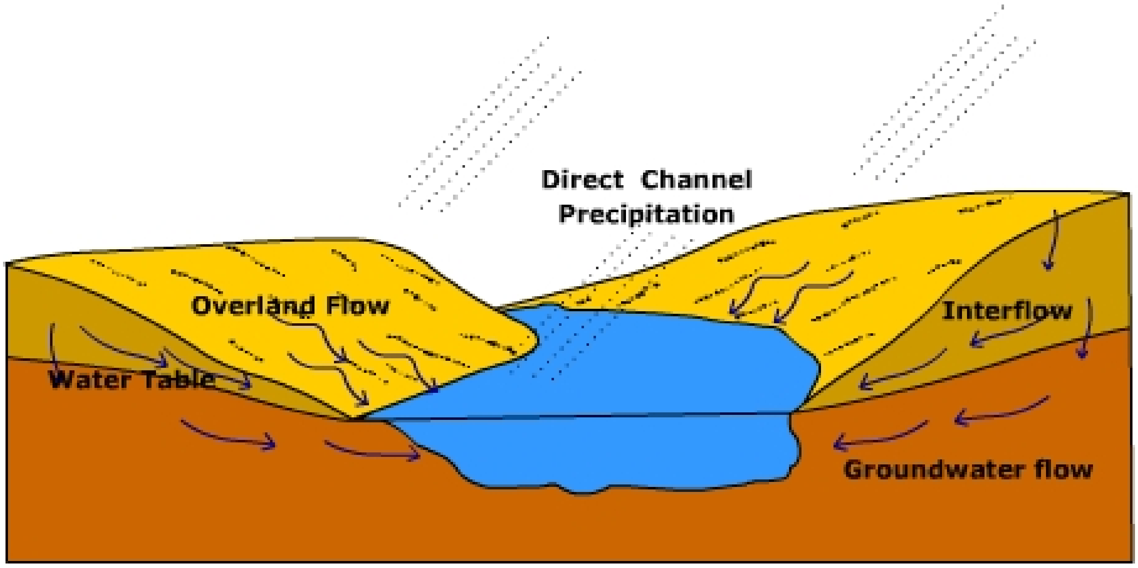


Figure 23 – Rainfall-Runoff process

Hydrodynamic model editor

Network (***.nwk11***) file and Cross Section (***.xns11***) file are given, so I need only to create the Boundary Conditions (***.bnd11***) file.

As I explain before, I'm going to use Up- and Down- Stream boundary conditions (discharge and water levels respectively) to set it up.

Three different Hydrodynamic model editors are going to be created. Each one of these, after different Manning values given, is going to fill in a file with simulated water levels according to the Manning values given before.

These simulated water levels time series (***.dfs0*** files) are as a result of Hydrodynamic simulation. This simulation will need of a Network (***.nwk11***) file, Cross Sections (***.xns11***) file, Boundary (***.bnd11***) file, Hydrodynamic (***.hd11***) file, and the results of Rainfall-Runoff NAM Simulation (***.res11***) file as inputs to start to compute.

The period studied is from 5th October 2005 to 5th October 2006 (one year) with a five minutes time step (5 min.). But first of all, I need to run an initial simulation with a Hypothetical Manning value, as a warm up to knows how the flow runs and make an idea to myself.

The chosen Manning Value is 30. Why 30? I could choose any value, but 30 (or ***n=1/M***, n = 1/30 = 0.033) is a value generally accepted in Catalunya by Water Catalan Agency (an official organism of my country) to start the rivers flood studies. With that value, and after fill in the simulation editor with the different models for a 05-06 year period, I obtain a time series water levels file.

Thanks to the file obtained and the control stations time series along the river, I can compare these levels in each control station, and, depending of differences between both files, I can say if that Manning value is close to the real situation or not as first approximation.

After the first approximation I need to calibrate the Manning parameter. Autocal is a generic tool for performing automatic calibration, parameter optimisation, sensitivity analysis and scenario management of the numerical modelling engines under MIKE Zero PFS (parameters files system) format for model input and the DFS (data file system) format for model output (for more detailed explanation see Appendix 1).

The Autocal results need to be checked. The user has to check if these results are out of range or not. Making the sensitivity analysis, the user will obtain the root mean square error (RMSE) for each Manning value. Thanks to RMSE values I can perform a graphic comparing the evolution of RMSE with Manning. In that way, I will find the optimal solution for Manning value where the graphic shows the lower line-point coordinate. The sensitivity analysis gives the user a standard deviation value. With that value multiplied by two will give the founded optimal range solution.

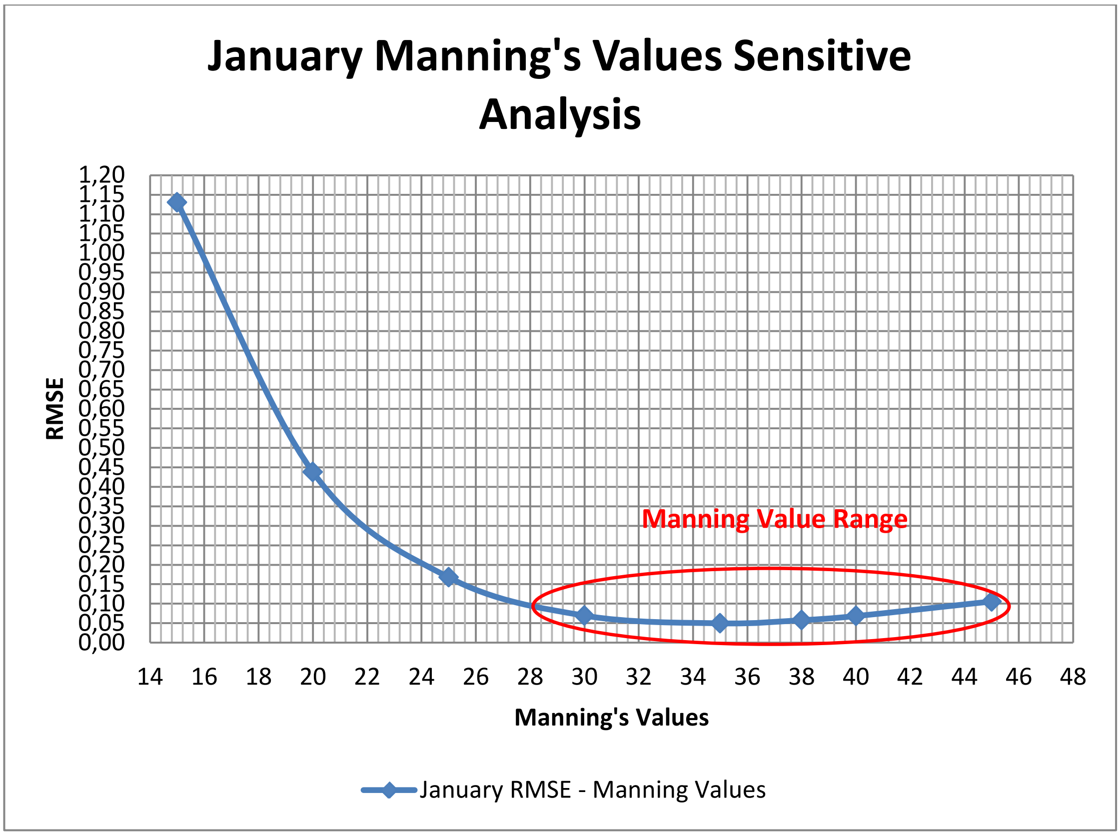


Figure 24 – Manning Sensitivity Analysis graphic (RMSE/Manning). October

A natural river system doesn’t have just one unique Manning value along it flow. As I have explained on the Chapter 2, Manning values varies thanks to many different concepts. The effects like vegetation, channel irregularity or alignment, silt, source, and surface roughness influence on our Manning value. That is the reason why I’m going to set up two different auto calibrations. That study will evaluate how affect the resistance to the flow. So I’m going to prepare two different cases: a unique Manning value along the river that vary during the time and three different Manning values, that varies during the time and length (Up-, Medium-, and Down- Stream).

The common sense tells us doesn’t exist the same resistance factor in the whole river. As the user knows, generally spoken, seasonal variation and the effects of transport and erosion will change our Manning value along the time, but also along the length.

The first case will be the Manning variation along the time whereas the second case will be the Manning variation along the time as well on length. The user will observe the variation of Manning value and therefore the flow resistance variation.

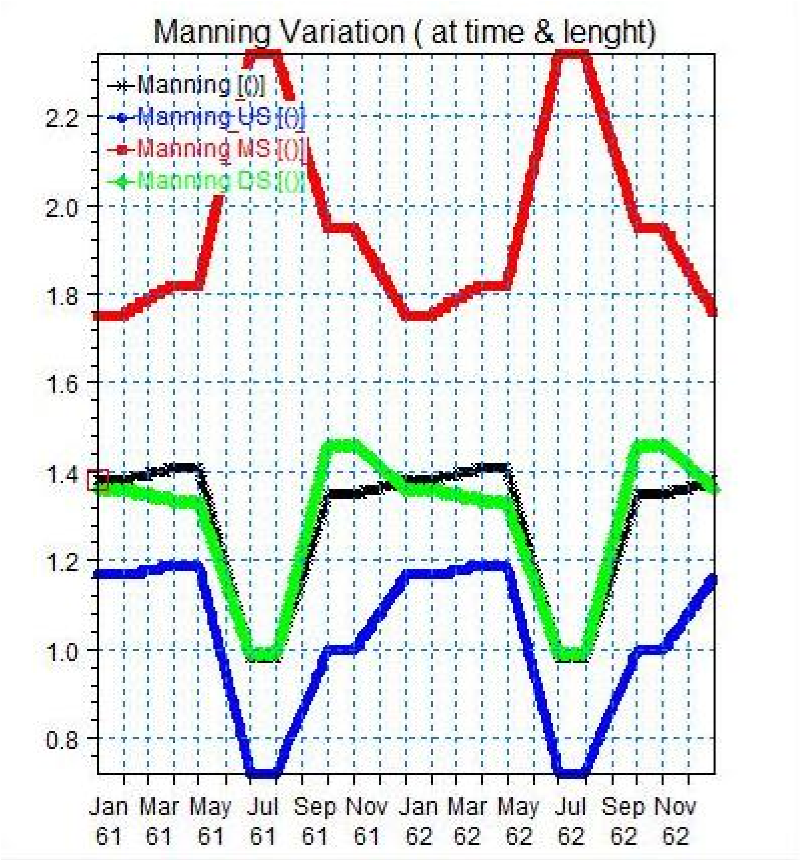


Figure 25 – Resistance factor variation during one year after Auto Calibration (r=1/M)

With the time series that I have obtained from the autocal, just need to run the simulation to obtain the simulated water levels time series and see how can affect to Vidaa River System our different Manning values comparing with the water level control stations.

Selected our best Manning scenario, next step is the study, from a long data rainfall time series, how can affect the climate change in our River and the change weather.

Stochastic Weather Generator

The software used to simulate weather data is called RainSim V3. It works using the Spatial Neyman-Scott Rectangular Pulses (SNSRP) Weather Generator (WG) model. The SNSRP is a generalization of the single-site Neyman-Scott Rectangular Pulses (NSRP) WG.

Thanks to the three rainfall data gauges given by DHI, I will obtain synthetic daily precipitation time series generates using Spatial Neyman-Scott Rectangular Pulses Weather Generator. These stations are located two of them in Up Stream head catchments and the last of them at the end of the river (Down Stream) on the Højer dam.

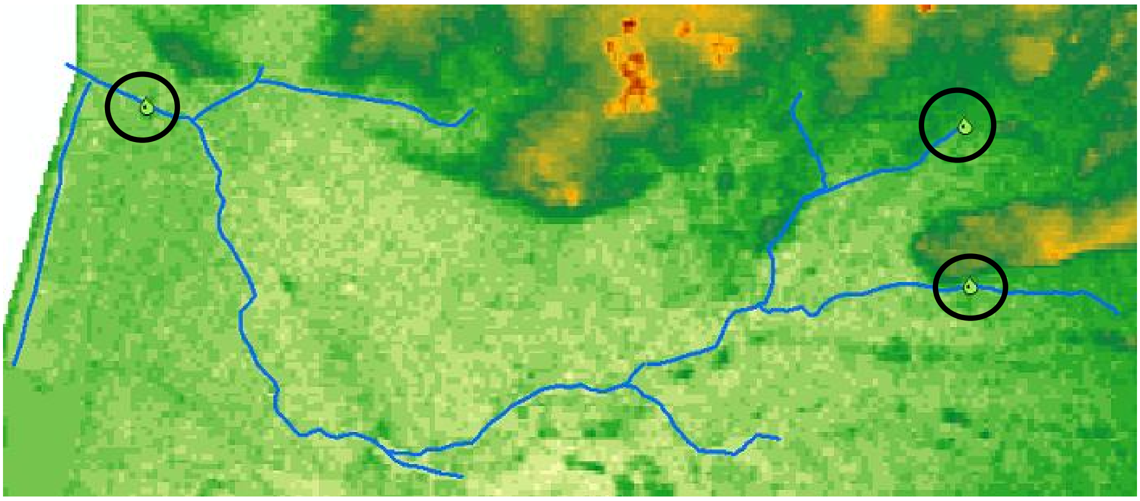


Figure 26 – Location of rainfall gauges used to generate simulated rainfalls

As it has been explained in "Chapter 3: Weather Generators", I need to make: an Analysis, a Fitting, and a Simulation.

First I obtain a set of observed time series, and I prepare a file defining the rainfall statistics of interest (statistics template) and a file defining the location(s) of the rain gauges and the properties of the observed time series (catchment definition).

Analysis then calculates the required statistics from the observed daily time series (observed statistics) since 1st January 1971 until 1st January 1986:

- Mean
- Variance
- Auto-lag correlation (1lag)
- Proportion dry days (1mm threshold)
- Skewness

In addition, inter-site correlation is also included.

Fitting then identifies the parameter set that, according to analytical expectation, best matches the observed statistics. It can also specify the corresponding expected statistics (fitted statistics).

Simulations generates synthetic time series using these parameters (fitted parameters), Since the simulated time series are likely to start at different times, have different file names and different time steps than the observed time series, a file is also output detailing the properties of the simulated time series (simulated catchment definition).

The simulated catchment definition may then be used with RainSim in the analysis mode to evaluate the rainfall statistics of the simulated time series. In summary, synthetic time series may be compared in terms of their statistics.

In that study it has been simulated synthetic rainfalls for 5, 10, 25, 50, 100, 200, 500, 1000, and 2000 years length, but only 10, 25, 50, and 100 will be used to run the last MIKE's simulations studies and to evaluate the extreme events that could happen.

Extreme Value Analysis

The extreme value analysis has been carried out using the simulated water levels time series. These time series are the results after run MIKE 11 using the synthetic rainfalls time series (obtained from RainSim WG), as inputs in NAM Rainfall-Runoff editor.

These simulated water levels will represent, after using EVA toolbox from MIKE by DHI (***DHI, 2007***), the extreme values events for different return periods.

Annual Maximum Series (AMS) has been used to carry out the extreme events analysis. Generalized Extreme Values distribution (GEV) has been used to carry out the probability distribution. For that specific distribution all the estimation methods can be applied, so three estimation methods have been used: method of moments (MOM), L-moment estimators (LMOM), and maximum likelihood (ML).

Different return periods have been selected: 10, 25, 50, 100, 200, and 500 years. Return periods for 50, 100, and 200 are selected to estimate floods.

Flow channeling project in the world is normally chosen with a return period of 50 or 100 years. In urban areas return periods are higher (200 years) and should be distinguished from the case where the overflow is a severe flood (if the levees are high on the ground) or the case where happens simply overrun. When there are no affected population return periods can be 25 or 50 years (farm land).

Flood Study

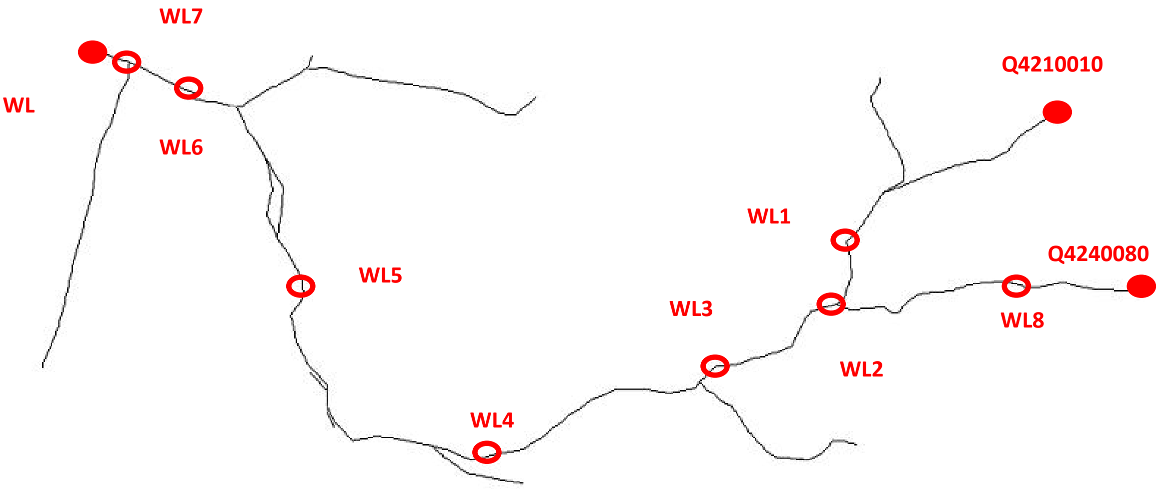
Thanks to the extreme event water levels values, the engineer can discuss which places in Vidaa River are close to be flooded and prepare an emergency plan or propose corrective measures to avoid floods.

Comparing the extreme events values with Vidaa cross sections and Vidaa control stations water levels, the engineer can estimate the floods gravity and the flood plains, making himself an idea until where the flood area can affect the adjacent land.

In that study, eight different points (see Figure below) along the Vidaa River have been checked. But only three of them will be exposed (the rest of the points can be consult in the Appendix 2).

The points selected are WL1, WL4, and WL5 (one in Up-, one in Medium-, and the last in Down- Stream). The point WL1 is located in the surroundings of Tønder which is the biggest town in the area. Therefore, the risk of flooding in this area will be of special interest.

The point WL4 is clearly influenced by the runoff from the upstream locations and by the water level at the outlet. Finally, the purpose of the point WL5 is to evaluate how can affect the Rudbøl Lake and the Høje Dam to the downstream water levels and floods.



Results

To have an idea about how is our river system; first of all, I have run a MIKE 11 simulation. I have used the results of Rainfall Runoff simulations and I have edited a Hydrodynamic simulation.

Using the files of rainfall and evapotranspiration time series I obtained my Rainfall and Runoff result. This result is going to be used as inputs (inflows from the sub catchments contributing to the river).

To run a Simulation I need a Network file, a Cross Section file, a Boundary Conditions file, and Hydrodynamic file. The first two files were given by DHI. Last two files were set up using different time series given by DHI too. As a Boundary Conditions were used the discharge time series from Vidaa and Gronaa head catchment (1978-2009 and 1960-2009 time periods respectively) and the water level time series (2000-2010 time period) at the end of the river. In Hydrodynamic parameter file editor I have specified a global uniform section value for the bed resistance (Manning value of M = 30 $m^{1/3}s^{-1}$) with a *wave approximation option of high order fully dynamic*.

Running the initial simulation and checking the results I have could have an idea of the Vidaa River system. Water levels time series output can be checked and compared with the control stations along the Vidaa River. Also we can observe what kind of slopes are on Vidaa River along the length of it (see figure below).

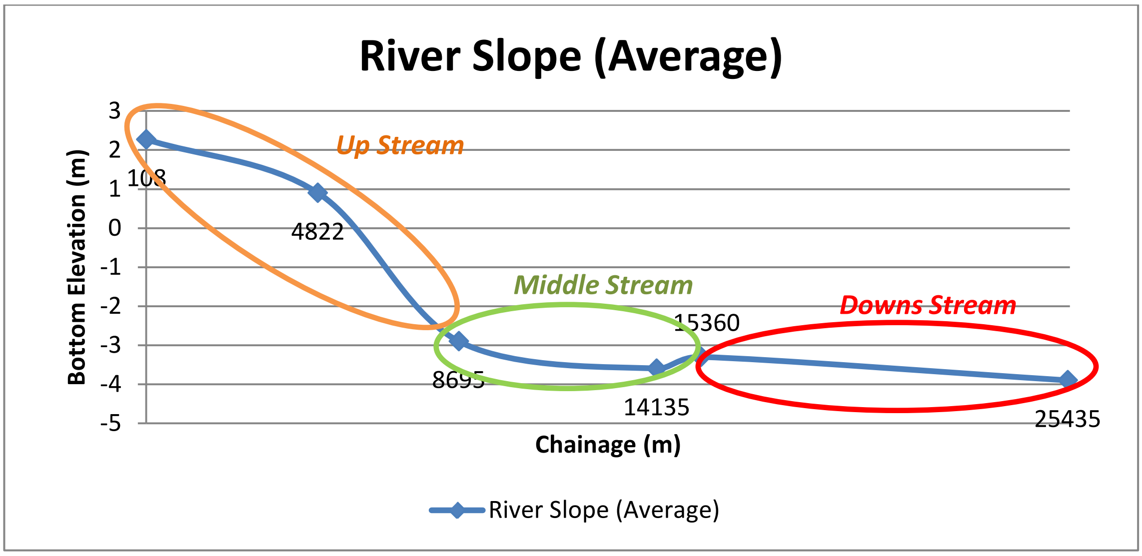


Figure 27 - Average slopes on Vidaa River

One can observe that the biggest slopes are upper the river stream and they are followed by a stream with smallest slopes. In this second part of the river the results show a zone where the river could act like a storage area; this area match with the wetlands and Rudbøl Lake.

Only with that graphic, the engineer can make himself a first idea: The highest velocities will be produced Up stream; the Medium stream will act laminating the flow like a deposit where the input discharge has to be equal to the output discharge but with a big volume and wet area; the Downs stream will flow with a lower velocities influenced by the wet lands and the lake.

Water levels serve us to decide if the resistance factor used in the simulation is quite good for our system. One has to compare the observed control stations water levels along Vidaa River with the simulated water levels.

The figures below show that comparison in three different point along the Vidaa River:

- Control Station H4210030 (this point is located surrounding to Tønder, the biggest village in the area).
- Control Station H4210065 (located between the wet lands and Rudbøl Lake).
- Control Station H4210080 (located in an intermediate point between Høje Dam and Rudbøl Lake).

Figure 28 - Water levels comparison between Observed and Simulated data in the Up Stream (Tonder)

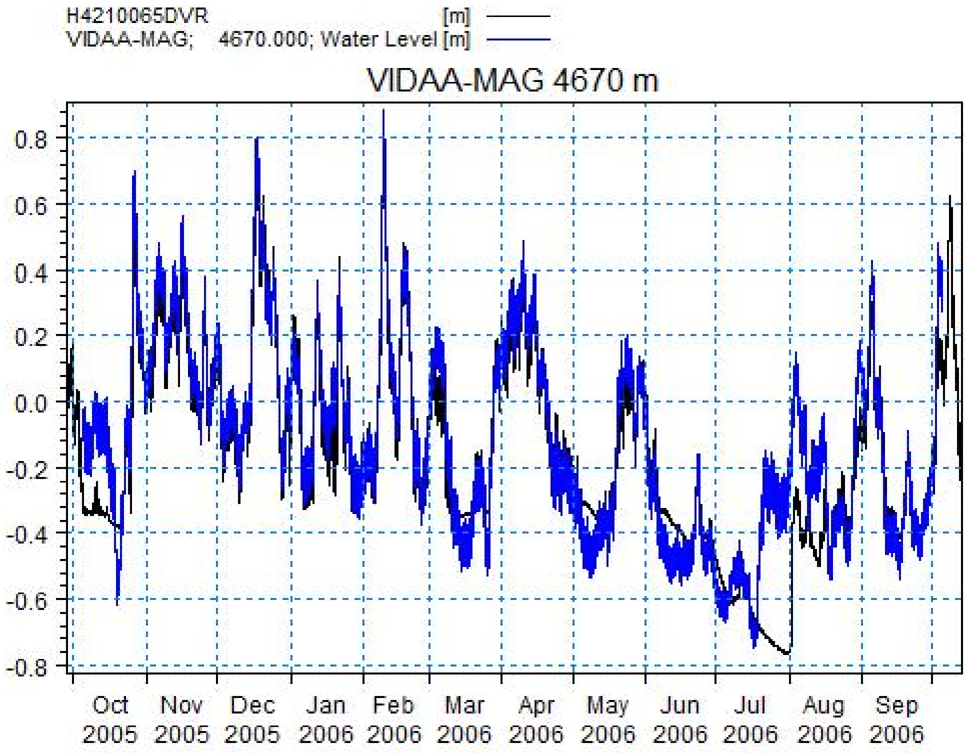


Figure 29 - Water levels comparison between Observed and Simulated data in the Medium Stream (Wet lands and Rudbol Lake)

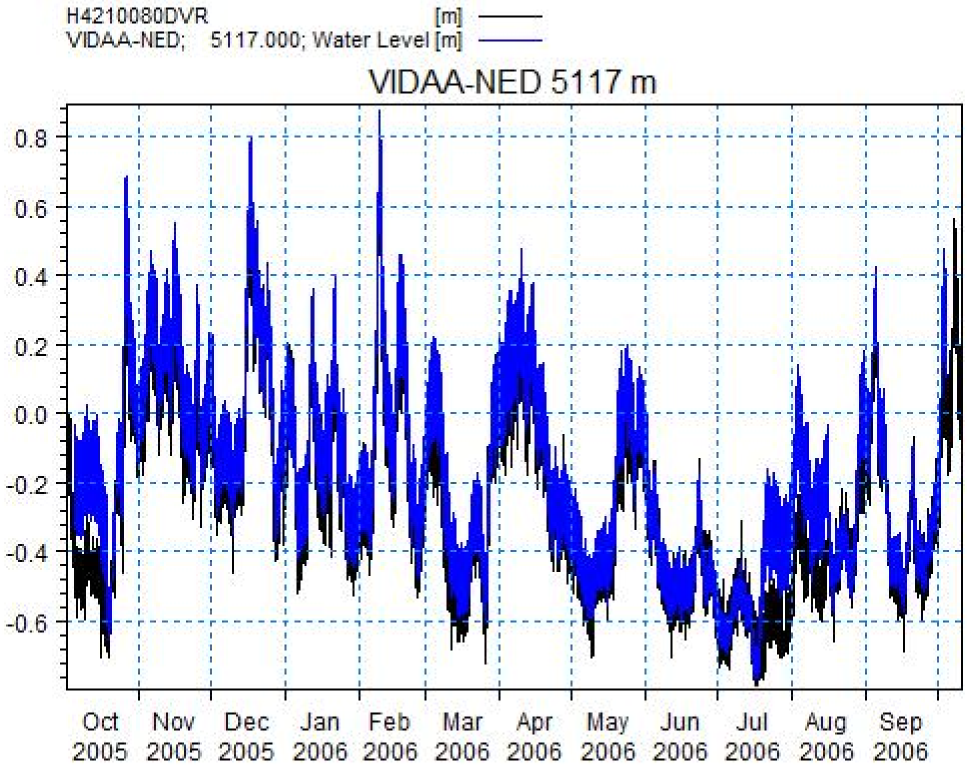


Figure 30 - Water levels comparison between Observed and Simulated data in the Down Stream (between Rudbol Lake and Hoje Dam)

As one can observe water levels are not exactly the same, but there are small difference between both data. Only on July and August the simulated data shows differences higher than 20 cm. If one thing that, even the best LIDAR topographies (*Laser Imaging Detection and Ranging)* have common errors as 15 cm, our water level differences are not so important and we can accept these results as good results.

All comparison between Observed Data and Simulated Data are showed in *Appendix 1*: One-dimensional calculation model

How I have explained in Chapter 2: Roughness factor (Manning coefficient value), the resistance factor, therefore Manning's value, is affected by several factors, they refer to variations in time and on flow way. The main idea is when resistance factor decrease, Manning value (M) increase and vice versa. If resistance factor increase, also the water level will increase too. As a general idea, is logical to think that vegetation growth, according weather season, will produce a higher resistance factor on Vida River banks and this will produce a water level increase (more probability to flood). In the same way, if a river has an irregular bottom, it produces more flow resistance, so our water level will increase. But if we have a river with a higher depth or quite width (or a lake), the existing strengths will not affect the water level because it action range will be smaller compared with depth or width.

For that reason, and because our simulated water levels in the initial simulation are not completely equals, one start with the autocalibration trying to find a best parameter, in that case Manning Value, to set up next simulations. Two autocalibration, and two post simulations, have been done: First of it, search a fitted Manning that varies along the time (changing with each season); Second of it, search a fitted Manning that varies along the time, but also along the river.

To make it, MIKE 11 autocalibration has been used. Parameter optimisation and sensitivity analysis has been done to keep in that results make sense. The results obtained with both autocalibrations are showed in the table below:

	Manning	**Manning**		
		Up Stream	**Middle Stream**	**Down Stream**
October	33.73	24.95	48.77	36.62
January	34.50	29.15	43.85	34.01
April	35.22	29.78	45.53	33.35
July	24.50	18.04	58.52	24.67

Table 10 - Manning values after a Parameter Optimisation from MIKE 11 Autocal

As a general idea, one has to find lower Manning values Up Stream. The higher slopes will generate higher flow velocities, and these flow velocities affect the river eroding it banks. If the river is eroded, the flow will transport different sediment grains. As higher will be the flow strength, higher the grains transported; and as higher diameter grains, higher resistance flow will be produced. Due to erode, the bottom channel will present irregularities. A straight and smooth bottom channel will produce a lower resistance flow factor.

The Vidaa River slopes are showed then:

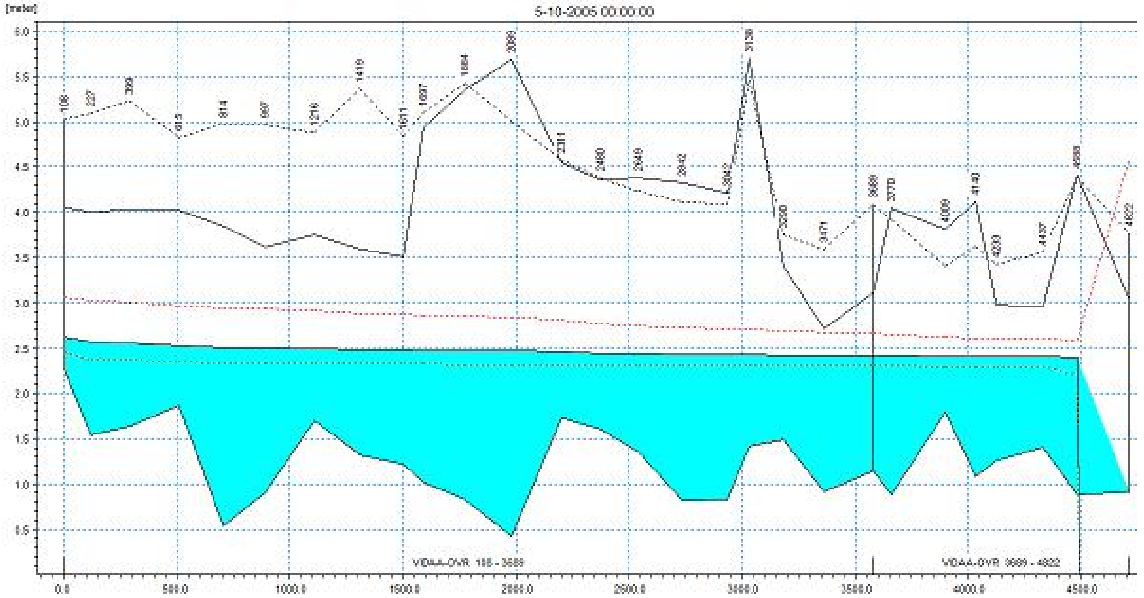


Figure 31 - Vidaa OVR bottom channel and slope

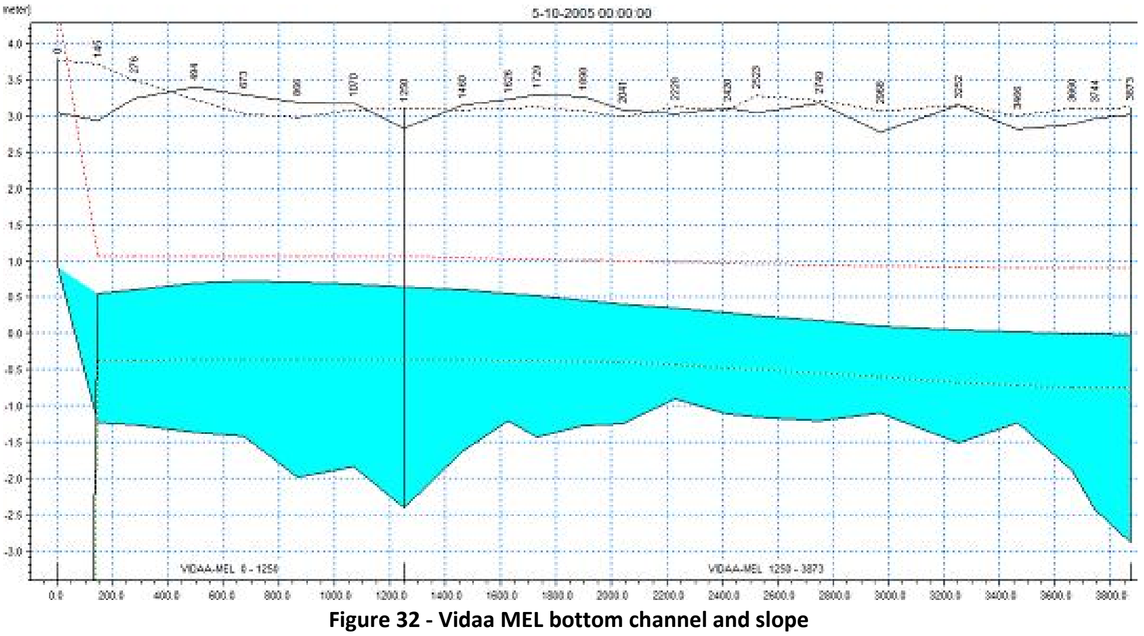


Figure 32 - Vidaa MEL bottom channel and slope
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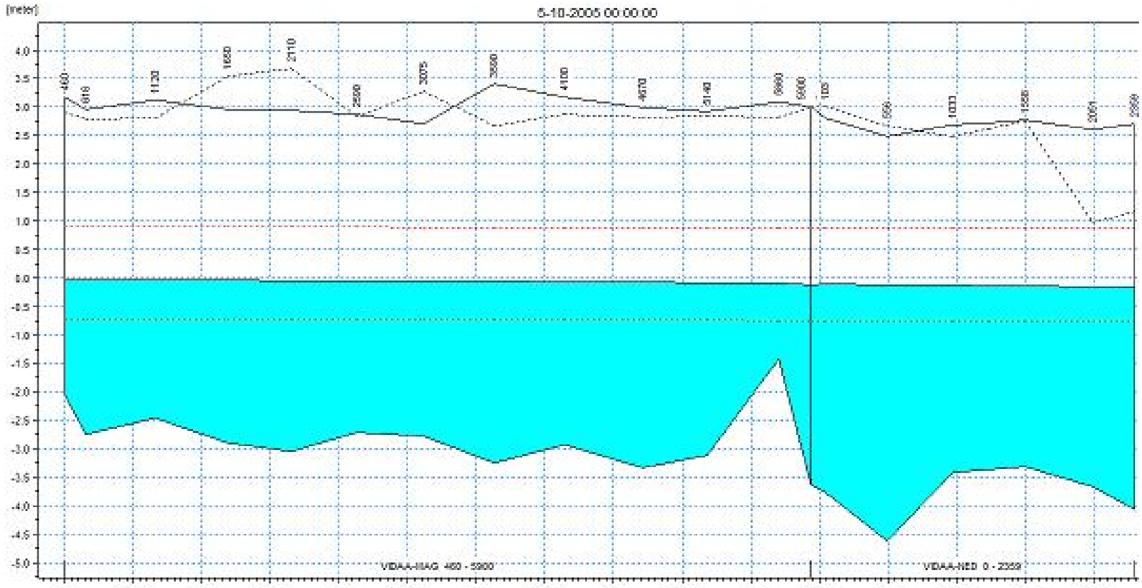


Figure 33 - Vidaa MAG bottom channel and slope

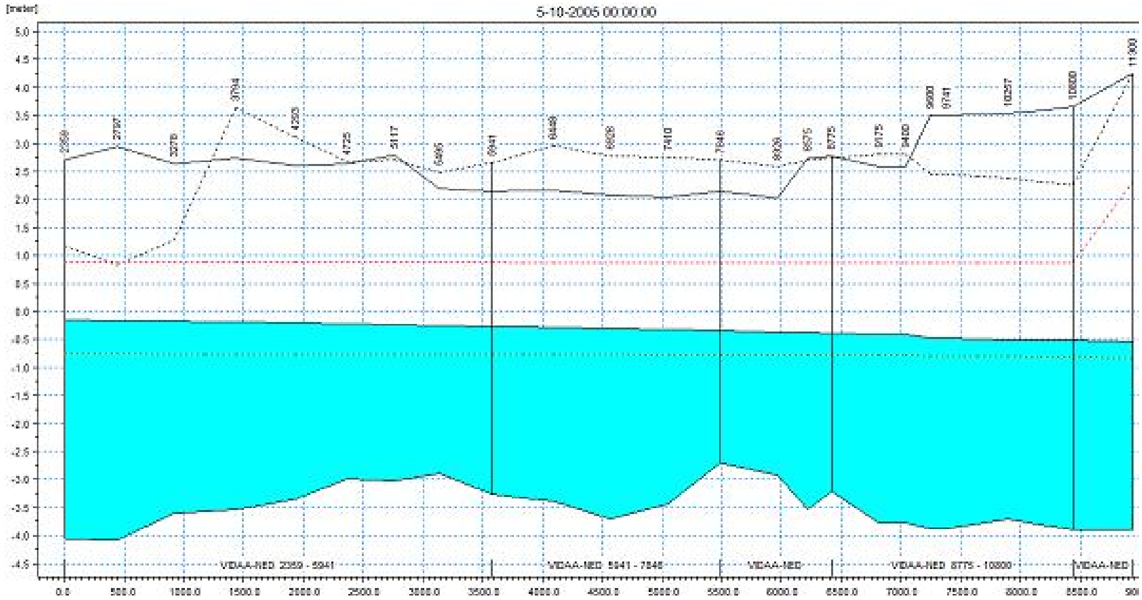


Figure 34 - Vidaa NED bottom channel and slope

As flow is following the stream course, due to the resistance factor, it velocity is decreasing, and coarse grains will silt up. Only the fine grains will be transported by flow, and the resistance factor will decrease. In that case, our Manning value will increase.

Another factor, explained in Chapter 2: Roughness factor (Manning coefficient value), is the vegetation effect and is related with time variation. Vegetation wills growth on Spring and Summer period but drop on Autumn and Winter. That factor affect significantly on river resistance factor because the plant produce a big effect on the obstruction flow, but as I explained before, it obstruction depends about many factors.

So the evolution of Manning value during the year will show an increase period (autumn and winter) and a decrease period (spring and summer) of it.

The results of *Table 10 - Manning values after a Parameter Optimisation from MIKE 11 Autocal,* show that Manning evolution on time and on time and length (*Appendix* show how Manning values are converging to it).

To keep in about our results, a sensitivity analysis has been done. The sensitivity analysis gives a Root Mean Square Error (RMSE) for each Manning value. Plotting RMSE against Manning Values, I can obtain the Manning value range to check it with the results obtained from the autocalibration.

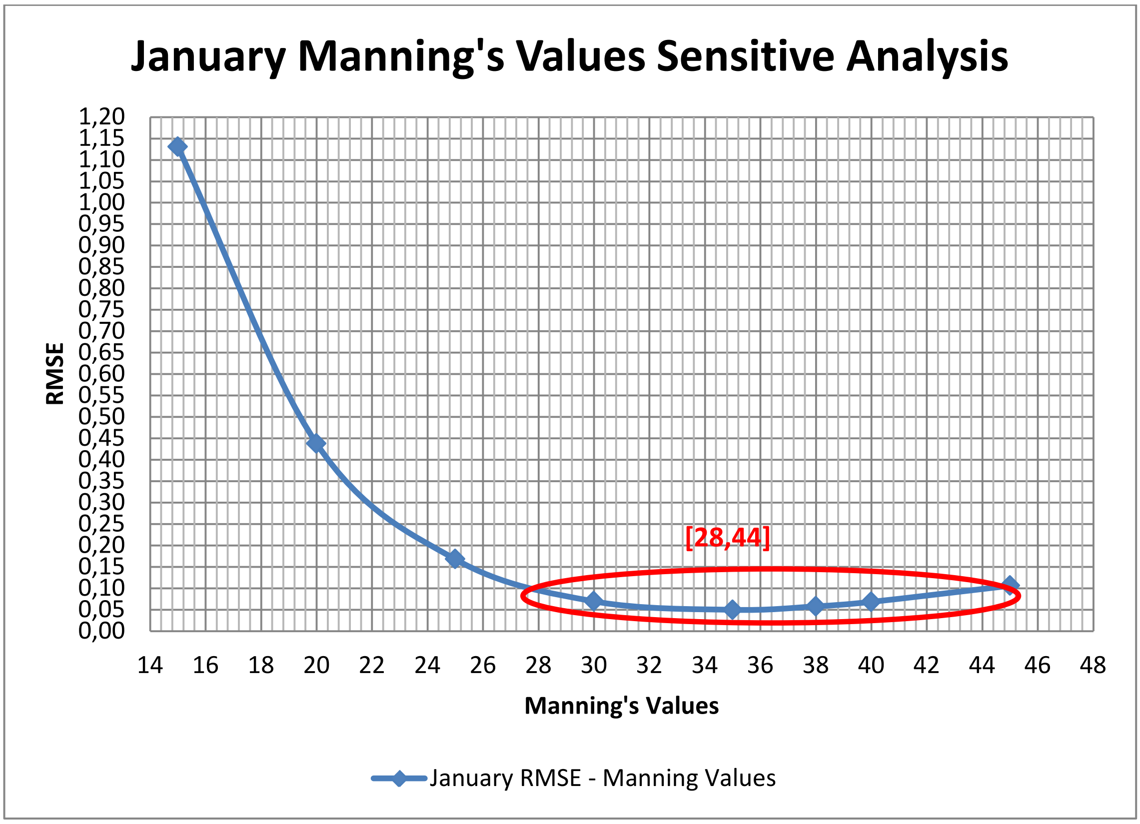


Figure 35 - January Manning values Sensitivity Analysis

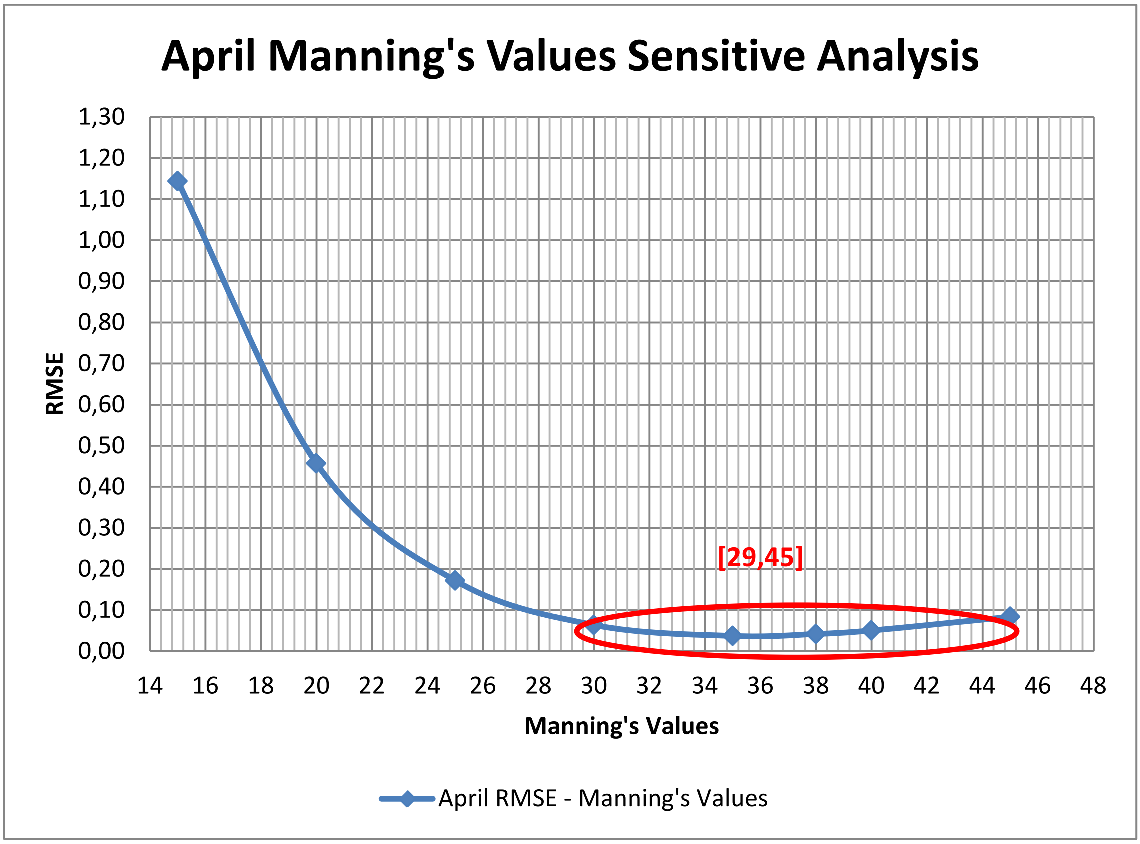


Figure 36 - April Manning values Sensitivity Analysis

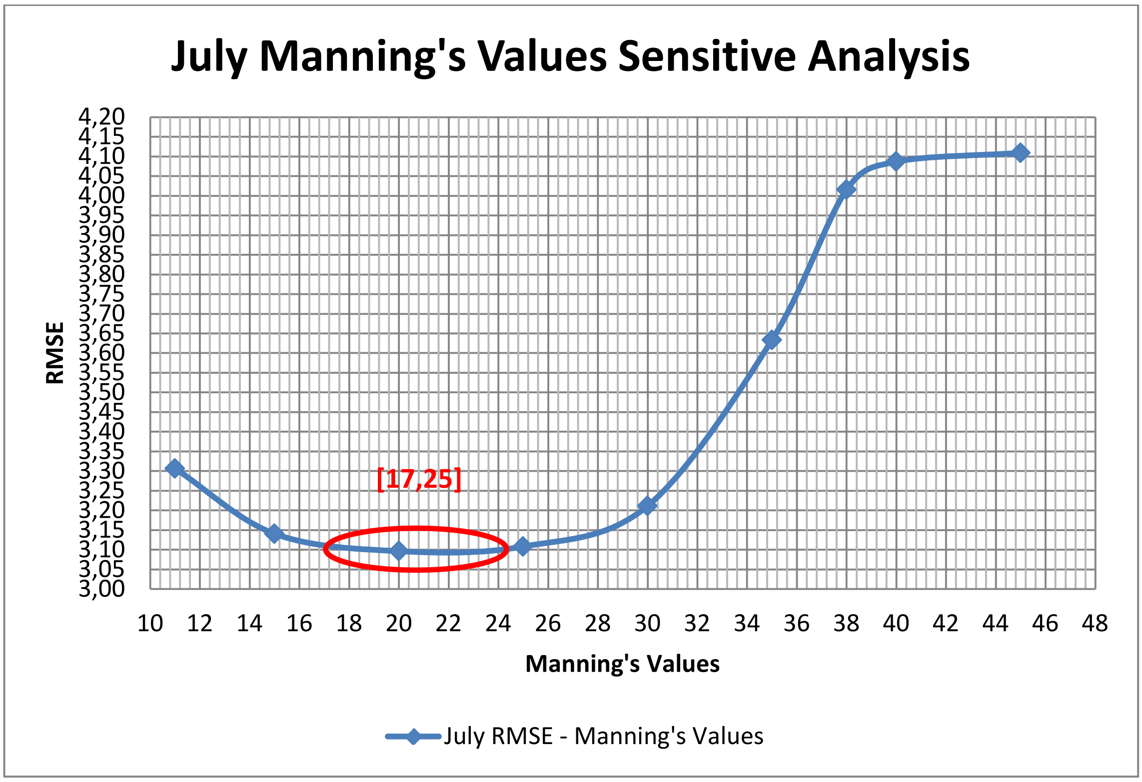


Figure 37 - July Manning values Sensitivity Analysis

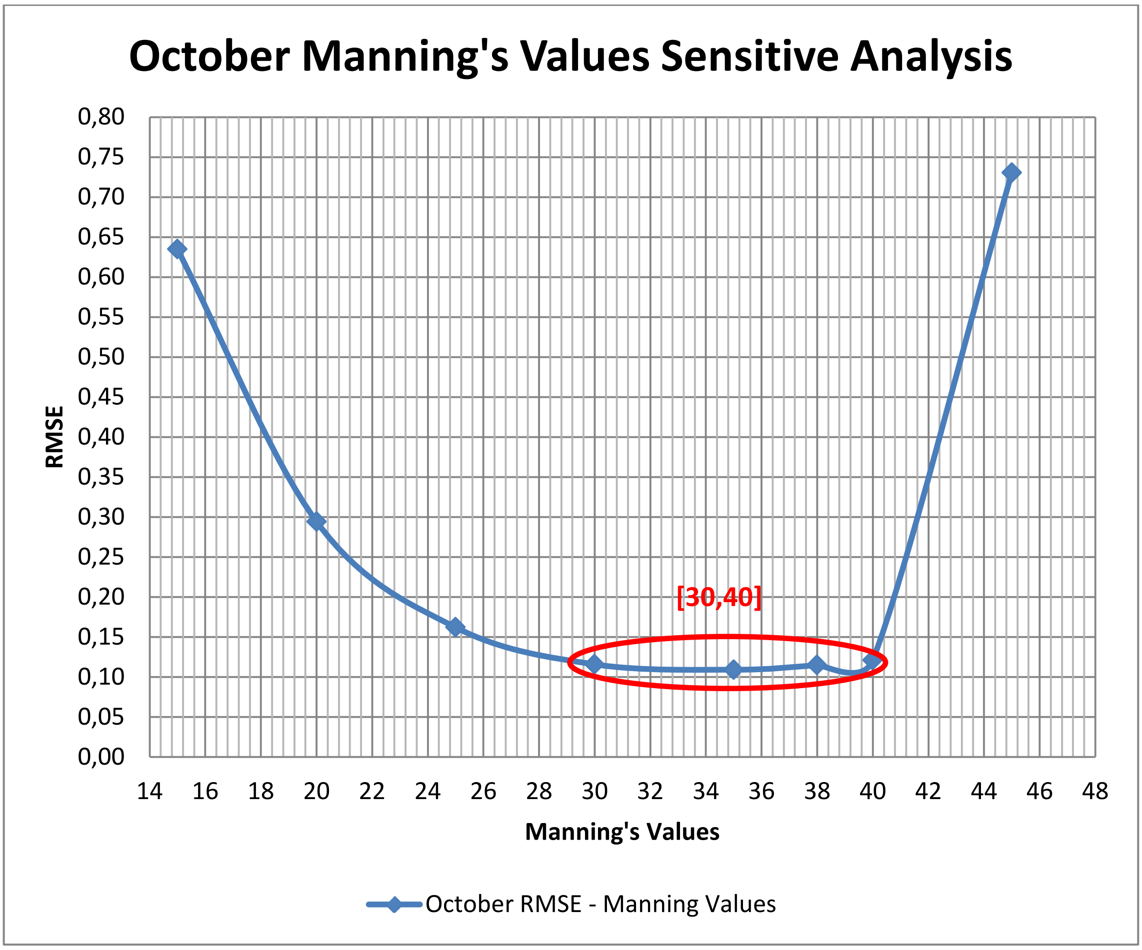


Figure 38 - October Manning values Sensitivity Analysis

Only on length variation the parameter optimisation gives out of range values on Summer Middle Stream. The common Manning values in a river are between 10 and 40. Higher Values than 40 are used in artificial channel, but not in natural streams.

The higher values on Middle Stream, higher than 40, are due to the lake influence. A lake act as a deposit, where input discharge is equal to output discharge. The lake, with it big water volume and wet area, laminates the Vidaa River flow and the strength produced by flow is minimum. The flow resistance effect of the Lake Bottom and Banks (with vegetation) is null or practically null. Big depths and large widths produce smallest resistance factor. That’s the reason because the software gives these higher Manning’s in Middle Stream.

The difference between Manning values varying on time ($M_{\Delta t}$) and Manning values varying on time and length ($M_{\Delta x,\Delta t}$) is because when the software models the river, if it is modelling $M_{\Delta t}$ all the stream has the same weight in the calculus, so Up- and Down-Stream will influence on Middle Stream. But, if it models $M_{\Delta x,\Delta t}$, each part will have their own weights, and the wet lands and lake will influence significantly the Vidaa River flows.

Comparing the water level graphics obtained from the new two simulations (first with $M_{\Delta t}$ and second with $M_{\Delta x,\Delta t}$ as a Boundary Conditions) with the initial Simulation, with a Manning value of 30, and the Observed data one can check that the differences between $M_{\Delta t}$ and $M_{\Delta x,\Delta t}$ are practically null, but they are closer to Observe data than Initial Simulation water levels data. So an engineer could use both Manning's to model the river because the water levels results will be practically the same (all water levels results are in Appendix 2).

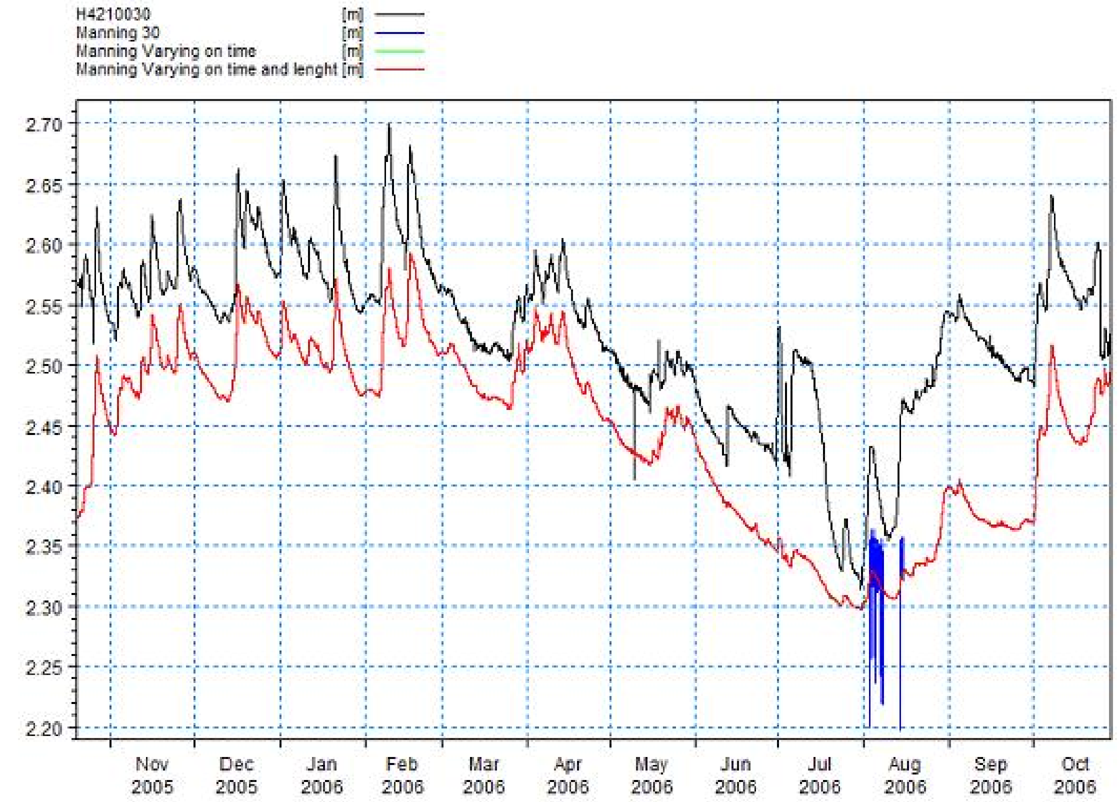


Figure 39 - Vidaa OVR 4588 water levels comparison (Up Stream)

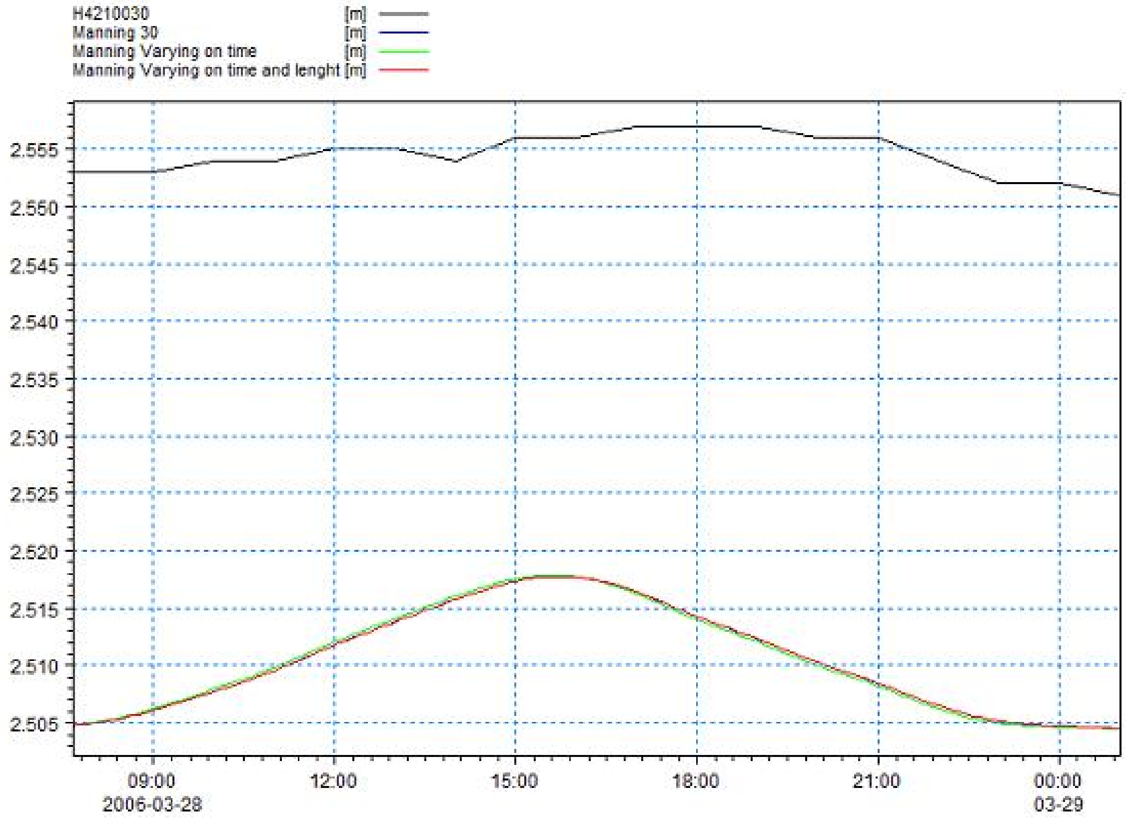


Figure 40 - Vidaa OVR 4588 water levels comparison (detailed)

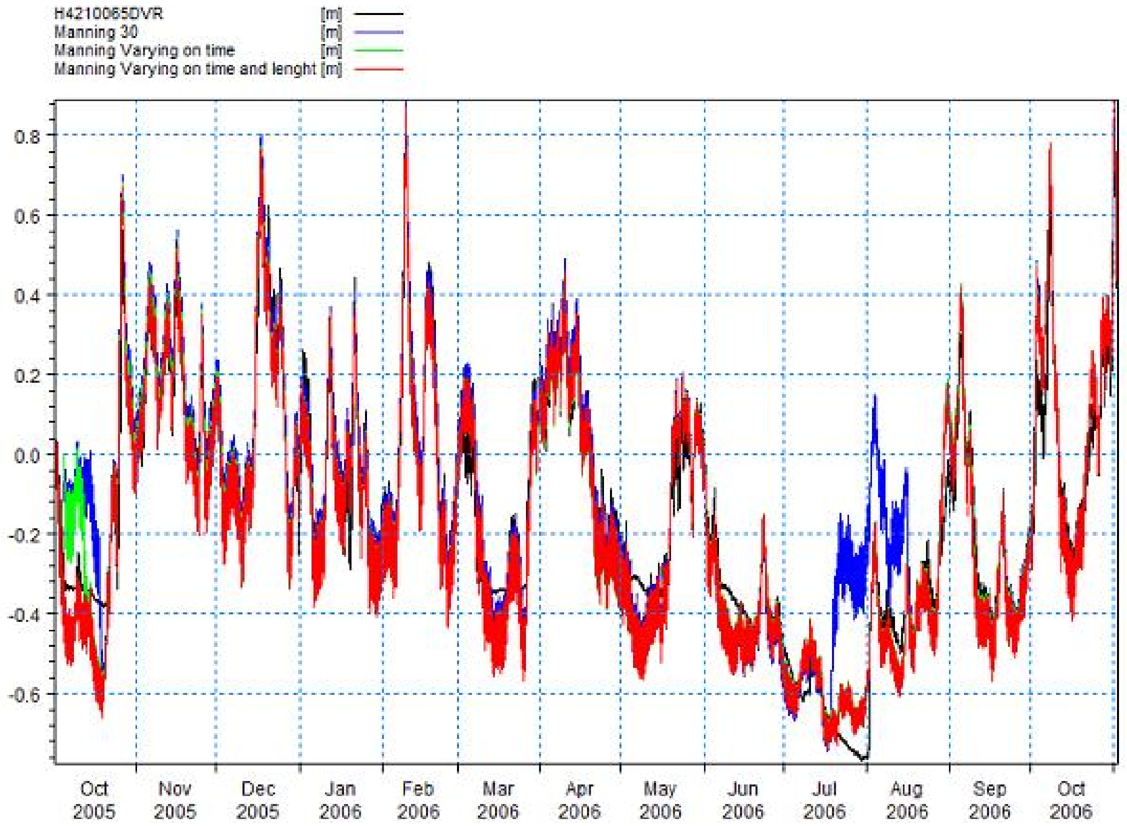


Figure 41 - Vidaa MAG 4670 water levels comparison (Middle Stream)

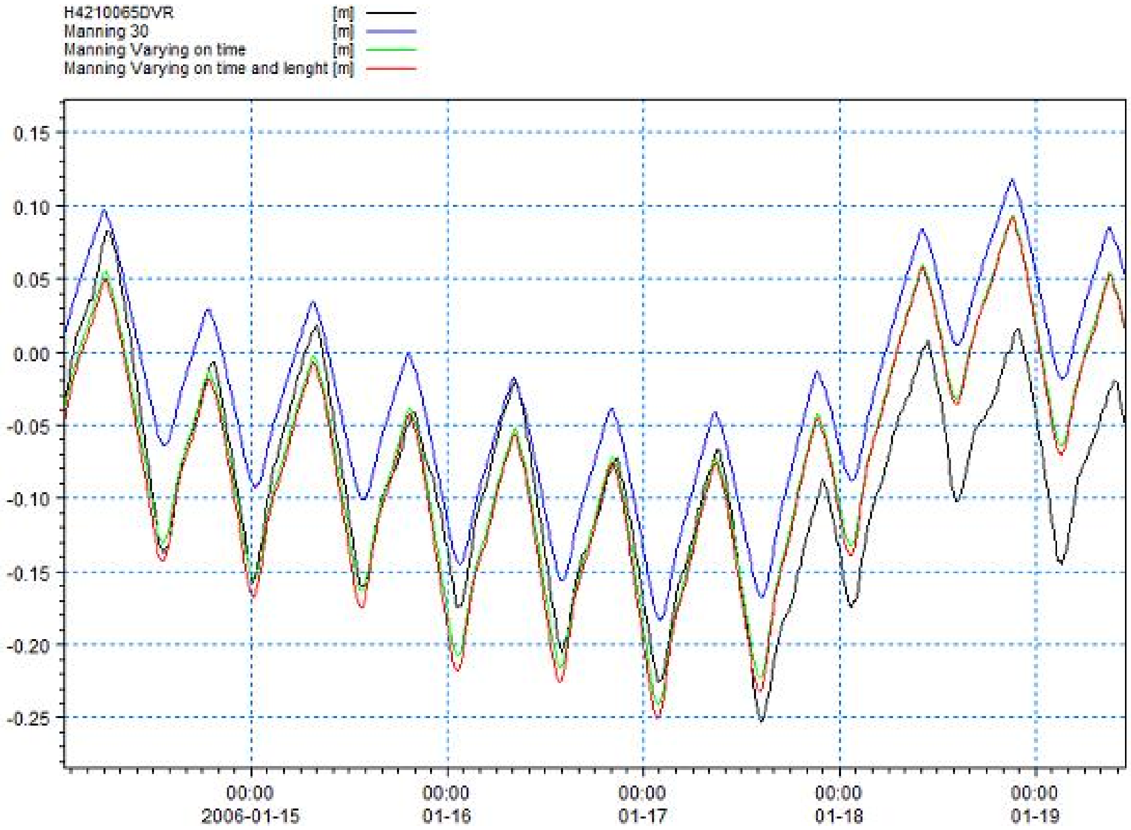


Figure 42 - Vidaa MAG 4670 water levels comparison (detailed)

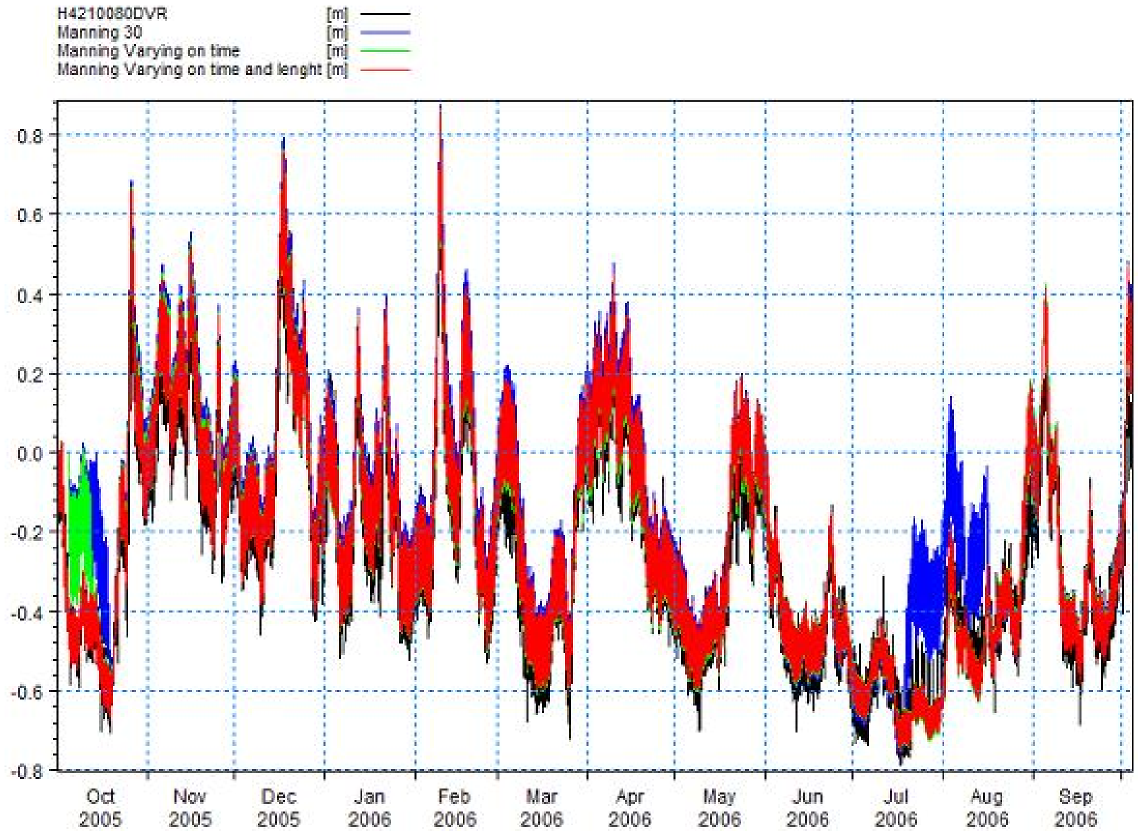


Figure 43 - Vidaa NED 5117 water levels comparison (Downs Stream)

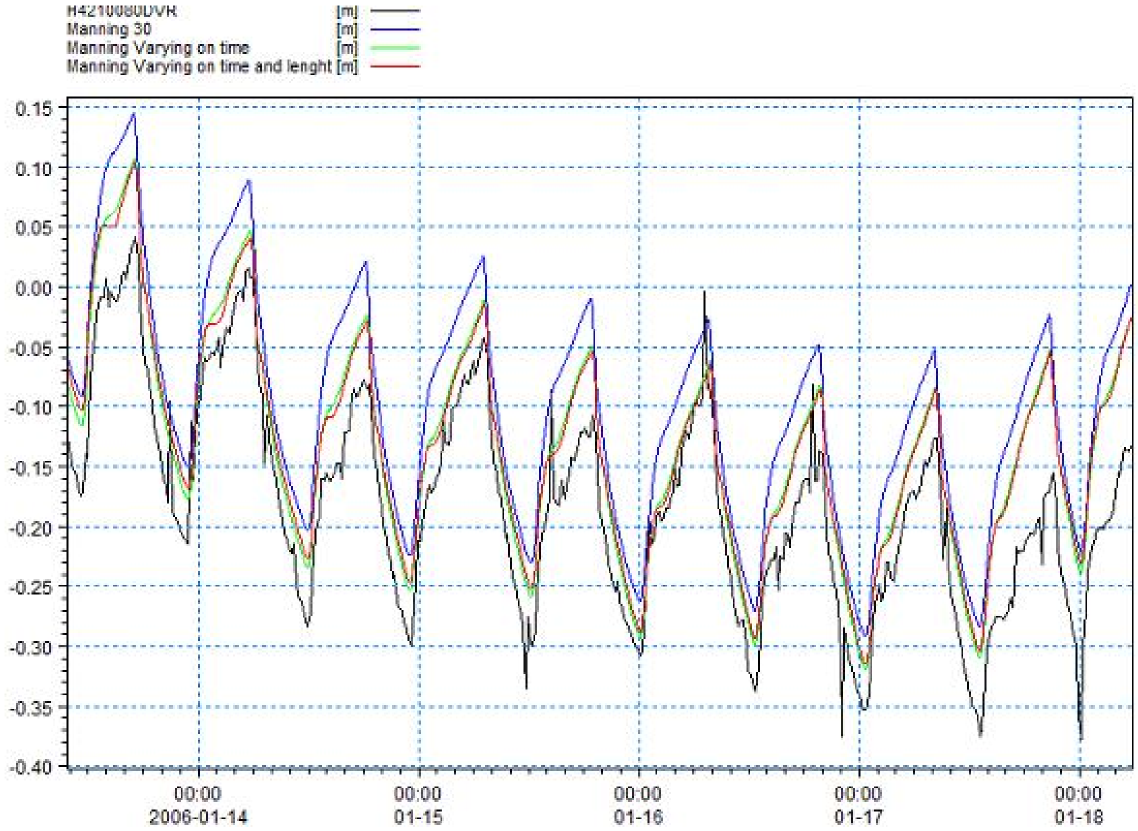


Figure 44 - Vidaa NED 5117 water levels comparison (detailed)

- **Uncertainty** – I cannot explain why the Manning Values ($M_{\Delta x,\Delta t}$) on Middle Stream evolve in a different way than Up- and Down- Stream. Even justify the values solutions I cannot found any theoretical explanation for it case.

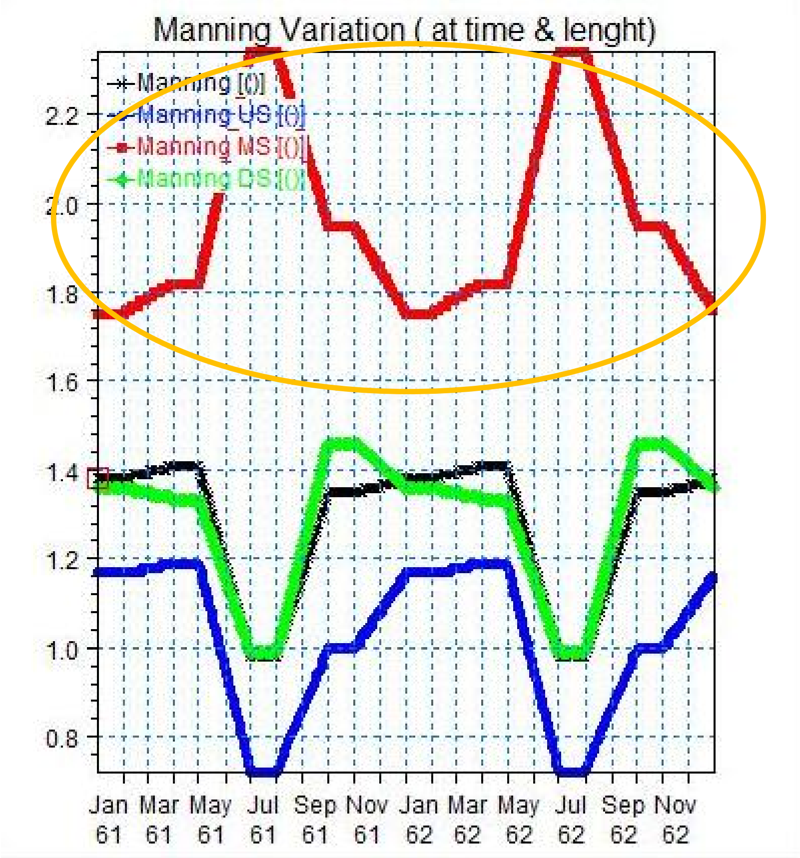


Figure 45 – Resistance factor variation during time (r=1/M)

Once I have defined Manning values for our river ($M_{\Delta x,\Delta t}$), is necessary to define new rainfall time series to study how can affect Vidaa River floods.

Thanks to rainfall observed data time series and stochastic weather generator, an engineer can make synthetic rainfall time series from short time periods to periods as long as he wants. The mean idea is create a long period's time series with the same statistical parameters characteristics. One needs to compare different parameters to obtain these time series. These parameters are:

- Mean
- Variance
- Correlation
- Dry day probability
- Skewness
- Lag Correlation

Thanks to RainSim, one can obtain these synthetic time series. In that case, I am going to use the observed rainfall time series from two head catchments (Vidaa OVR and Gronaa_TM) and the observed rainfall time series from the end of the river (downstream). The common period between these rain gauges is 15 years (1/1/1971 – 1/1/1986). After fitted the statistical parameters, and found the best option that will be more realistic compared with the observed data, one can simulate it to obtain the new synthetic rainfall time series choosing as long will be the data time series (5, 10, 25, 50, 100, 200, 500, 1000, and 2000 years have been chosen).

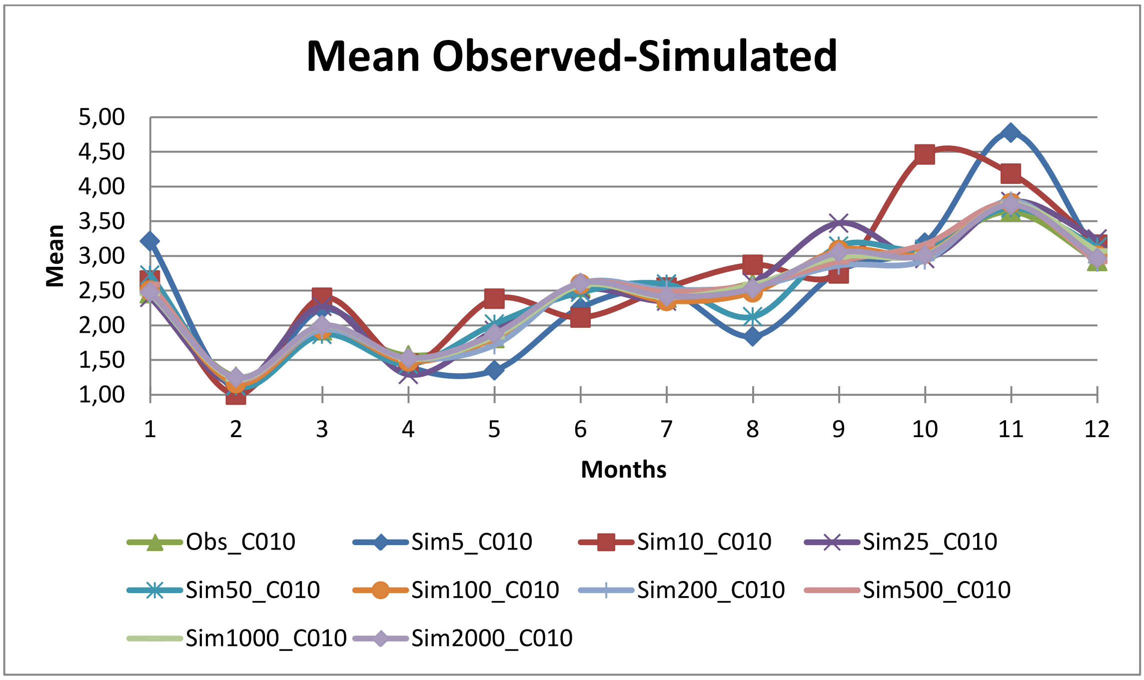


Figure 46 - Monthly mean precipitation value for Vidaa OVR head catchment

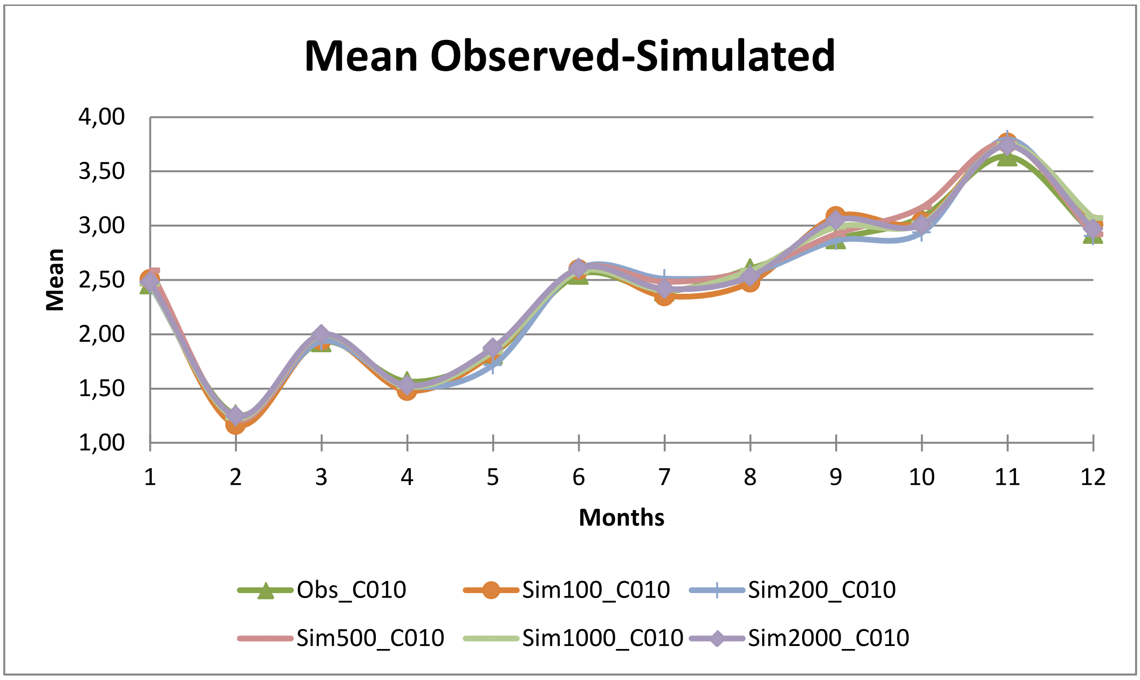


Figure 47 - Monthly mean precipitation value for Vidaa OVR head catchment (detailed)

Figure 46 and *Figure 47* show the monthly mean precipitations value for Vidaa OVR head catchment. Plots for mean precipitation for the 3 stations are presented in Appendix 4. The observed monthly mean precipitation is compared to the results obtained using SNSRP Weather Generator for different time periods. Both plots give a good representation of the monthly mean precipitation when the time period is higher. Similar results are obtained for the rest of the station

Figure 48 and *Figure 49* show the monthly variance for Vidaa OVR head catchment. Plots for variance for the 3 stations are presented in Appendix 4. As mean precipitation, both plots, observed data and SNSRP data, gives a good representation of the monthly variance when the time period is higher.

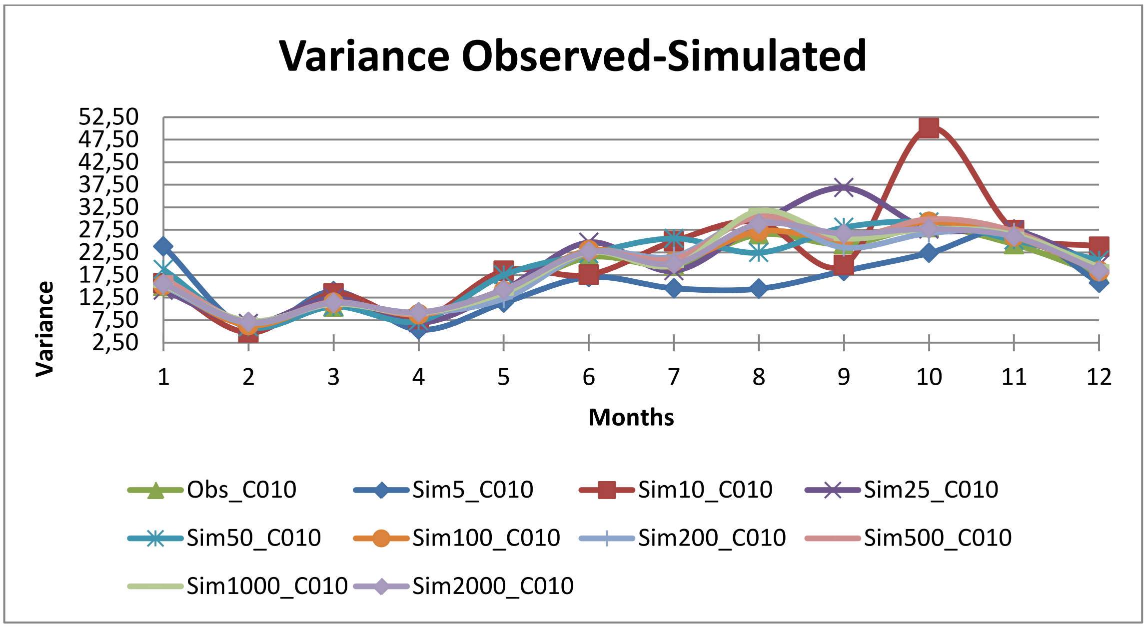


Figure 48 - Monthly Variance value for Vidaa OVR head catchment

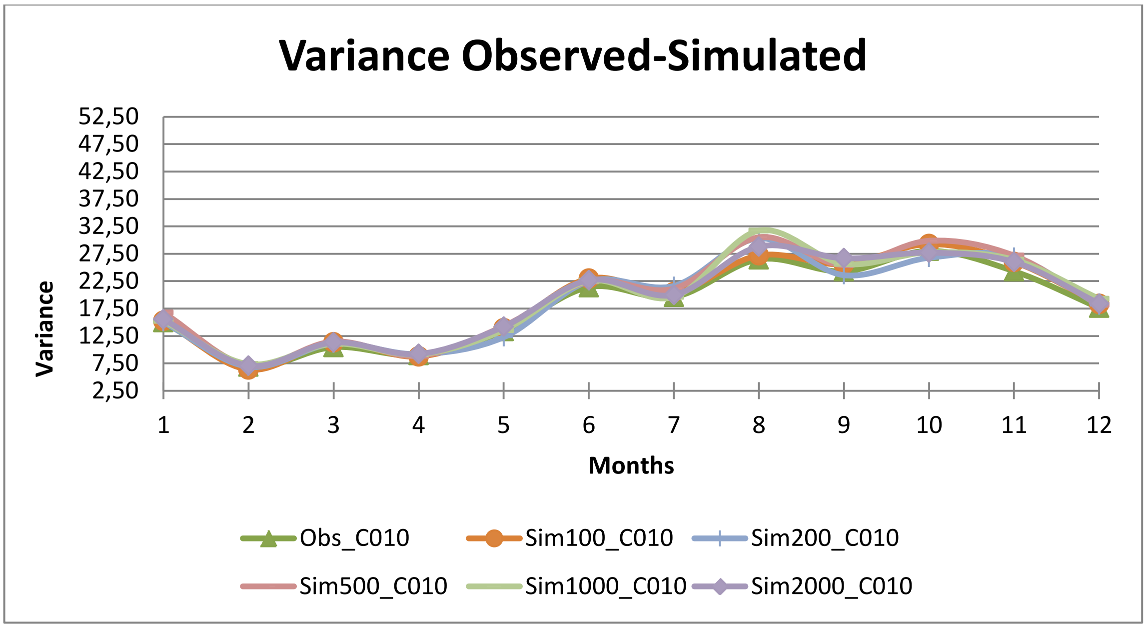


Figure 49 - Monthly Variance value for Vidaa OVR head catchment (detailed)

The green line in *Figure 50* and *Figure 51* show the probability of dry days (Pdry) for observed data for each month, while the other lines show the regional monthly average probability of dry days. A threshold value of 1.0 mm was used to define wet and dry days. In general, higher time periods gives a good representation of the probability of dry days.

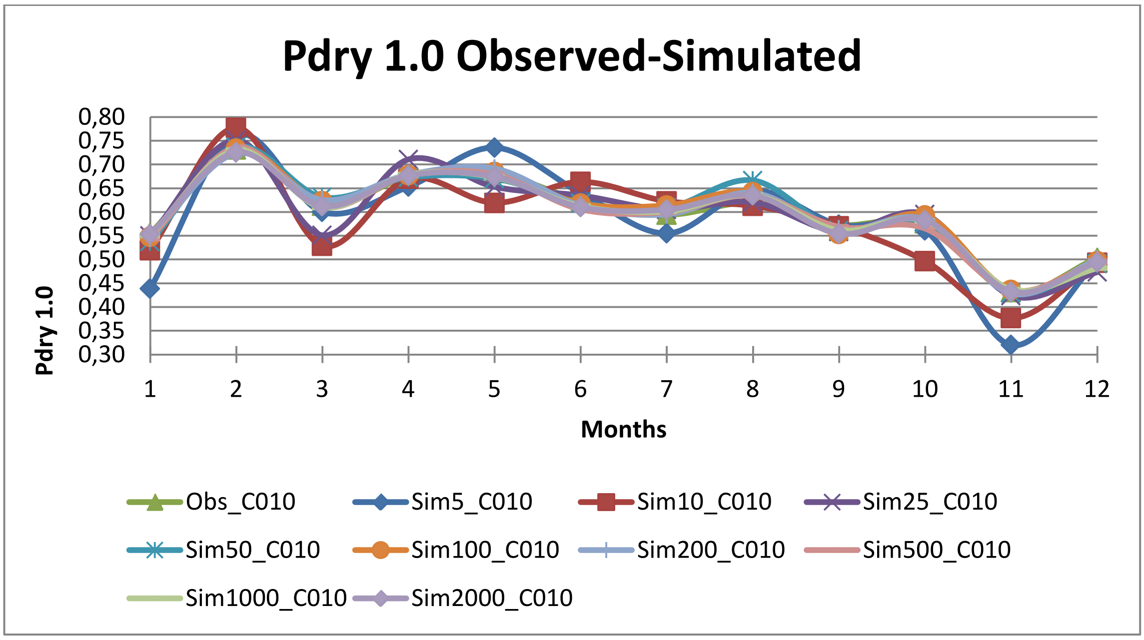


Figure 50 - Monthly Probability of dry day value for Vidaa OVR head catchment

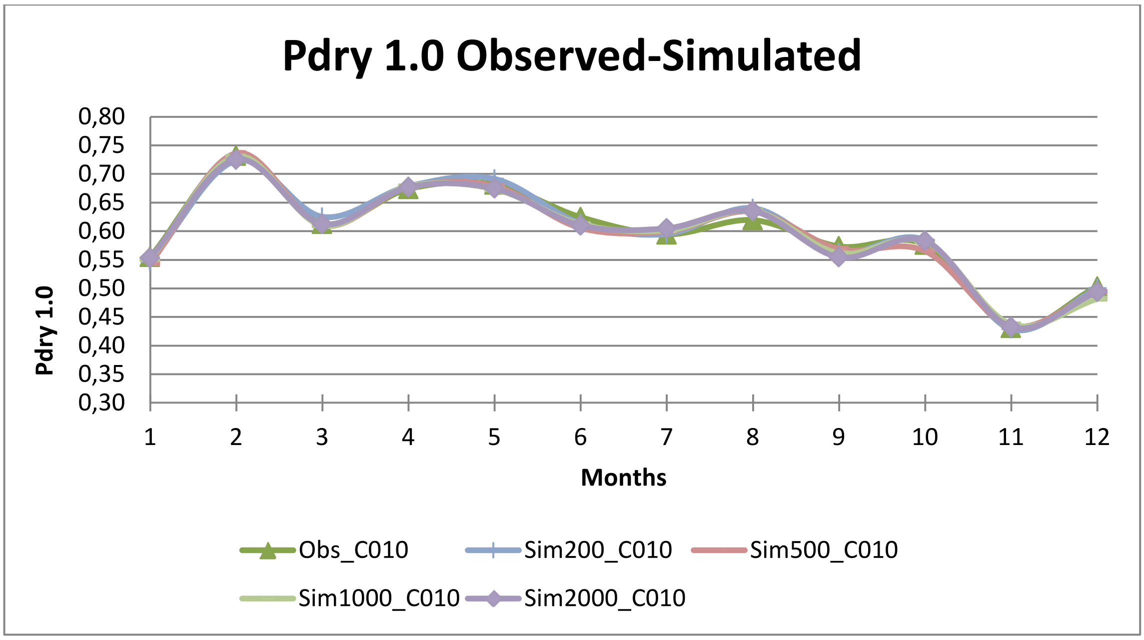


Figure 51 - Monthly Probability of dry day value for Vidaa OVR head catchment (detailed)

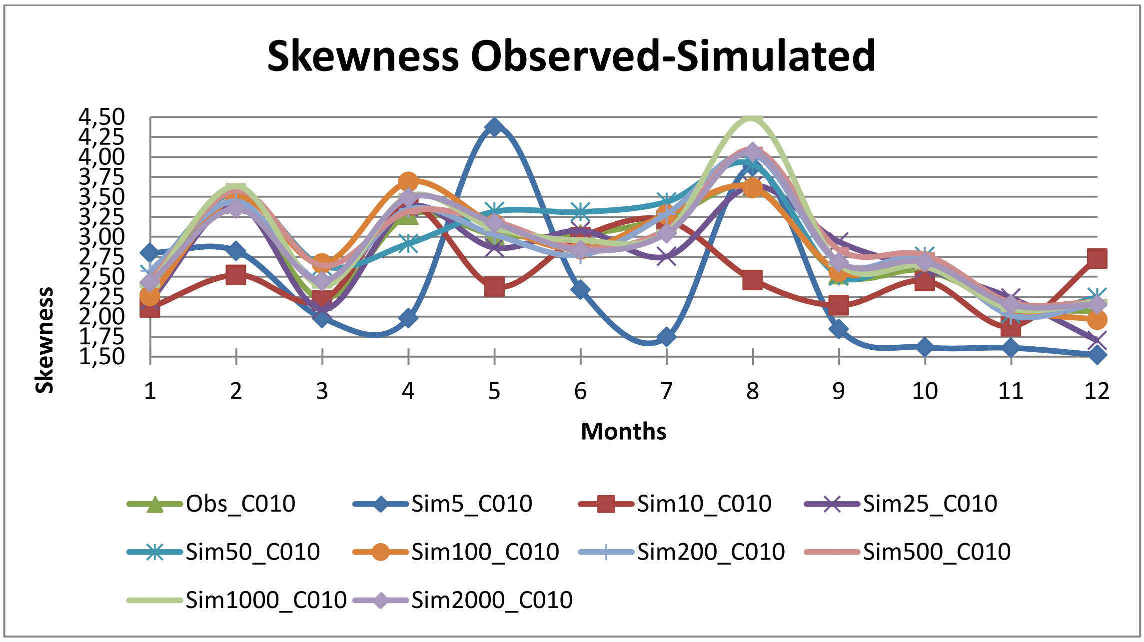


Figure 52 - Monthly Skewness value for Vidaa OVR head catchment

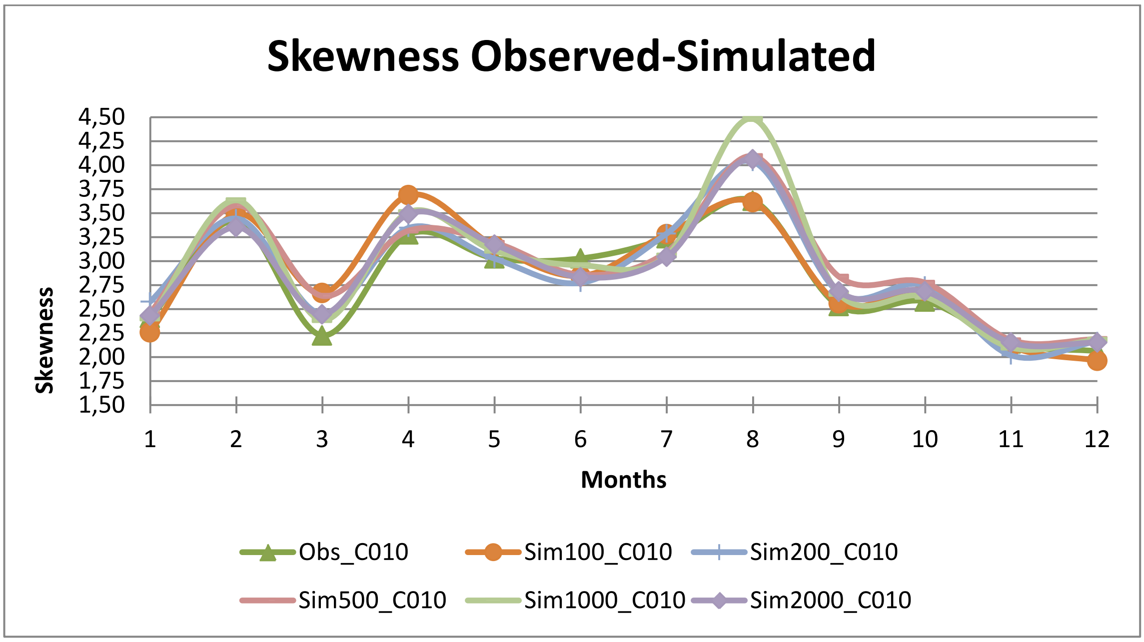


Figure 53 - Monthly Skewness value for Vidaa OVR head catchment (detailed)

Skewness is of special interest because it is an indicator of how well extreme avents are represented. It is unlikely to fit the distribution well in the tail without including some highr-order property in the fitting procedure. Skewness is defined as:

$$Skw = \frac{E(x-\mu)^3}{\sigma^3}$$

Where μ and σ are the mean and standard deviation of x, *E(t)* is the expected value of *t*. *Figure 53* show that, even with long time periods simulated, generally skewness is overestimate.

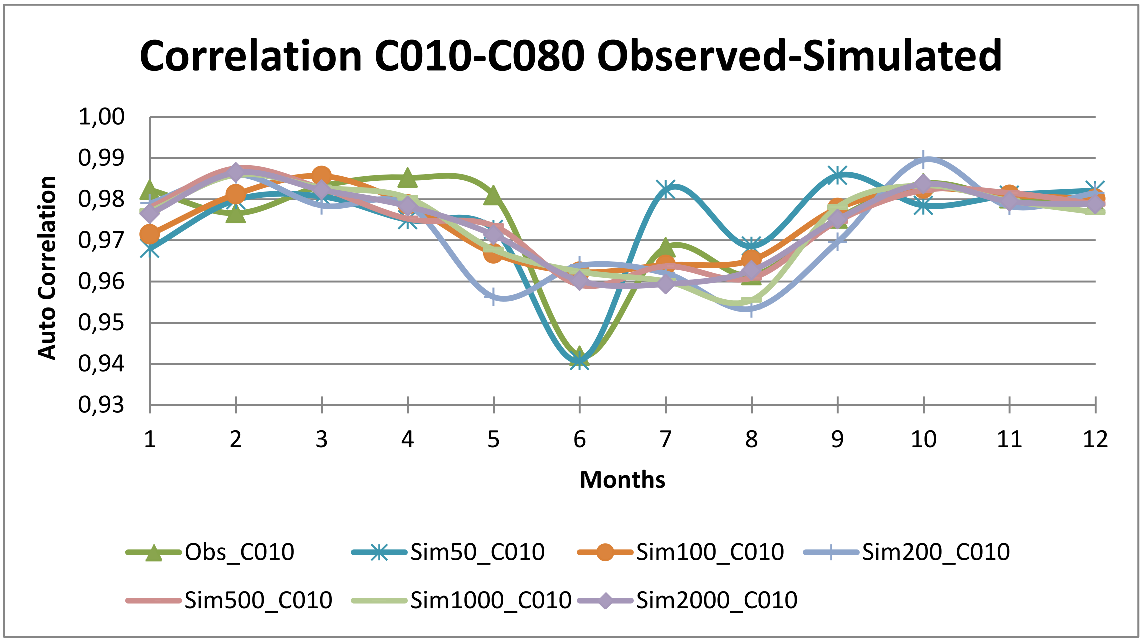


Figure 54 - Monthly Autocorrelation value for Vidaa OVR head catchment

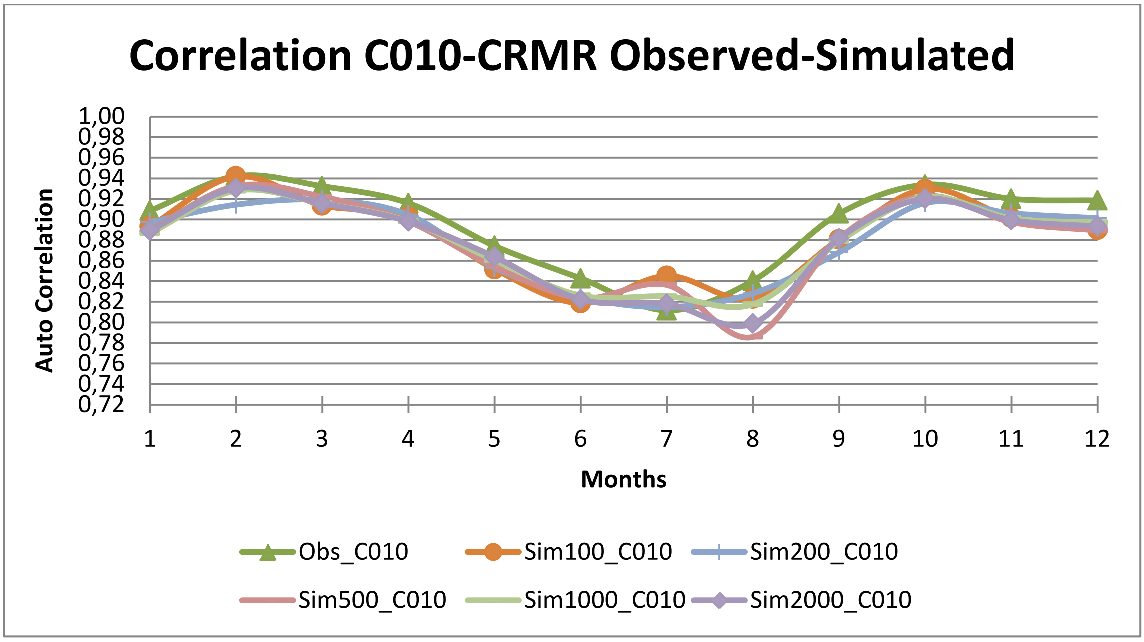


Figure 55 - Monthly Autocorrelation value for Vidaa OVR head catchment (detailed)

Figure shows the inter-site correlation. As expected (see in Appendix 4the autocorrelation with the other two stations and the Figure 56 - Correlation between stations), it is observed that the correlation between stations decreases when the distance increases.

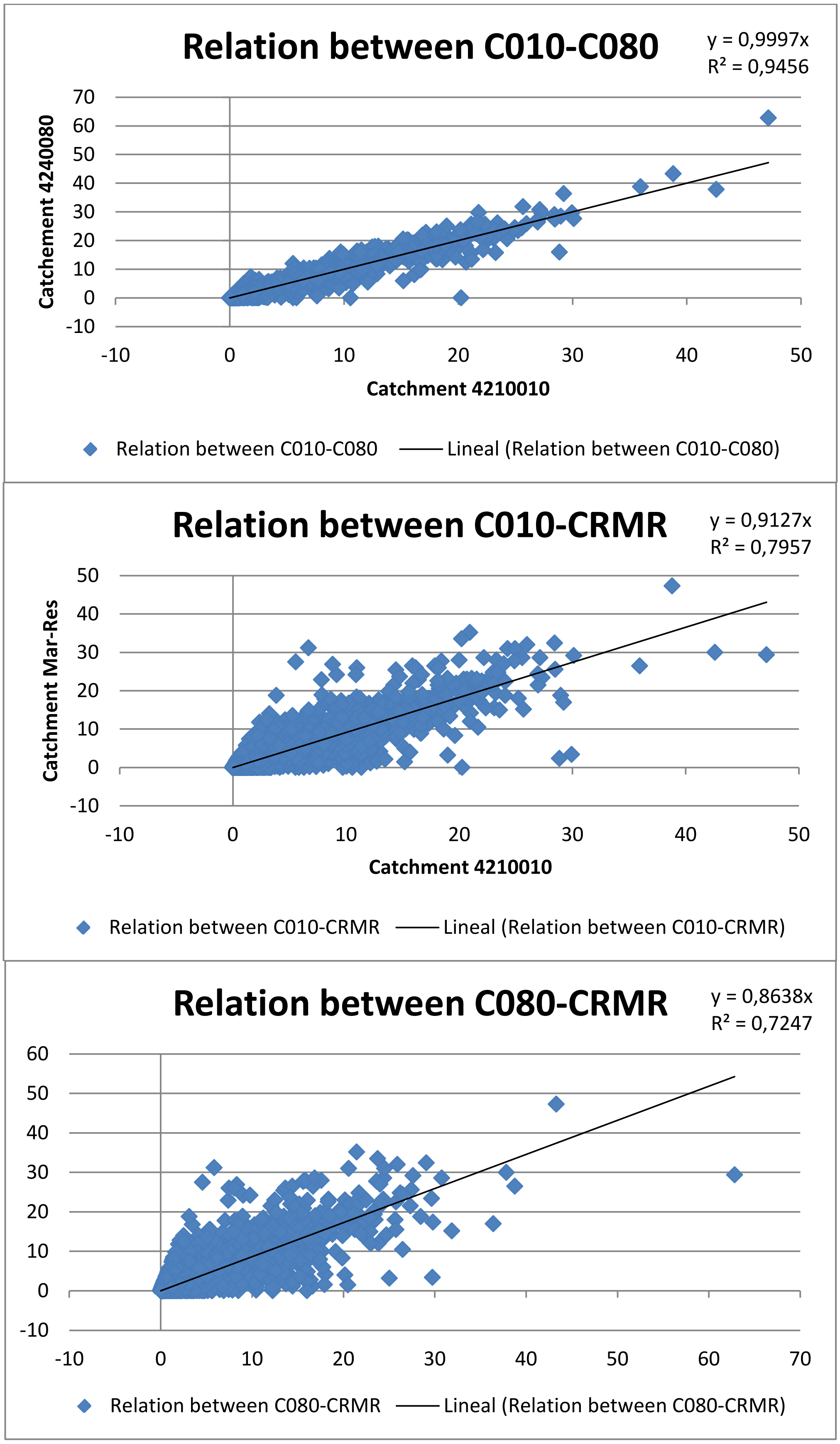


Figure 56 - Correlation between stations

After obtain synthetic rainfall data and run them as a new input in NAM Rainfall-Runoff model, MIKE 11 will run simulations for the difference long time periods (10, 25, 50, and 100 years) obtaining the new simulated water level according these long time periods. Only these four time periods have been run due to the high computational cost and duration with higher periods.

Extreme value analysis gives the engineer the extreme event for each year of the simulation period (extreme time series, see *Figure57 , Figure58 , and Figure59*), and allow to compare with the observed extreme water levels.

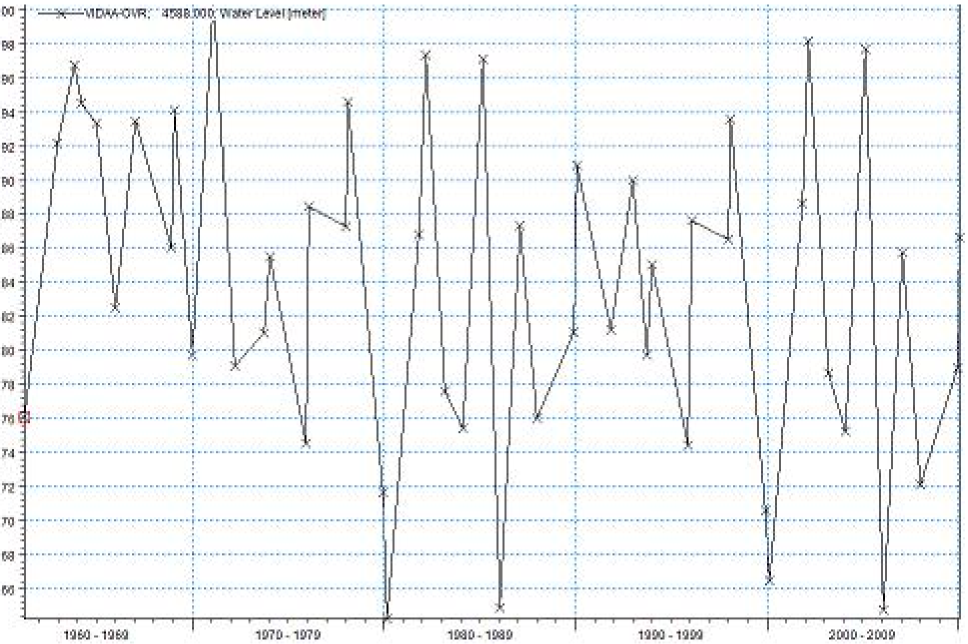


Figure 57 - Extreme events time series Vidaa OVR (50 years)

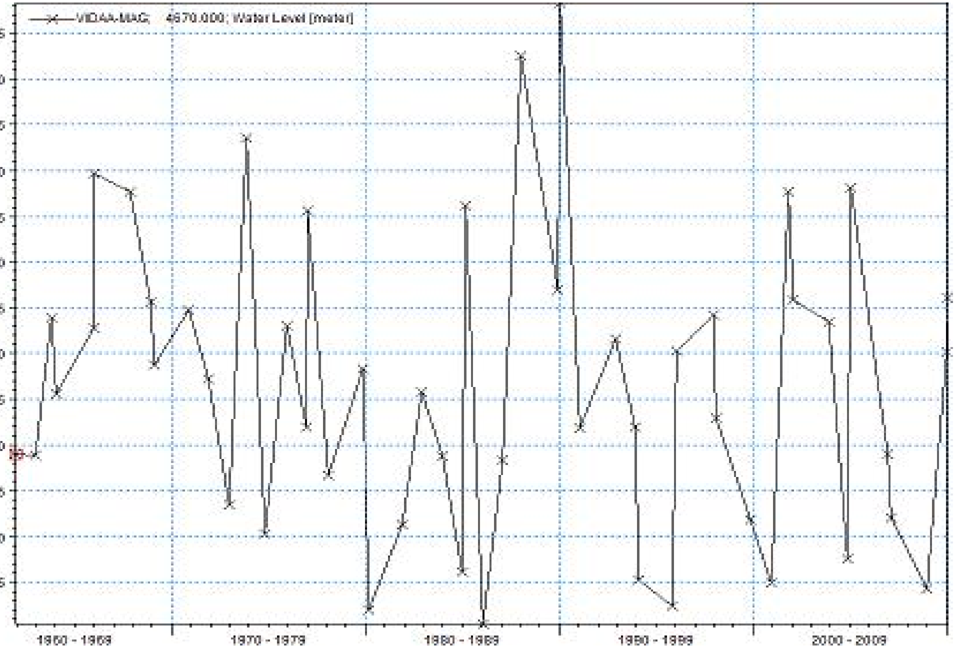


Figure 58 - Extreme events time series Vidaa MAG (50 years)

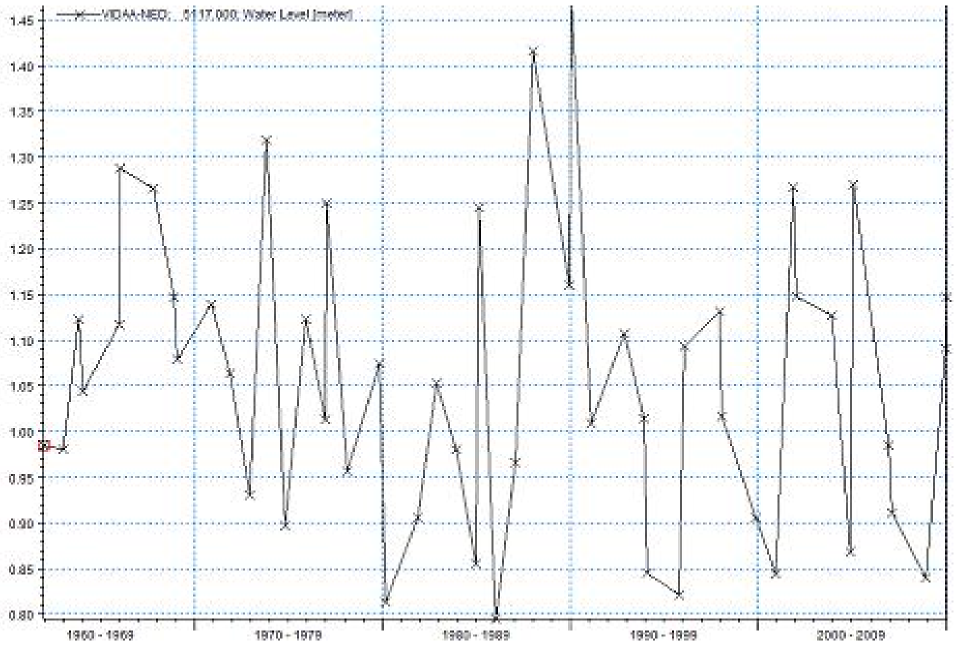


Figure 59 - Extreme events time series Vidaa NED (50 years)

The empirical cumulative distribution function (CDF) has been fitted to the observed extreme values series using a Generalized Extreme Values distribution (GEV).

Figure60 show the empirical cumulative distribution function (CDF) of extreme events for the weather generators time series data for the control station WL1 (Appendix 4 contains the plots for the rest of the stations).

One can observe that the maximum difference from observed data and the different water levels (according duration time period) series is about 15 – 25 cm, been the Methods of Moments (MOM) that best show the extreme events compared to observed data. Time period of 50 and 100 years are the closest lines to observe data, with minimum differences between them about 10 cm. Also MOM is the estimation method that gives a higher water level in each return period compared with L-moment estimators (LMOM) and maximum likelihood (ML) that underestimate these values.

In addition, a CDF has been fitted to the observed extreme values series. The fitted distribution is shown as a solid line and the 95% confidence intervals are shown in dash lines (see *Figure61*).

The estimated extreme value series using the WG are considered to fit well if the values of the estimated extreme events fall inside 95% confidence interval.

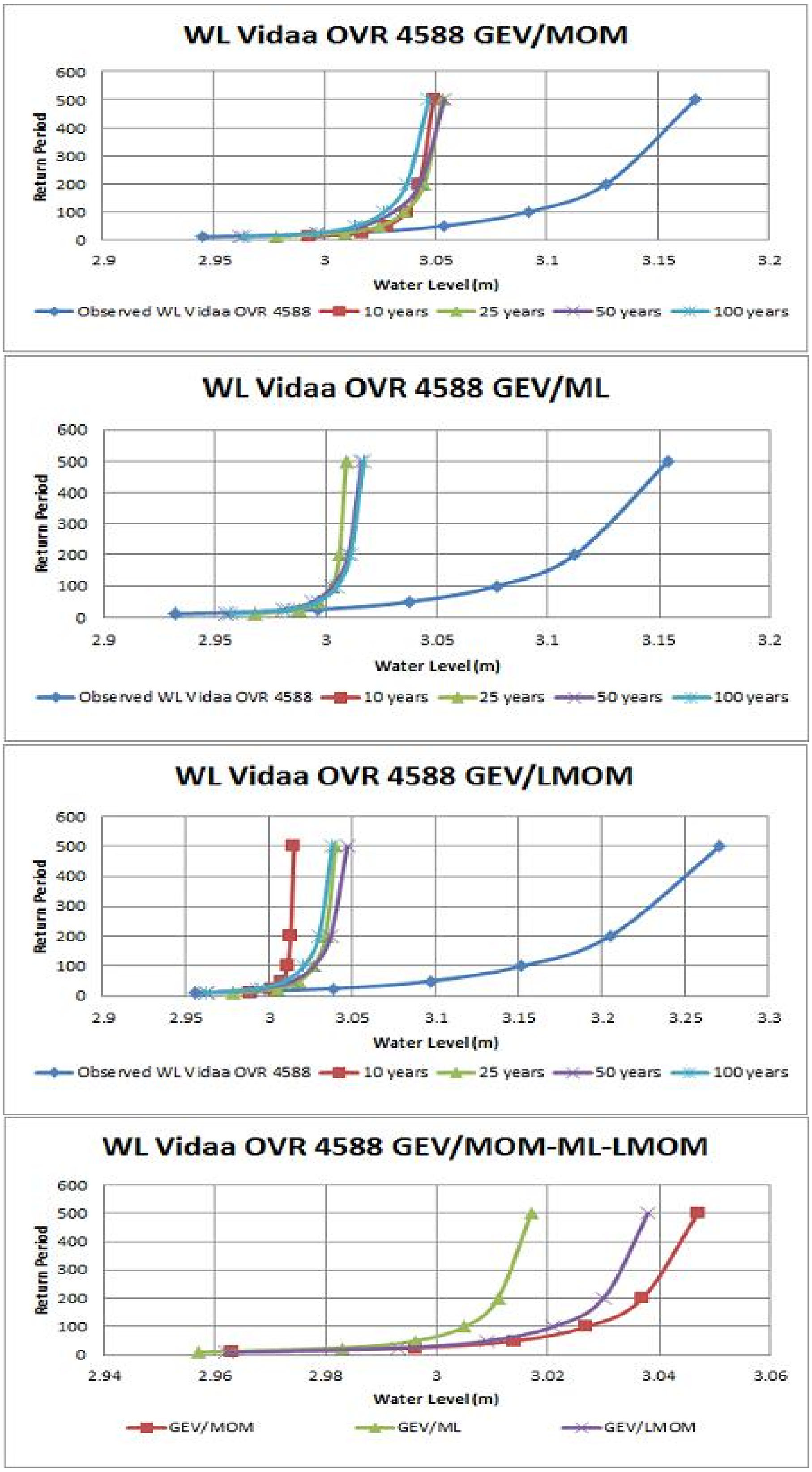


Figure 60 - Extreme value events for different return periods using a GEV distribution and three different estimation methods

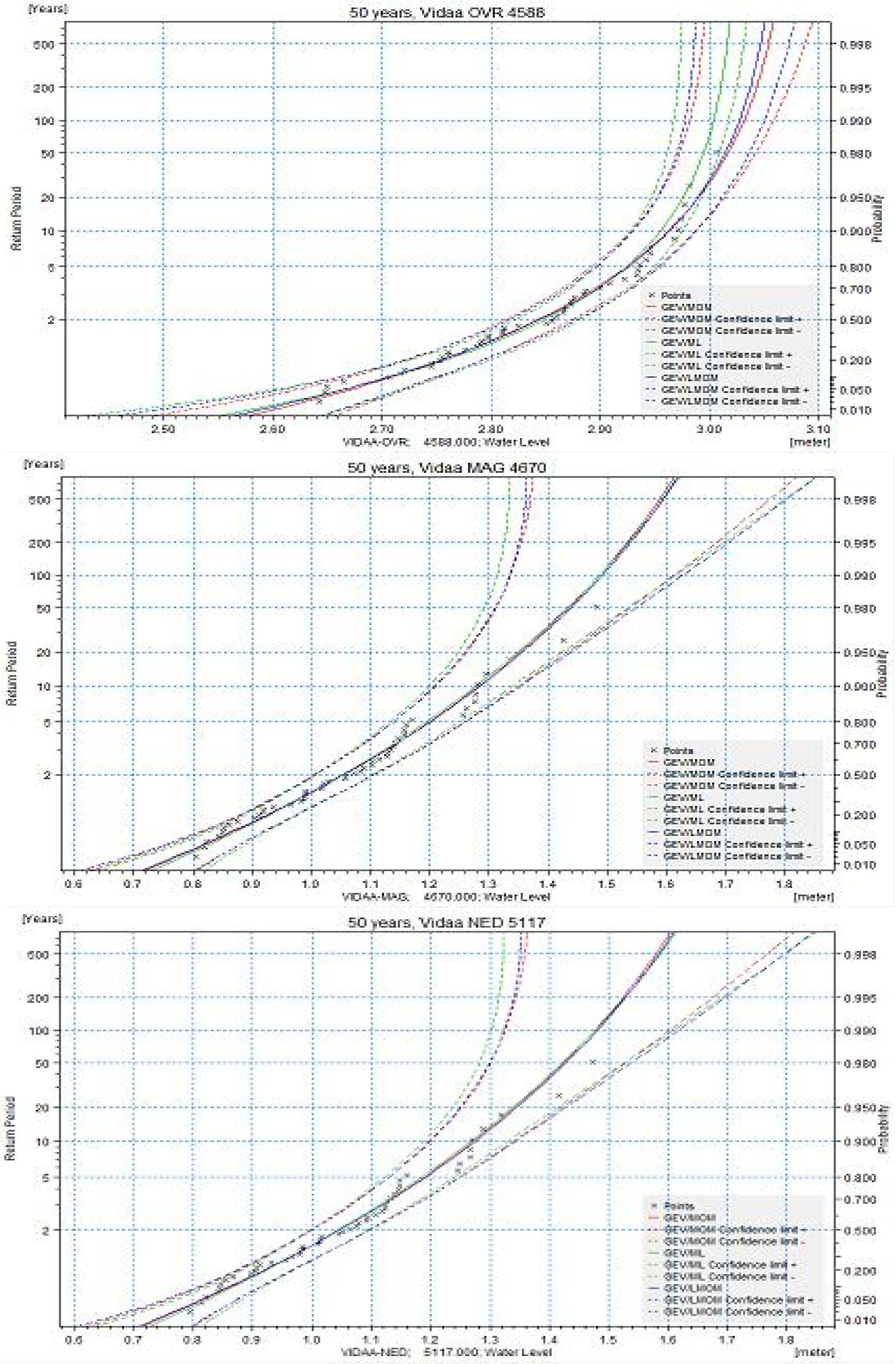


Figure 61 - Fitted distribution for each estimation method

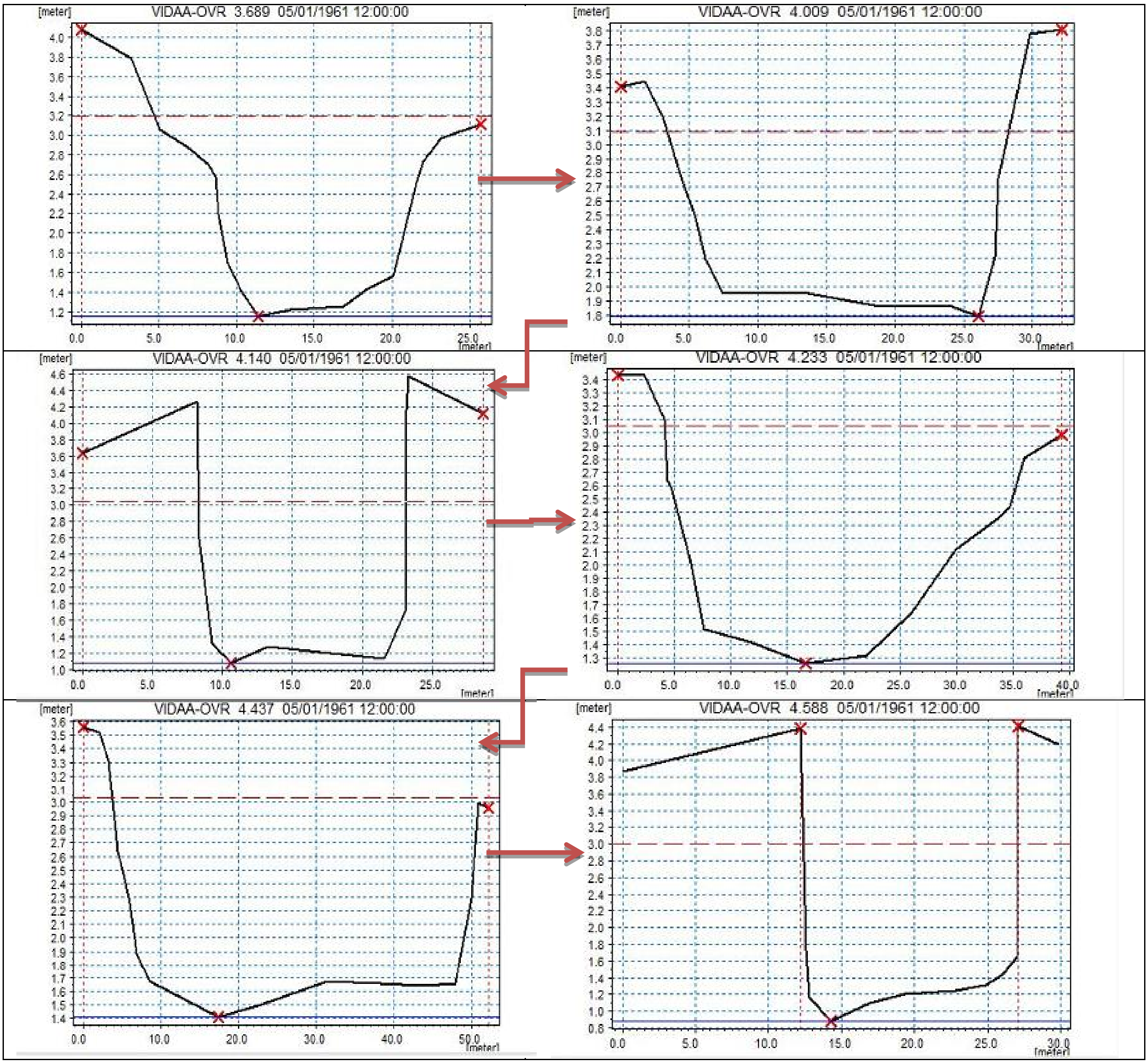
Flow channelling project in the world is normally chosen with a return period of 50 or 100 years. In urban areas return periods are higher (200 years) and should be distinguished from the case where the overflow is a severe flood (if the levees are high on the ground) or the case where happens simply overrun. When there are no affected population return periods can be 25 or 50 years (farm land). Return periods for 50, 100, and 200 are selected to estimate floods in points WL1, WL4, and WL5.

The extreme events for the different return periods according to the estimation methods are showed in *Table11* . Method of Moments results have been selected to flood study.

50 years	RP	GEV/MOM	GEV/ML	GEV/LMOM
Vidaa OVR 4588	10	2.962	2.955	2.963
	25	2.997	2.981	2.996
	50	3.017	2.994	3.014
	100	3.031	3.003	3.027
	200	3.043	3.01	3.037
	500	3.054	3.016	3.047
Vidaa MAG 4670	10	1.283	1.278	1.286
	25	1.375	1.371	1.378
	50	1.434	1.432	1.439
	100	1.487	1.487	1.492
	200	1.535	1.537	1.539
	500	1.589	1.595	1.595
Vidaa NED 5117	10	1.272	1.267	1.275
	25	1.363	1.36	1.367
	50	1.423	1.422	1.427
	100	1.476	1.477	1.48
	200	1.524	1.527	1.528
	500	1.579	1.586	1.584

Table 11 - Extrem water level values for point WL1, WL4, and WL5. Values from GEV/MOM with a return period of 50, 100, and 200 years are going to be used to flood study

Return period of 200 years have been checked in WL1 to avoid possible flooding in this area. WL1 is located surrounding Tønder, the biggest town in the area. The results showed in the *Figure62* , permit us to make sure than extreme events are not going to affect Tønder. The water level only exceeds the banks on it left side (flow direction) while Tønder is located in it right side. Even with a return period of 500 years, Tønder will be safe.


VIDAA-OVR 3.689 05/01/1961 12:00:00

VIDAA-OVR 4.009 05/01/1961 12:00:00

VIDAA-OVR 4.140 05/01/1961 12:00:00

VIDAA-OVR 4.233 05/01/1961 12:00:00

VIDAA-OVR 4.437 05/01/1961 12:00:00

VIDAA-OVR 4.588 05/01/1961 12:00:00

Figure 62 - Extrem water level event in Tonder

Where the dash line is the extreme water level event value in point WL1.

By contrast, in points WL4 and WL5, the extreme events will exceed the river banks (right and left bank). The difference between return periods of 50, 100, and 200 are practically null, we are talking about 10 cm. But the flood plains extend 40 – 50 m out of the banks in Vidaa MAG (WL4, wet lands) and 25m out of the banks in Vidaa NED (WL5, downstream).

Fortunately, these two areas are wet lands (WL4) and farm lands (WL5) where floods are not so important.

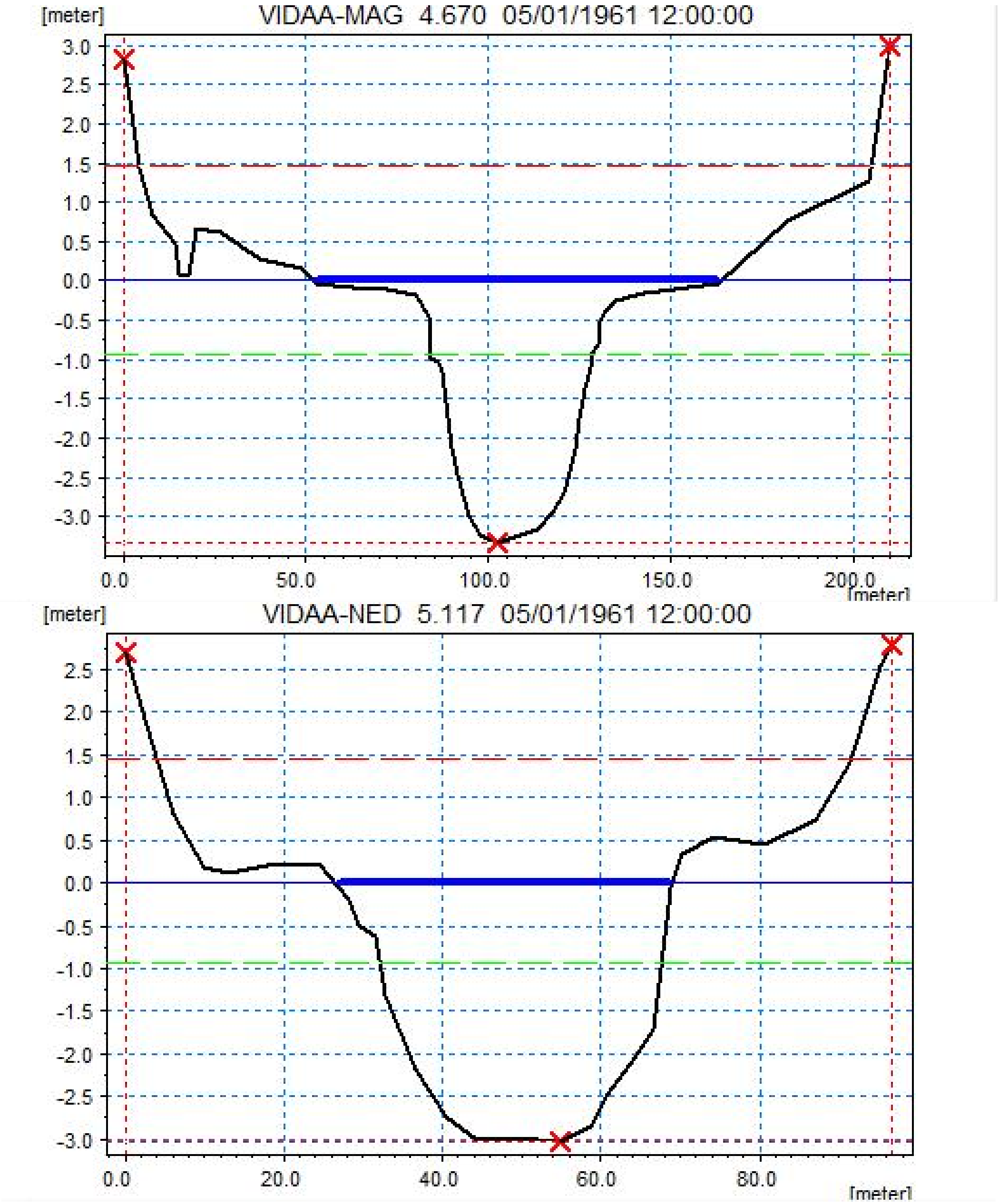


Figure 63 - Extreme water levels events in points WL4 and WL5 (Wet lands and farm lands)

Conclusions

This project shows the importance of Manning value when a river modelled has been made. Variations in Manning values will affect the water levels. As this study shows, different possibilities about Manning can be taking into account: Unique Manning value, Manning value that vary on time, and Manning value that vary on time and length. Last two options get close the simulated water levels with observed data and the difference between them are quite similar, so the user can chose anyone of them to model the river.

To estimate floods is necessary to have good rainfall time series. Sometimes, these time series are short or present important gaps on them. Stochastic weather generators help the user to create synthetic time series from observed rainfall data with different long time periods. These synthetic time series will be obtain thanks to fit the observed data and generate these news data with the same statistical parameters, in order to create time series with the same precipitation occurrence process.

The new synthetic series, with longer time periods, will be used to run the model obtaining news water levels data. Thanks to Extreme Value Analysis tools, these water levels obtained from the simulation will give us the opportunity to study the extreme events produced in those time periods. Extreme Value Analysis tools calculate the probability and frequency that rainfall can happen for a specific value in a specific return period. These return period values will be used to size bridges, weirs, culverts, and, of course, to avoid floods.

In that study, three different points have been taking into account to study overflows. The most important of these points is Tønder, the biggest town in this area. But fortunately, the floods are not going to happen on it village, the flow will be between the river banks even in the worst extreme event.

The other two points are located in the Middle- and Down- stream. Overflow will be extending 50 meters and 25 meters respectively from each bank station. The overflow will flood wet lands and farm lands respectively.

This study is a good way to know about the floods probability, and the locations where the flow will overflow. It will be a first risk analysis trial. To complete that study, a 2D model would be necessary, where an engineer will know about the flow velocities distribution, happened on our system, and the depths along all the cross sections, in order to know what kind of floods is happening (dangerous, moderate or mild).

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CHAPTER 5: HIDROLOGICAL STUDY

RESULTS

APPENDIX 1: ONE-DIMENSIONAL CALCULATION MODEL Page

Appendix 1: One-dimensional calculation model

In the last 20 years researchers and engineers have been used different kind of models to simulate Flood Risks Assessment. Models are useful to reproduce reality from number of simplifications, it allows resolve complex situations. Numerical simulation allows solving continuous differential equations defining a physical process by its discretization algebraic relationships expressed in terms of finite differences evaluated in a number of representative points Study domain.

The simulation allows the solution progress in time through its discretization in time steps generally variable value. The equations to describe the water behavior in surface irrigation are the Saint Venant shallow water model.

The simulator allows the progress of the solution in time through its discretization in time steps generally variable value. The equations to describe the behavior of water in surface irrigation are the model of Saint Venant shallow water. The application of certain hypothesis allows the use of one-dimensional and two-dimensional models based on Saint Venant equations to solve the water flow in plots.

Dimensional equations are rigorously applied in situations where water flow can be considered one-dimensional, I mean, the front moves in a straight line and are considered negligible lateral water movements. Nowadays, computer technological advancement has promoted the widespread use of hydrodynamic models, which solves the problem more precisely. The equations that make up the hydrodynamic model are:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + i = 0$$

$$\frac{1}{gA} \times \frac{\partial Q}{\partial t} + \frac{2Q}{gA^2} \times \frac{\partial Q}{\partial x} + (1 + Fr^2) \times \frac{\partial h}{\partial x} = S_0 - S_f \qquad (1)$$

Where are:

A	(Wet cross sectional area)	Q	(Discharge)
i	(Infiltration rate)	g	(Gravity acceleration)
Fr	(Froude Number)	h	(Water depth)
S_0	(Slope)	S_f	(Friction slope)

Most of the river simulations are performed today using this kind of model because to delimitate floodplains or to sizing infrastructure such bridges, are perfectly valid. The commercials models most commonly used are: MIKE11 (Denmark Hydrological Institute, DHI) and HEC-RAS (the United States Army Corps of Engineers, USACE).

Figure 64 – Logos from the most commercial hydrodynamic models commonly used

MIKE 11

Introduction

MIKE 11 is a computer program that simulates flow and water level, water quality and sediment transport in rivers, flood plains, irrigation canals, reservoirs and other inland water bodies. MIKE 11 is a one dimensional river model. It was developed by DHI Water – Environmental – Health.

MIKE 11 has long been known as a software tool with advanced interface facilities. Since the beginning, MIKE 11 was operated through an efficient interactive menu system with systematic layouts and sequencing of menus. That is within that framework where the latest “Classic” version of MIKE 11 – version 3.20 was developed.

The new generation of MIKE 11 combines the features and experiences from the MIKE 11 “Classic” period, with the powerful Windows based user interface including graphical editing facilities and improved computational speed gained by the full utilization of 32-bit technology.

On the input/edit side MIKE 11 features:

- Graphical data input/editing
- Simultaneously input/editing of various data types
- Copy & paste facility for direct import (export) from e.g. spread sheet programs
- Fully integrated tabular and graphical windows
- Importing of river network and topography data from ASCII text files
- User defined layout of all graphical views (colours, font settings, lines, marker types, etc.)

On the Output side, advanced presentation facilities are available, including:

- Coloured horizontal plan graphics for the system data and results
- Animated presentation of results in horizontal, longitudinal and time series plot
- Synchronised animation of results
- Presentation of external time series
- Copy & paste facility for exporting results tables or the presentation graphics into other applications (spread sheet, word processing or others).

Modules

The Hydrodynamic (HD) module is the nucleus of the MIKE 11 modelling system and forms the basis for most modules including Flood Forecasting, Advection-Dispersion, Water Quality and Non-cohesive sediment transport modules. The MIKE 11 HD module solves the vertically integrated equations for the conservation of continuity and momentum, i.e. the Saint Venant equations.

The primary feature of the MIKE 11 modelling system is the integrated modular structure with a variety of add-on modules each simulating phenomenon related to river systems.

In addition to the HD module described above, MIKE 11 includes add-on modules for Hydrology, Advection-Dispersion, and Models for various aspects of Water Quality, Cohesive sediment transport and Non-cohesive sediment transport.

- ***HD module***: it provides fully dynamic solution to complete nonlinear Saint Venant equations, diffusive wave approximation and kinematic wave approximation, Muskingum method and Muskingum-Cunge method for simplified channel routing. It can automatically adapt to subcritical flow and supercritical flow. It has ability to simulate standard hydraulic structures such as weirs, culverts, bridges, pumps, energy loss and sluice gates.
- ***GIS Extension***: it is an extension of Arc Map from ESRI providing features for catchment/river delineation, cross-section and Digital Elevation Model (DEM) data, pollution load estimates. Flood visualization/animation as 2D maps and results presentation/analysis using Temporal Analyst.
- ***RR module***: it is a rainfall and runoff module, including the unit hydrograph method (UHM), a lumped conceptual continuous hydrological model and a monthly soil moisture accounting model. It includes an auto-calibration tool to estimate model parameter based on statistics data of comparison of simulated water levels/discharges and observations.
- ***SO module:*** it is structure operation module. It simulates operational structures such as sluice gates, weirs, culverts, pumps, bridges with operating strategies.
- ***DB module:*** it is dam break module. It provides complete facilities for definition of dam geometry, breach development in time and space as well as failure mode.

- ***Autocal module***: it is automatic calibration tool. It allows automisation of the calibration process for a wide range of parameters, including rainfall runoff parameters, Manning's number, head loss coefficients, water quality parameters etc.
- ***AD module:*** it is advection dispersion module. It simulates transport and spreading of conservative pollutants and constituents as well as heat with linear decay.
- ***ST/GST module:*** it is non-cohesive sediment module. It simulates transport, erosion and deposition of non-cohesive and graded non-cohesive sediments, including simulations of river morphology.
- ***ACS module:*** it is cohesive sediment module. It has 3-layer bed description, including quasi-2D erosion.
- ***ECO Lab module:*** it is ecological modelling. It can simulate BOD/DO, Ammonia, Nitrate, Eutrophication, Heavy metal and Wetlands. It includes standard templates that are well documented and have been used extensively in numerous applications worldwide. Based on predefined process template, one can develop his/her own templates.
- ***MIKE 11 Stratified module:*** it models vertical density differences such as salinity or temperature in two-layer or multi-layered stratified water bodies.
- ***MIKE 11 Real Time module:*** it is a simulation package and GIS front-end for setting up operational flood forecasting systems. It includes real-time updating and Kalman filtering.

Applications

MIKE 11 has been used in hundreds of application around the world. Its main application areas are flood analysis and alleviation design, real-time flood forecasting, dam break analysis, optimization of reservoir and canal gate/structure operations, ecological and water quality assessments in rivers and wetlands, sediments transport and river morphology studies, salinity intrusion in rivers and estuaries.

Working with the MIKE 11

MIKE 11 includes multiple editors each operating on different types of data. Data from these editors must be saved in separate editor files – utilizing the default MIKE 11 file extensions as listed below.

MIKE 11 editor/file	File extension	MIKE 11 editor/file	File extension
Network	*.NWK11	ECO Lab parameter	*.ECOLab11
Cross-Section	*.XNS11	ST parameter	*.ST11
Boundary	*.BND11	FF parameter	*.FF11
Time Series	*.DFS0	Rainfall Runoff parameter	*.RR11
HD parameter	*.HD11	Simulation	*.SIM11
AD parameter	*.AD11	Result	*.RES11

Table 12 – MIKE 11 input name and extensions files

MIKE 11 comprises a number of different editors in which data can be implemented and edited independently of each other. As a consequence of the system of separated editor-files, no direct linkage exists between the different editors if they are opened individually. That is, it will not be possible to e.g. view the locations of cross-sections specified in the cross-section file in the Graphical view of the network editor (Plan plot) if these editors are opened individually.

The Simulation Editor (.sim11)

The integration and exchange of information between each of the individual data is achieved by use of the MIKE 11 Simulation editor. The Simulation Editor serves two purposes:

- It contains simulation and computation control parameters and is used to start the simulation.
- It provides a linkage between the graphical view of the network editor and the other MIKE 11 editors as illustrated in the figure below.

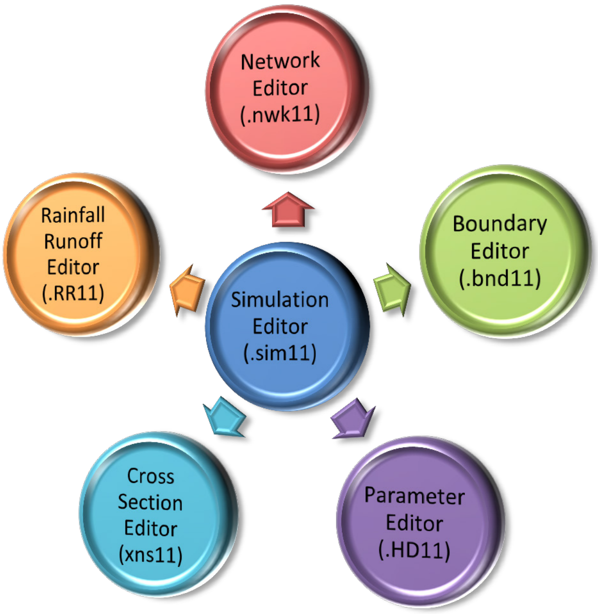
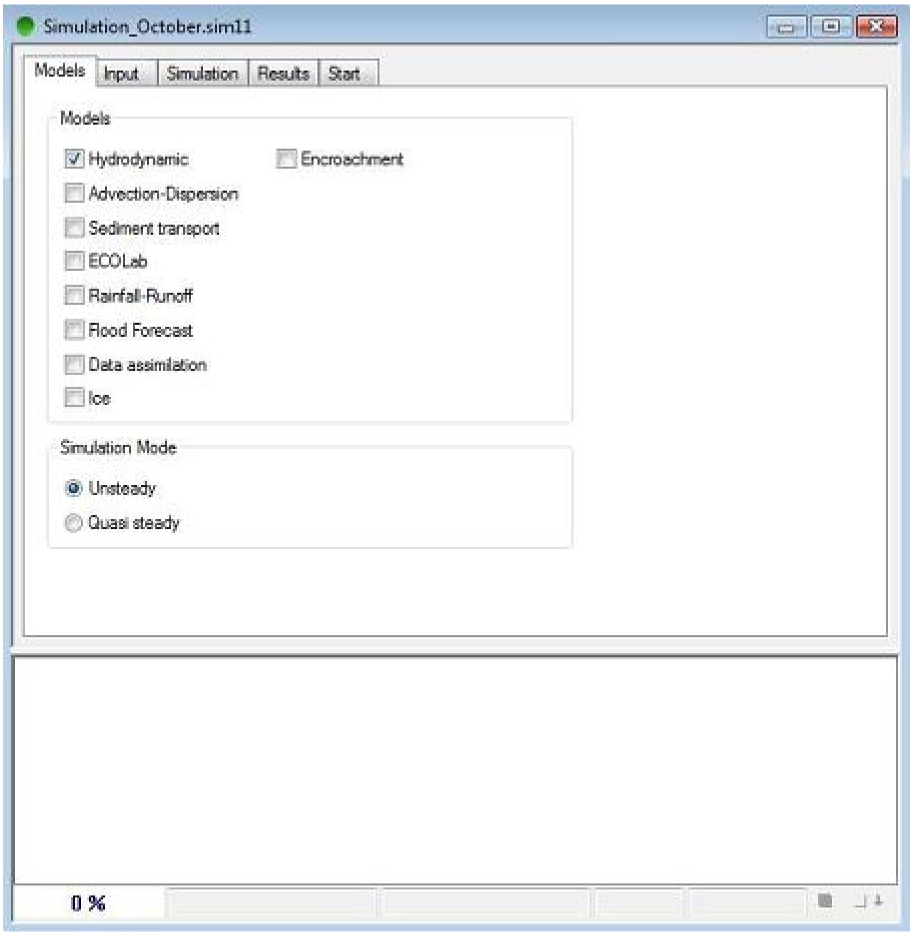


Figure 65 – Relation between MIKE 11 editors

Once the editor filenames are specified on the Input Property page, the information from each of the editors is automatically linked. That is, I will be able to display and access all data from the individual editors (such as cross-sectional data, boundary conditions and different types of parameter file information) on the graphical view of the river network editor. An alternative is to select a file from the File Menu which will recall the appropriate editor. The edit menu can then be used to edit the objects.

Models



Simulation_October.sim11

Models | Input | Simulation | Results | Start

Models

☑ Hydrodynamic
☐ Advection-Dispersion
☐ Sediment transport
☐ ECOLab
☐ Rainfall-Runoff
☐ Flood Forecast
☐ Data assimilation
☐ Ice
☐ Encroachment

Simulation Mode

● Unsteady
○ Quasi steady

0 %

Figure 66 – Models tab from MIKE 11 Simulation Editor

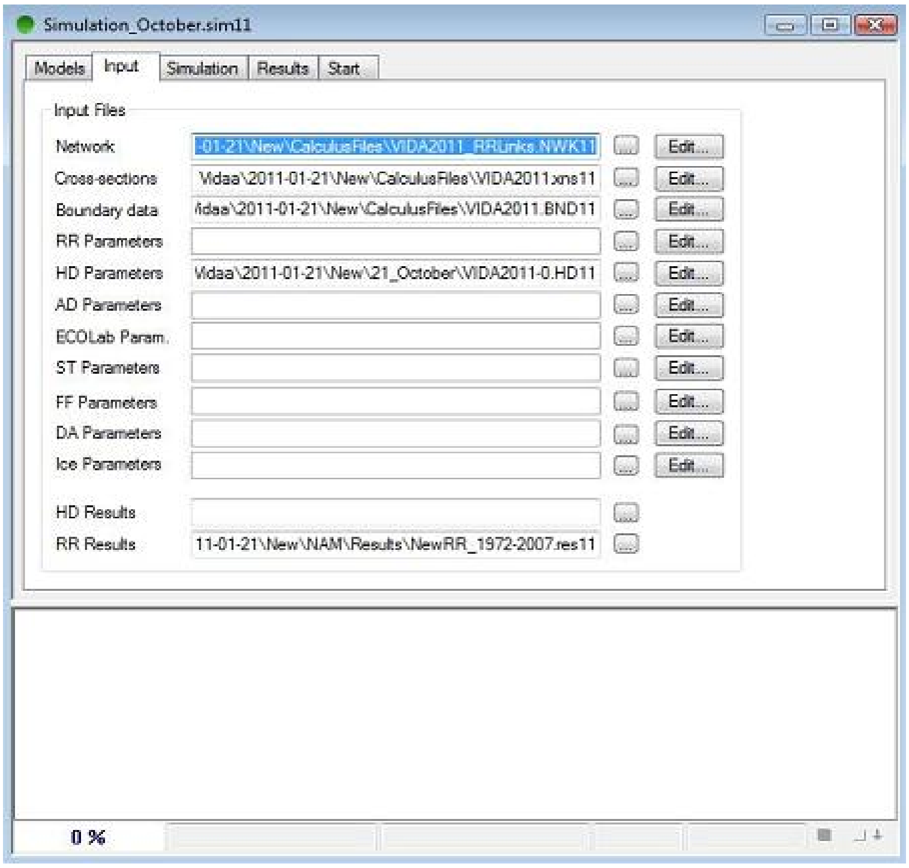
This page (look at Figure 67) is used to define the simulation models to execute and the simulation mode (unsteady or quasi unsteady). One can chose between different models listed below:

- Hydrodynamic (HD)
- Advection-Dispersion (AD)
- Sediment Transport (ST)
- ECO Lab (including Water Quality modelling etc.)
- Rainfall-Runoff (RR)
- Flood Forecast (FF)
- Data Assimilation (DA)
- River Ice modelling (Ice)

Some of the models that can be selected are dependent on other modules in a simulation and it is therefore required to have more modules selected. This rules for model-dependency is implement such that once a model is selected there will be an automatic selection of eventual dependent models (e.g. Selection of FF-model selects HD-model also, Selection of ECOLab selects AD-model also etc.)

Finally one has to choose between Unsteady and Quasi Steady. The HD calculations are based on hydrodynamic flow conditions in the unsteady flow. On the other hand, the calculations of Quasi Steady model are based on steady flow conditions. That is the reason why in that study one uses the unsteady model.

Input



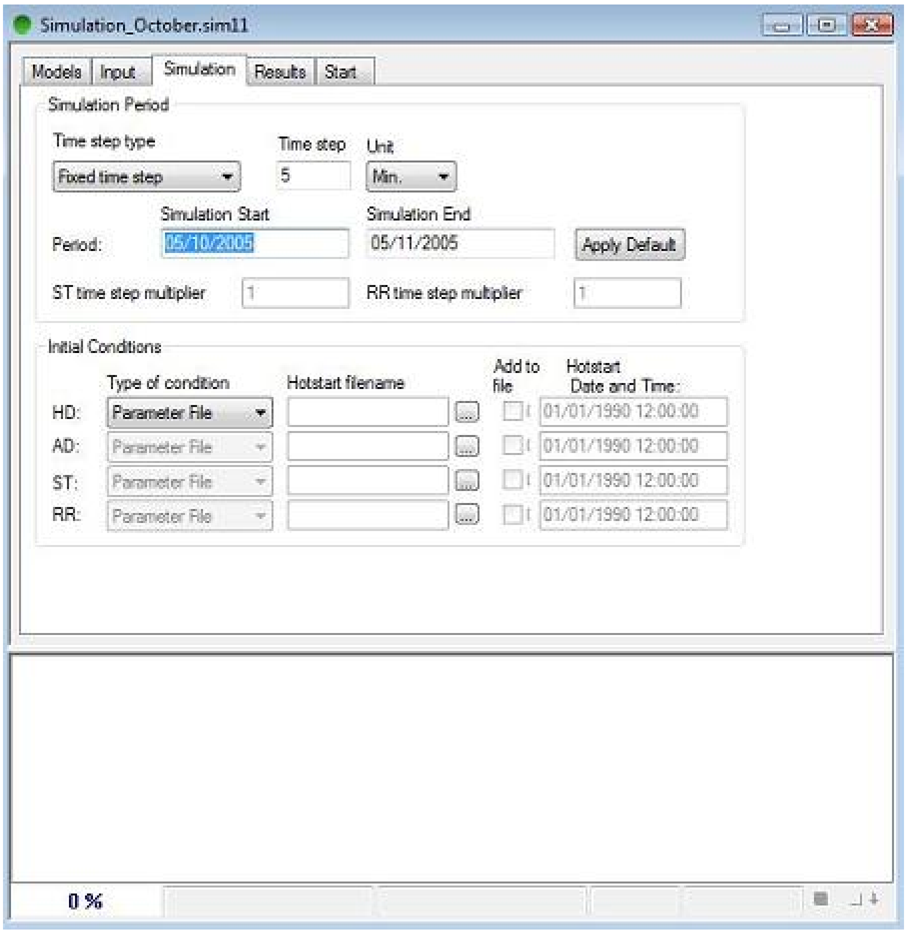
Network: -01-21\New\CalculusFiles\VIDA2011_RRLinks.NWK11
Cross-sections: Vidaa\2011-01-21\New\CalculusFiles\VIDA2011.xns11
Boundary data: /idaa\2011-01-21\New\CalculusFiles\VIDA2011.BND11
RR Parameters:
HD Parameters: Vidaa\2011-01-21\New\21_October\VIDA2011-0.HD11
AD Parameters:
ECOLab Param.:
ST Parameters:
FF Parameters:
DA Parameters:
Ice Parameters:

HD Results:
RR Results: 11-01-21\New\NAM\Results\NewRR_1972-2007.res11

Figure 67 – Input tab from MIKE 11 Simulation Editor

The inputs are based on the model selection from the Models Property Page a number of filename fields becomes active, and the user is required to specify a range of input file names.

Simulation



Simulation_October.sim11

Simulation Period

Time step type: Fixed time step
Time step: 5
Unit: Min.

Period: Simulation Start 05/10/2005 Simulation End 05/11/2005

ST time step multiplier: 1
RR time step multiplier: 1

Initial Conditions

	Type of condition	Hotstart filename	Add to file	Hotstart Date and Time:
HD:	Parameter File		☐	01/01/1990 12:00:00
AD:	Parameter File		☐	01/01/1990 12:00:00
ST:	Parameter File		☐	01/01/1990 12:00:00
RR:	Parameter File		☐	01/01/1990 12:00:00

0 %

Figure 68 – Simulation tab from MIKE 11 Simulation Editor

The simulation property page contains details of simulation time, time stepping specifications and initial conditions for each of the chosen types of models.

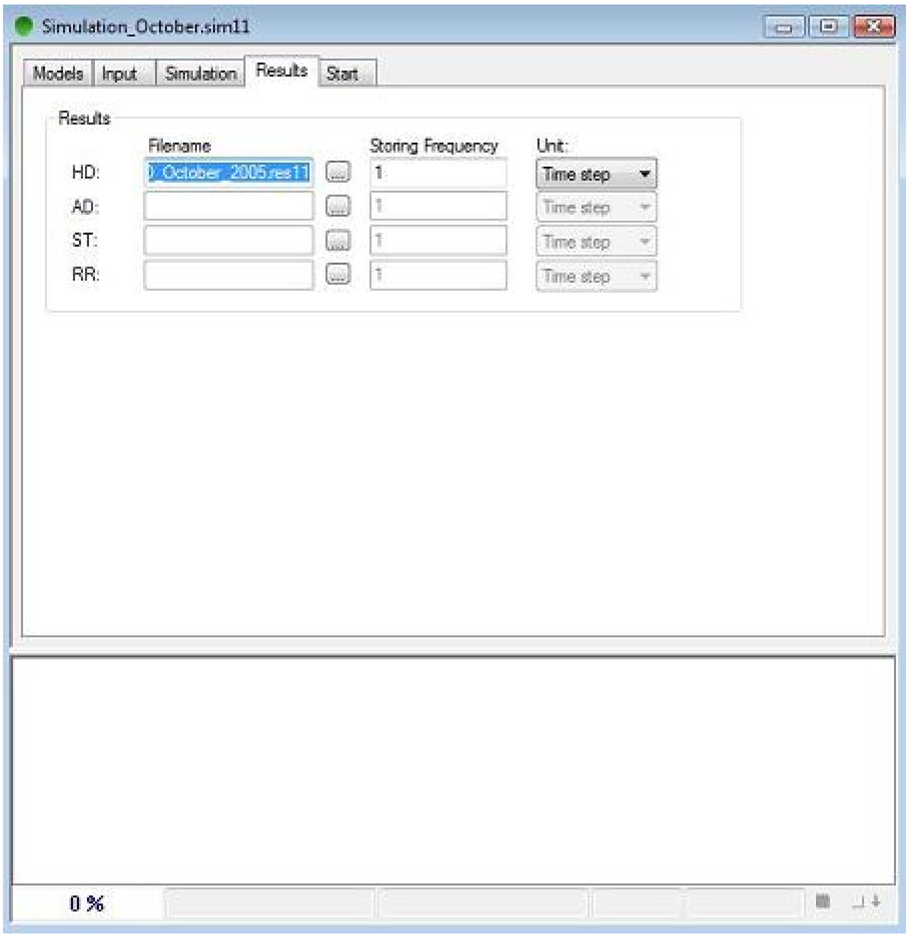
Time stepping type is specified as either: Fixed time step, Tabulated time step or Adaptive time step. In case fixed time step is oneself selected the time step is specified in the editable text with heading time step and the units is given in the unit selection list.

On Period boxes one has to write the date and time for the start and end of the simulation period. The standard windows date time format is used.

Initial Conditions need to be specified. For each of the modules HD, AD, ST and RR the following can be specified:

- **Type of condition**:
    - ***Steady State***: HD only.
    - ***Parameter File***: The initial conditions will be taken from the parameter file relevant to the module in question.
    - ***Hotstart***: The initial conditions will be loaded from an existing result file.
    - ***Steady + Parameter***: HD only.
- **Hotstart Filename**: the name of the existing result file from which the initial conditions should be loaded.
- **Add to File**: The result of the current simulation will be added to the end of the hotstart file. Any information (in the hotstart file) after the simulation start date will be lost. This part of the file will be replaced by the new simulation results.
- **Hotstart Date and Time**: The date and time at which the initial conditions are loaded from the hotstart file. If the "Add to File" has been selected the hotstart date and time will be taken as a simulation start.

Results



Results

	Filename	Storing Frequency	Unit:
HD:	_October_2005.res11	1	Time step
AD:		1	Time step
ST:		1	Time step
RR:		1	Time step

Figure 69 – Result tab from MIKE 11 Simulation Editor

For each of the modules selected on the Models Property Page the user should specify a filename for saving of the simulation results.

The filename cannot be edited if the flag “Add to File” has been selected on the Simulation Property Page. In this case the selected hotstart file will become the result file as well.

To limit the size of the results files oneself can specify a save step interval. The storing frequency may be specified either as the number of time step intervals between each saving of the results or as specific time the latter, however, demands that the specified storing time frequency is a multiple of the time step.

Start

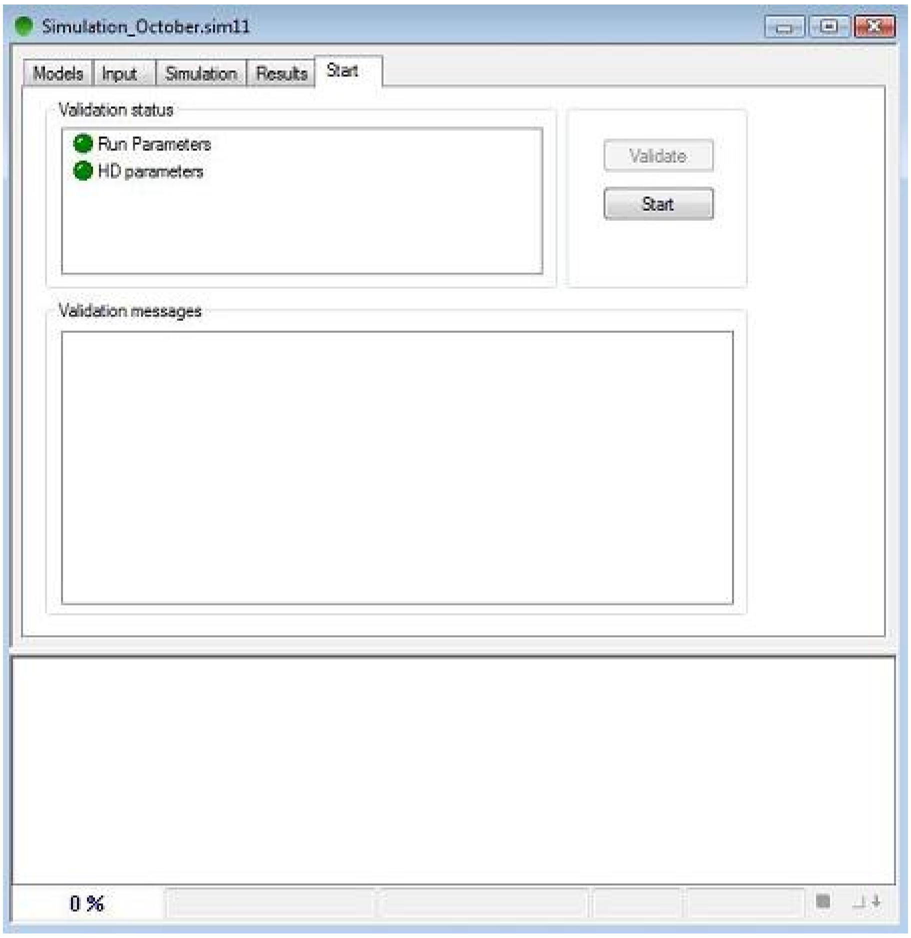
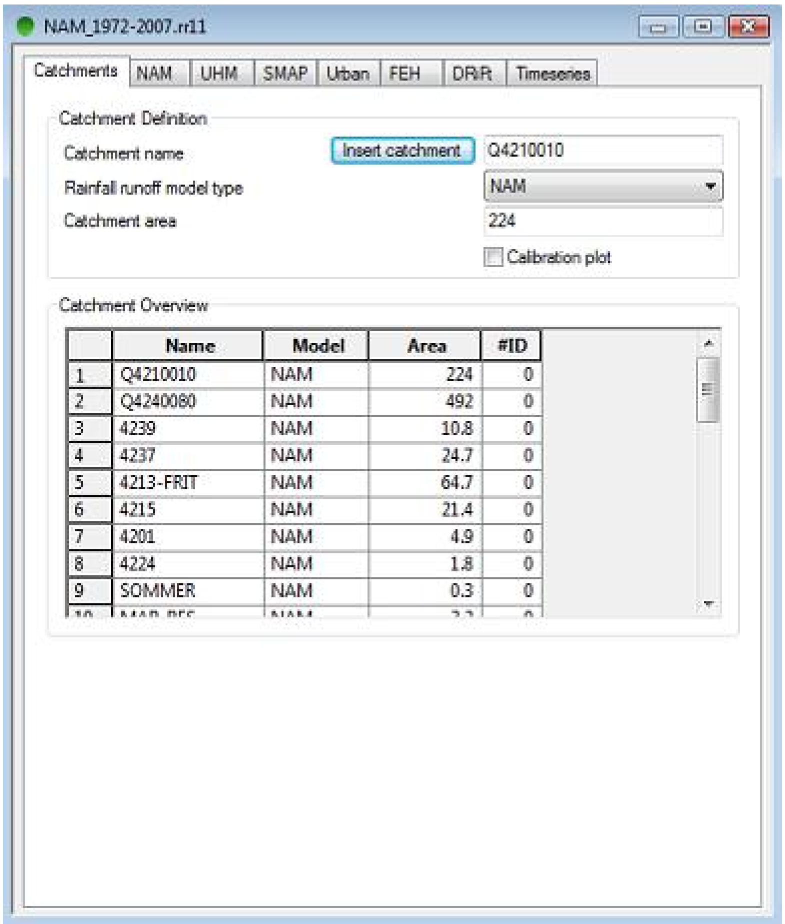


Figure 70 – Start tab from MIKE 11 Simulation Editor

If all specified input files exist, the “Start” button can be pressed and the simulation will commence. Any error or warning message from the simulation sill be presented in the log-part of the editor and additionally, saved in a file with the same as the simulation file and ***.log*** extension. After the simulation results can be viewed using MIKE View.

The Rainfall-Runoff Editor (.rr11)



Catchment Definition

Catchment name: Q4210010
Rainfall runoff model type: NAM
Catchment area: 224
☐ Calibration plot

Catchment Overview

	Name	Model	Area	#ID
1	Q4210010	NAM	224	0
2	Q4240080	NAM	492	0
3	4239	NAM	10.8	0
4	4237	NAM	24.7	0
5	4213-FRIT	NAM	64.7	0
6	4215	NAM	21.4	0
7	4201	NAM	4.9	0
8	4224	NAM	1.8	0
9	SOMMER	NAM	0.3	0

Figure 71 – Rainfall-Runoff Editor view

The Rainfall-Runoff Editor is used to define each modeled catchment area. One needs to give a name to each catchment as well as the Rainfall-Runoff model type and the catchment area. All these catchments are reported below:

Name	Model	Area
Q4210010	NAM	224
Q4240080	NAM	492
4239	NAM	10.8
4237	NAM	24.7
4213-FRIT	NAM	64.7
4215	NAM	21.4
4201	NAM	4.9
4224	NAM	1.8
SOMMER	NAM	0.3
4253-MAR-RES	NAM	3.2
4223	NAM	65.8
4223	NAM	65.8
4250	NAM	0.9
4233	NAM	15.8
4227	NAM	17.3
4229	NAM	2.9
4235	NAM	1
4231	NAM	3.1
4225	NAM	30.6
4217	NAM	21.4
4208	NAM	6.5
4205	NAM	6.9
4220	NAM	1.1
4219	NAM	0.7
4209	NAM	2.7
4211	NAM	5.9
4203	NAM	1.5
4213-PUMP	NAM	7.5
4251-MAR-NORD	NAM	2.4
4252-MAR-SYD	NAM	4.4
4221	NAM	131
4222	NAM	24.9

Table 13 - Catchments definition from Vidaa River System

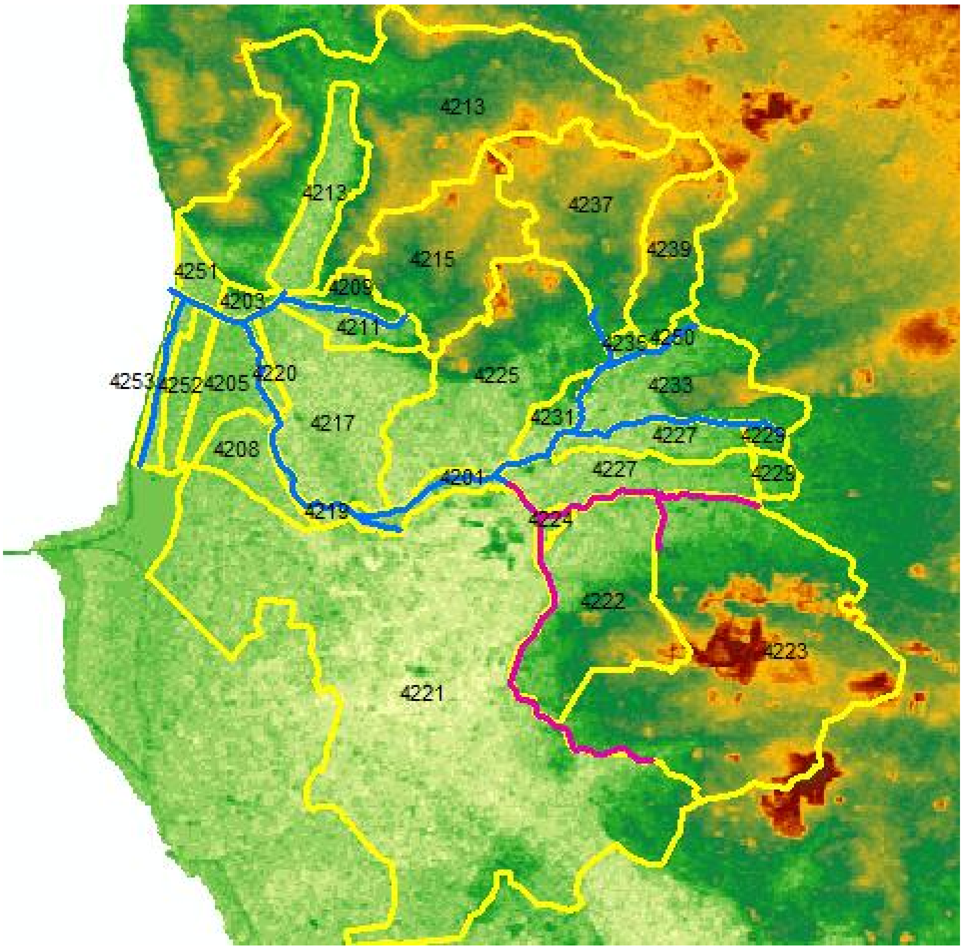


Figure 72 – Vidaa River catchment map

This Editor provides us the following facilities:

- Input and editing of rainfall-runoff and computational parameters required for rainfall-runoff modelling.
- Specification of time series. Time series are specified on the Time series page within the Rainfall Runoff Editor.
- Calculation of weighted rainfall through a weighting of different rainfall stations to obtain catchment rainfall.
- Digitising of catchment boundaries and rainfall stations in a graphical display (Basin View) including automatic calculation of catchment areas and mean area rainfall weights.
- Presentation of Results. Specification of discharge stations used for calibration and presentation of results.

One can chose between different kinds of model catchment types. The parameters required for each Rainfall-Runoff model type are specified in separate pages in the editor. Following models can be selected:

- ***NAM***: a lumped, conceptual rainfall-runoff model, simulating the overland-, inter-, and base-flow components of catchment runoffs as a function of the moisture contents in four storages. Nam includes a number of optional extensions, including an advanced snow-melt routine and a separate description of the hydrology within irrigated areas.
- ***UHM***: the Unit Hydrograph Module includes different loss models (constant, proportional) and the SCS method for estimating storm runoff.
- ***SMAP***: a monthly soil moisture accounting model.
- ***Urban***: two different model runoff computation concepts are available in the Rainfall Runoff Module for fast urban runoff: A) Time/area Method and B) Non-linear Reservoir (kinematic wave) Method.
- ***Combined***: The runoff from a number of catchments, constituting parts of a larger catchment, can be combined into a single runoff series. Each of the sub-catchments must be specified separately by name, model type, parameters, etc. The combined catchment can be defined only after the sub- catchments have been created. The combined catchment is defined in the group for combined catchments, which is activated when selecting combined catchment. The runoff from the combined catchment is found by simple addition of the simulated flow from the sub- catchments.

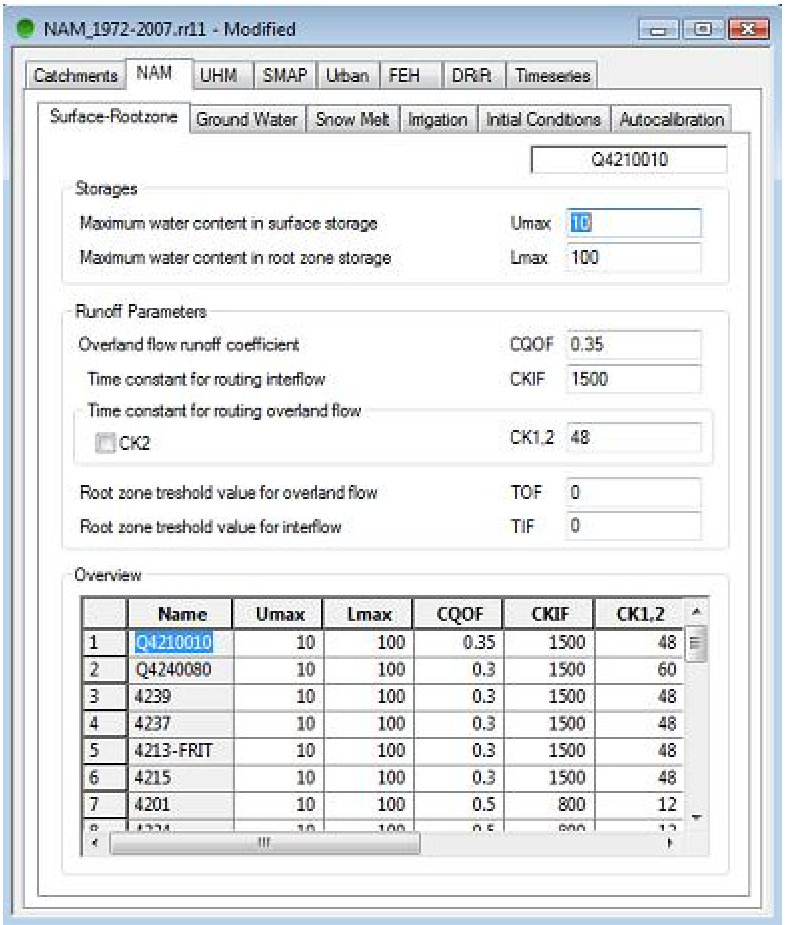
The NAM Rainfall-Runoff model

The NAM model is a deterministic, lumped and conceptual Rainfall-Runoff model accounting for the water content in up to 4 different storages. NAM can be prepared in a number of different modes depending on the requirement, As default, NAM is prepared with 9 parameters representing the Surface Zone, Root Zone and the Ground Water Storages. In addition NAM contains provision for:

- Extended description of the ground water component.
- Two different degree day approaches for snow melt.
- Irrigation schemes.
- Automatic calibration of the 9 most important (default) NAM parameters.

Parameters for all options are described below:

Surface-root zone



Q4210010

Storages

Maximum water content in surface storage Umax 10

Maximum water content in root zone storage Lmax 100

Runoff Parameters

Overland flow runoff coefficient CQOF 0.35

Time constant for routing interflow CKIF 1500

Time constant for routing overland flow

☐ CK2 CK1,2 48

Root zone treshold value for overland flow TOF 0

Root zone treshold value for interflow TIF 0

Overview

	Name	Umax	Lmax	CQOF	CKIF	CK1,2
1	Q4210010	10	100	0.35	1500	48
2	Q4240080	10	100	0.3	1500	60
3	4239	10	100	0.3	1500	48
4	4237	10	100	0.3	1500	48
5	4213-FRIT	10	100	0.3	1500	48
6	4215	10	100	0.3	1500	48
7	4201	10	100	0.5	800	12

Figure 73 – Surface-Root zone tab from MIKE 11 Rainfall-Runoff Editor (NAM model)

Parameters used in the surface and the root zones are described below:

- ***Maximum water content in surface storage (Umax)***: Represents the cumulative total water content of the interception storage (on vegetation), surface depression storage and storage in the uppermost layers (a few cm) of the soil. Typically values are between 10 – 20 mm.
- ***Maximum water content in root zone storage (Lmax)***: Represents the maximum soil moisture content in the root zone, which is available for transpiration by vegetation. Typically values are between 50 – 300 mm.
- ***Overland flow runoff coefficient (CQOF)***. Determines the division of excess rainfall between overland flow and infiltration. Values ranges between 0.0 and 1.0.
- ***Time constant for interflow (CKIF)***: Determines the amount of interflow, which decreases with larger time constants. Values in the ranges of 500 – 1000 hours are common.
- ***Time constants for routing overland flow (CK1,2)***: Determines the shape of hydrograph peaks. The routing takes place through two linear reservoirs (serial connected) with the same time constant (CK1 0 CK2). High, sharp peaks are simulated with small time constants, whereas low peaks, at a later time, are

simulated with large values of these parameters. Values in the range of 3 – 48 hours are common.

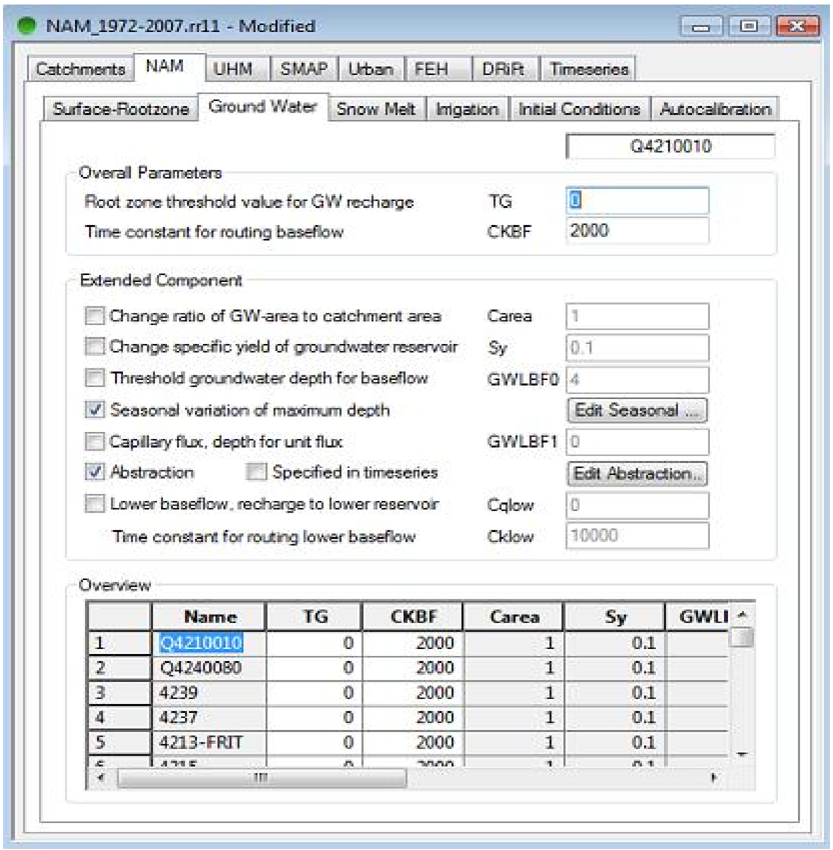
- ***Root zone threshold value for overland flow (TOF)***: Determines the relative value of the moisture content in the root zone (L/Lmax) above which overland flow is generated. The main impact of TOF is seen at the beginning of a wet season, where an increase of the parameter value will delay the start of runoff as overland flow. Threshold value range between 0 and 70% of Lmax, and the maximum values allowed is 0.99.
- ***Root zone threshold value for inter flow (TIF)***: Determines the relative value of the moisture content in the root zone (L/Lmax) above which interflow is generated.

Parameters values used for each catchment are showed below:

Name	Umax	Lmax	CQOF	CKIF	CK1,2	TOF	TIF
Q4210010	10	100	0.35	1500	48	0	0
Q4240080	10	100	0.3	1500	60	0	0
4239	10	100	0.3	1500	48	0	0
4237	10	100	0.3	1500	48	0	0
4213-FRIT	10	100	0.3	1500	48	0	0
4215	10	100	0.3	1500	48	0	0
4201	10	100	0.5	800	12	0	0
4224	10	100	0.5	800	12	0	0
SOMMER	10	100	0.5	800	12	0	0
4253-MAR-RES	10	100	0.5	800	12	0	0
4223	10	100	0.5	800	12	0	0
4250	10	100	0.5	800	12	0	0
4233	10	100	0.5	800	12	0	0
4227	10	100	0.5	800	12	0	0
4229	10	100	0.5	800	12	0	0
4235	10	100	0.5	800	12	0	0
4231	10	100	0.5	800	12	0	0
4225	10	100	0.5	800	12	0	0
4217	10	100	0.5	800	12	0	0
4208	10	100	0.5	800	12	0	0
4205	10	100	0.5	800	12	0	0
4220	10	100	0.5	800	12	0	0
4219	10	100	0.5	800	12	0	0
4209	10	100	0.5	800	12	0	0
4211	10	100	0.5	800	12	0	0
4203	10	100	0.5	800	12	0	0
4213-PUMP	10	100	0.5	800	12	0	0
4251-MAR-NORD	10	100	0.5	800	12	0	0
4252-MAR-SYD	10	100	0.5	800	12	0	0
4221	10	100	0.5	800	12	0	0
4222	10	100	0.5	800	12	0	0

Table 14 - NAM catchments parameter values from Vidaa River System

Ground Water



Q4210010

Overall Parameters

Root zone threshold value for GW recharge TG 0

Time constant for routing baseflow CKBF 2000

Extended Component

☐ Change ratio of GW-area to catchment area Carea 1

☐ Change specific yield of groundwater reservoir Sy 0.1

☐ Threshold groundwater depth for baseflow GWLBF0 4

☑ Seasonal variation of maximum depth

☐ Capillary flux, depth for unit flux GWLBF1 0

☑ Abstraction ☐ Specified in timeseries

☐ Lower baseflow, recharge to lower reservoir Cqlow 0

Time constant for routing lower baseflow Cklow 10000

Overview

	Name	TG	CKBF	Carea	Sy	GWLI
1	Q4210010	0	2000	1	0.1	
2	Q4240080	0	2000	1	0.1	
3	4239	0	2000	1	0.1	
4	4237	0	2000	1	0.1	
5	4213-FRIT	0	2000	1	0.1	

Figure 74 – Ground Water tab from MIKE 11 Rainfall-Runoff Editor (NAM model)

For most NAM application only the Time constant for routing baseflow CKBF and possibly the Root zone threshold value for ground water recharge TG need to be specified and calibrated. However, to cover also a range of special cases, such as ground water storages influenced by river level variations, a number of additional parameters can be modified (see below):

- ***Ratio of ground water catchment to topographical (surface water) catchment area (Carea).***
- ***Specific yield for the ground water storage (Sy).***
- ***Maximum ground water depth causing baseflow (GWLBF0)***
- ***Seasonal variation of maximum depth.***
- ***Depth for unit capillary flux (GWLBF1).***
- ***Abstraction.***
- ***Lower base flow. Recharge to lower reservoir (Cqlow).***
- ***Time constant for routing lower baseflow (Cklow).***

In that study one doesn't take into account these additional parameters, only TG and CKBF, the other parameters are input as usual values.

Parameters values used for each catchment are showed below:

Name	TG	CKBF	Carea	Sy	GWLBF0	GWLBF1	Cqlow	Cklow
Q4210010	0	2000	1	0.1	4	0	0	10000
Q4240080	0	2000	1	0.1	4	0	0	10000
4239	0	2000	1	0.1	4	0	0	10000
4237	0	2000	1	0.1	4	0	0	10000
4213-FRIT	0	2000	1	0.1	4	0	0	10000
4215	0	2000	1	0.1	4	0	0	10000
4201	0	1500	1	0.1	4	0	0	10000
4224	0	1500	1	0.1	4	0	0	10000
SOMMER	0	1500	1	0.1	4	0	0	10000
4253-MAR-RES	0	1500	1	0.1	4	0	0	10000
4223	0	1500	1	0.1	4	0	0	10000
4250	0	1500	1	0.1	4	0	0	10000
4233	0	1500	1	0.1	4	0	0	10000
4227	0	1500	1	0.1	4	0	0	10000
4229	0	1500	1	0.1	4	0	0	10000
4235	0	1500	1	0.1	4	0	0	10000
4231	0	1500	1	0.1	4	0	0	10000
4225	0	1500	1	0.1	4	0	0	10000
4217	0	1500	1	0.1	4	0	0	10000
4208	0	1500	1	0.1	4	0	0	10000
4205	0	1500	1	0.1	4	0	0	10000
4220	0	1500	1	0.1	4	0	0	10000
4219	0	1500	1	0.1	4	0	0	10000
4209	0	1500	1	0.1	4	0	0	10000
4211	0	1500	1	0.1	4	0	0	10000
4203	0	1500	1	0.1	4	0	0	10000
4213-PUMP	0	1500	1	0.1	4	0	0	10000
4251-MAR-NORD	0	1500	1	0.1	4	0	0	10000
4252-MAR-SYD	0	1500	1	0.1	4	0	0	10000
4221	0	1500	1	0.1	4	0	0	10000
4222	0	1500	1	0.1	4	0	0	10000

Table 15 - NAM Ground Water parameter values from Vidaa River System

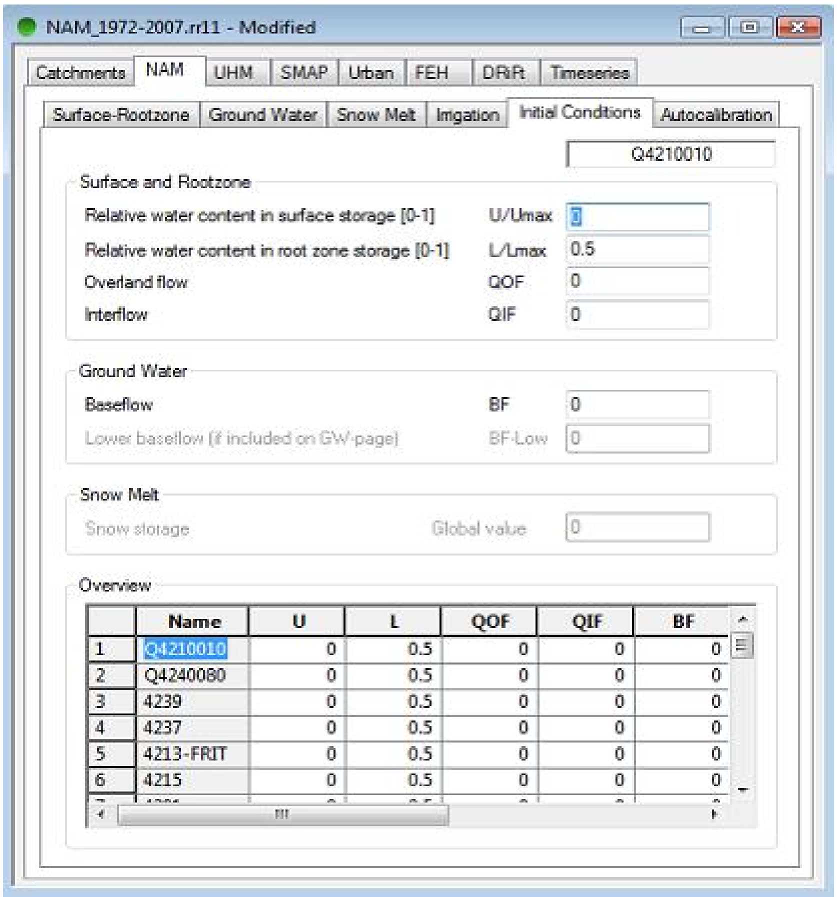
Snow Melt

The snow module simulates the accumulation and melting of snow in a NAM catchment. In this study, one takes into account no exist snow accumulation or it is not too important as take into account.

Irrigation

Minor irrigation schemes within a catchment will normally have negligible influence on the catchment hydrology, unless transfer of water over the catchment boundary is involved. That is not our subject, for that reason, one, doesn't include the irrigation in that study.

Initial Conditions



Q4210010

Surface and Rootzone
Relative water content in surface storage [0-1] U/Umax 0
Relative water content in root zone storage [0-1] L/Lmax 0.5
Overland flow QOF 0
Interflow QIF 0

Ground Water
Baseflow BF 0
Lower baseflow (if included on GW-page) BF-Low 0

Snow Melt
Snow storage Global value 0

Overview

	Name	U	L	QOF	QIF	BF
1	Q4210010	0	0.5	0	0	0
2	Q4240080	0	0.5	0	0	0
3	4239	0	0.5	0	0	0
4	4237	0	0.5	0	0	0
5	4213-FRIT	0	0.5	0	0	0
6	4215	0	0.5	0	0	0

Figure 75 – Initial Conditions tab from MIKE 11 Rainfall-Runoff Editor (NAM model)

The initial conditions are described below:

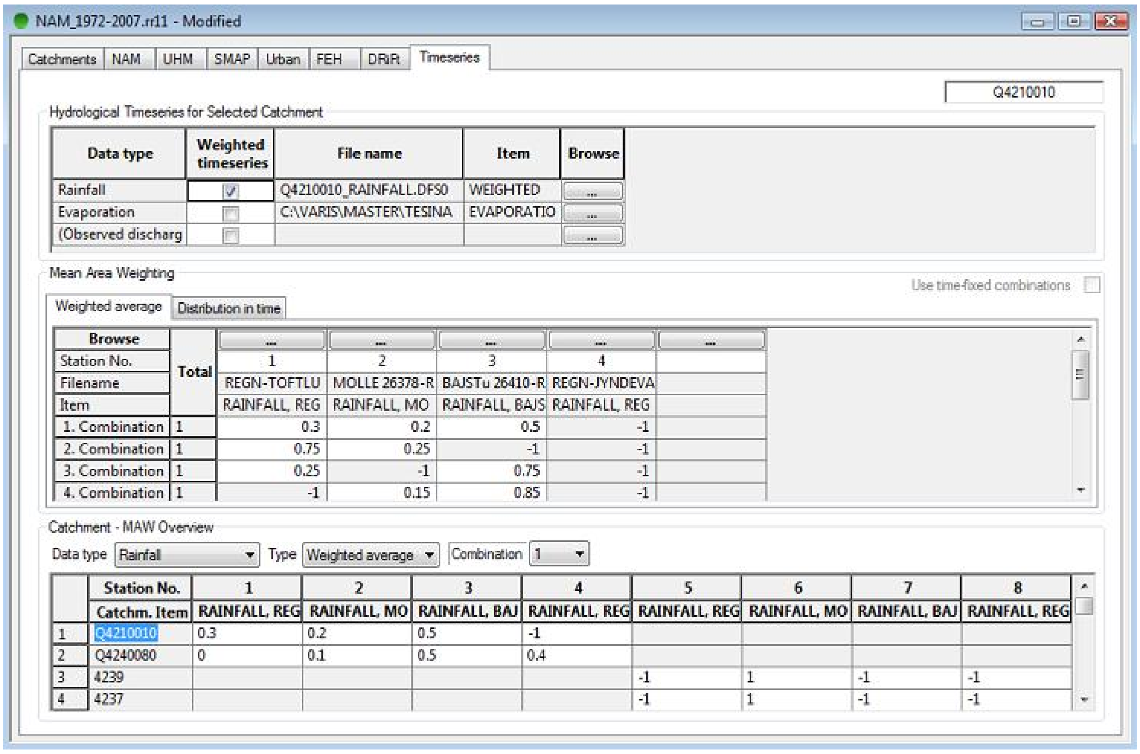
- ***Surface Root zone***: The initial relative water contents of surface and root zone storage must be specified as well as the initial values of overland flow and interflow.
- ***Ground water***: Initial values for baseflow must always be specified. When lower baseflow are included a value for the initial lower baseflow must also be specified.
- ***Snow melt***: Initial values of the snow storage are specified when the snow melt routine is used (not in that study).

Parameters values used for each catchment are showed below:

Name	U	L	QOF	QIF	BF	BFlow	Snow stor.
Q4210010	0	0.5	0	0	0	0	0
Q4240080	0	0.5	0	0	0	0	0
4239	0	0.5	0	0	0	0	0
4237	0	0.5	0	0	0	0	0
4213-FRIT	0	0.5	0	0	0	0	0
4215	0	0.5	0	0	0	0	0
4201	0	0.5	0	0	0	0	0
4224	0	0.5	0	0	0	0	0
SOMMER	0	0.5	0	0	0	0	0
4253-MAR-RES	0	0.5	0	0	0	0	0
4223	0	0.5	0	0	0	0	0
4250	0	0.5	0	0	0	0	0
4233	0	0.5	0	0	0	0	0
4227	0	0.5	0	0	0	0	0
4229	0	0.5	0	0	0	0	0
4235	0	0.5	0	0	0	0	0
4231	0	0.5	0	0	0	0	0
4225	0	0.5	0	0	0	0	0
4217	0	0.5	0	0	0	0	0
4208	0	0.5	0	0	0	0	0
4205	0	0.5	0	0	0	0	0
4220	0	0.5	0	0	0	0	0
4219	0	0.5	0	0	0	0	0
4209	0	0.5	0	0	0	0	0
4211	0	0.5	0	0	0	0	0
4203	0	0.5	0	0	0	0	0
4213-PUMP	0	0.5	0	0	0	0	0
4251-MAR-NORD	0	0.5	0	0	0	0	0
4252-MAR-SYD	0	0.5	0	0	0	0	0
4221	0	0.5	0	0	0	0	0
4222	0	0.5	0	0	0	0	0

Table 16 - NAM Initial Conditions parameter values from Vidaa River System

Time Series



Q4210010

Hydrological Timeseries for Selected Catchment

Data type	Weighted timeseries	File name	Item	Browse
Rainfall	☑	Q4210010_RAINFALL.DFS0	WEIGHTED	...
Evaporation	☐	C:\VARIS\MASTER\TESINA	EVAPORATIO	...
(Observed discharg	☐			...

Mean Area Weighting

Browse	Total	...	...	...	...	...
Station No.		1	2	3	4	
Filename		REGN-TOFTLU	MOLLE 26378-R	BAJSTu 26410-R	REGN-JYNDEVA	
Item		RAINFALL, REG	RAINFALL, MO	RAINFALL, BAJS	RAINFALL, REG	
1. Combination	1	0.3	0.2	0.5	-1	
2. Combination	1	0.75	0.25	-1	-1	
3. Combination	1	0.25	-1	0.75	-1	
4. Combination	1	-1	0.15	0.85	-1	

Catchment - MAW Overview

Data type: Rainfall
Type: Weighted average
Combination: 1

	Station No.	1	2	3	4	5	6	7	8
	Catchm. Item	RAINFALL, REG	RAINFALL, MO	RAINFALL, BAJ	RAINFALL, REG	RAINFALL, REG	RAINFALL, MO	RAINFALL, BAJ	RAINFALL, REG
1	Q4210010	0.3	0.2	0.5	-1				
2	Q4240080	0	0.1	0.5	0.4				
3	4239					-1	1	-1	-1
4	4237					-1	1	-1	-1

Figure 76 – Time Series tab from MIKE 11 Rainfall-Runoff Editor (NAM model)

The Time series page serves two purposes: Input of time series and calculation of weighted time series (see Figure 77).

The input time series for all the rainfall-runoff simulations are specified on this page. The time series are used as boundary data to a MIKE 11 simulation. Following data types can be used:

- ***Rainfall***.
- ***Evaporation***.
- ***Temperature.***
- ***Irrigation.***
- ***Abstraction.***
- ***Radiation.***
- ***Degree-day coefficient.***
- ***Observed Discharge.***

Rainfall uses a time series, representing the average catchment rainfall. The time interval between values may vary through the input series. The rainfall specified at a given time should be the rainfall volume accumulated since the previous value.

The potential ***evaporation*** is typically given as monthly values. Like rainfall, the time for each potential evaporation value should be the accumulated volume at the end of the period it represents.

The ***calculation of weighted time series*** usually needs only be made once. Once the calculation is made the result are stored in time series that can be used for subsequent rainfall-runoff modeling runs.

If the rainfall data, weights or number of catchments changes the calculation must be repeated.

The Mean Areal Weighting calculation can be performed in two ways:

1. Directly within the Rainfall Runoff Editor (the calculation is made without requiring a model run).
2. During the simulation (carried out as a part of the model run)

It is recommended to use option 1. This will ensure that the available periods of the inputs files known in the simulations editor.

Where complete time series for all stations are available for the entire period of interest only one weight combination is required. Where data is missing from one or more stations during the period of interest different weight combinations can be specified for different combinations of missing data.

Thus, so one must use the weighted time series available to get the definitive Rainfall-Runoff Editor file (***.RR11***). With that file one can run the ***Rainfall-Runoff (RR) Simulation*** to get the results that later will be used on the ***Hydrodynamic (HD) simulation.***

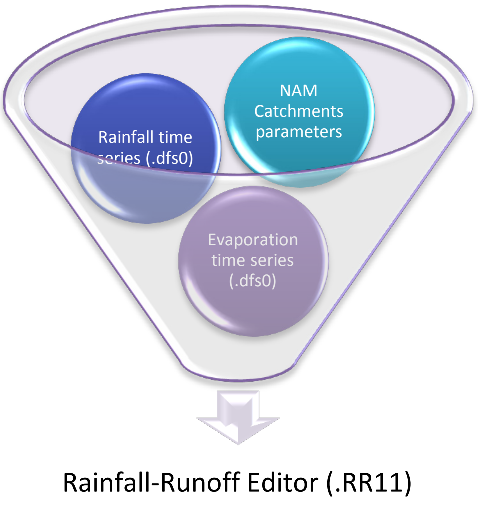
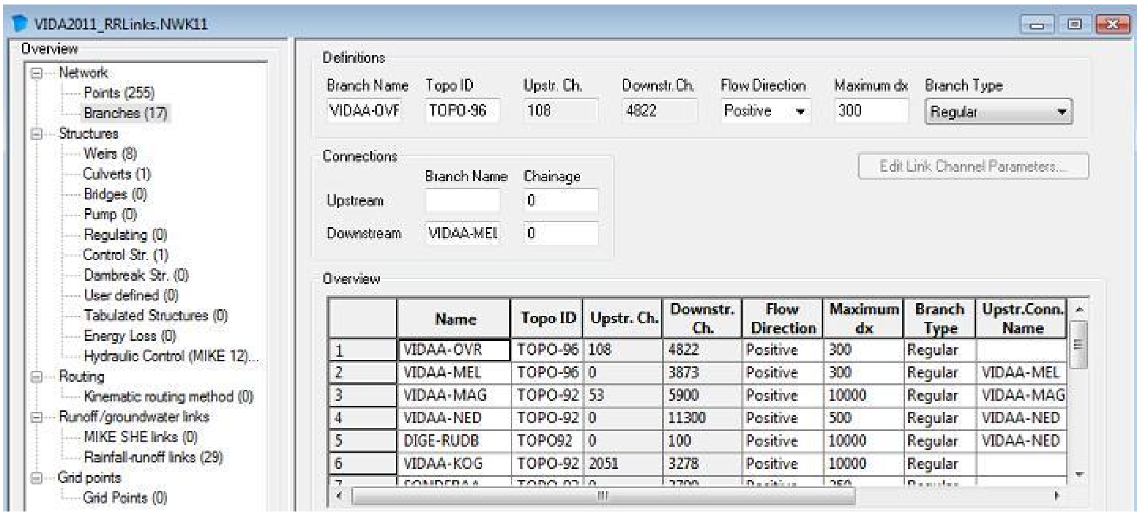


Figure 77 – Scheme about files used on Rainfall-Runoff Editor (NAM model)

The Network Editor (.NWK11)



Definitions

Branch Name	Topo ID	Upstr. Ch.	Downstr.Ch.	Flow Direction	Maximum dx	Branch Type
VIDAA-OVF	TOPO-96	108	4822	Positive	300	Regular

Connections

	Branch Name	Chainage
Upstream		0
Downstream	VIDAA-MEL	0

Overview

	Name	Topo ID	Upstr. Ch.	Downstr. Ch.	Flow Direction	Maximum dx	Branch Type	Upstr.Conn. Name
1	VIDAA-OVR	TOPO-96	108	4822	Positive	300	Regular	
2	VIDAA-MEL	TOPO-96	0	3873	Positive	300	Regular	VIDAA-MEL
3	VIDAA-MAG	TOPO-92	53	5900	Positive	10000	Regular	VIDAA-MAG
4	VIDAA-NED	TOPO-92	0	11300	Positive	500	Regular	VIDAA-NED
5	DIGE-RUDB	TOPO92	0	100	Positive	10000	Regular	VIDAA-NED
6	VIDAA-KOG	TOPO-92	2051	3278	Positive	10000	Regular	

Figure 78 – Tabular View from MIKE 11 Network Editors

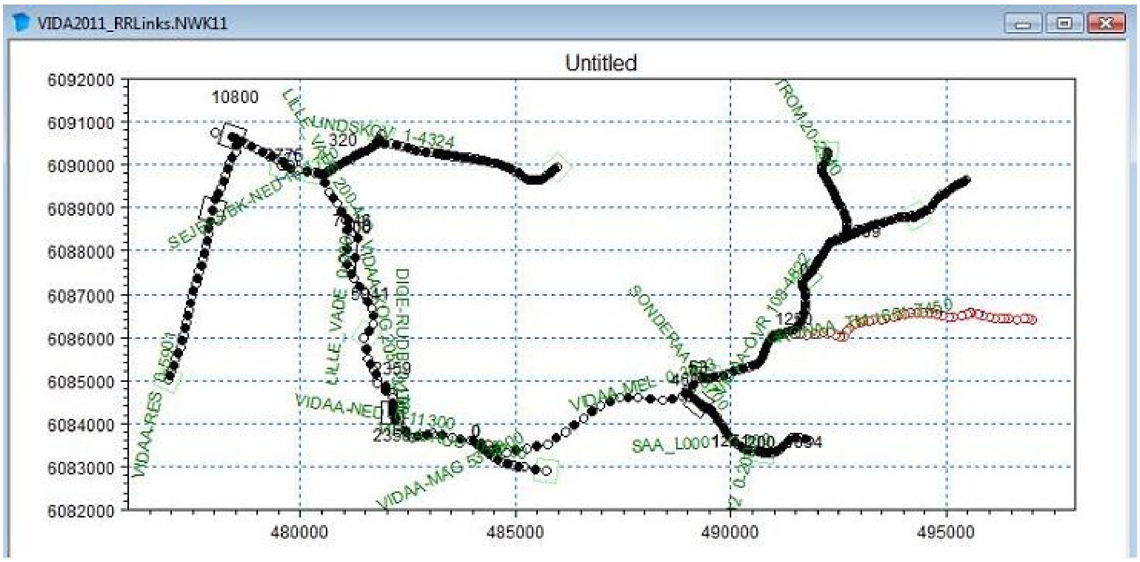


Figure 79 – Graphical View from MIKE 11 Network Editors

The Network editor is a very central unit in the MIKE 11 Graphical User Interface. From the graphical view (the plan plot) of the network editor, it is possible to display information from all other data editors in MIKE 11. The Network editor consists of two views, a tabular view (see Figure 79), where the river network data are presented in tables, and a graphical view (see Figure 80), where graphical editing of the river network can be performed as well as data from other editors can be accessed for editing etc.

The main functions of the network editor are to:

- Provide editing facilities for data defining the river network, such as:
    - Digitisation of points and connection of river branches.
    - Definition of weirs, culverts and other hydraulic structures.
    - Definition of catchments connecting the river model to a rainfall run-off model.
- Provide an overview of all data included in the river model simulation. Overview is provided via the possibility of presenting items from the different data editors on the plan plot, graphical view. The different items can be presented using symbols and lines of different colours and size – all controlled by the user via the “Settings”, “Network” dialog from the graphical view.

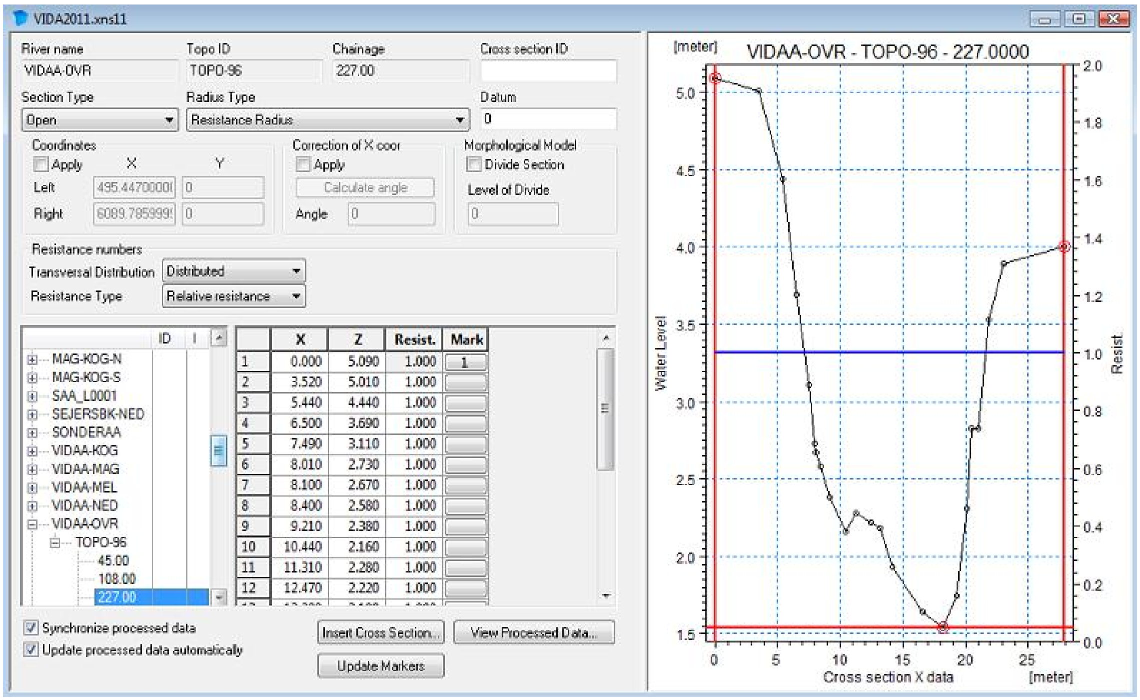
The Tabular View of the network editor contains a large group of subpages in which the numerical values behind most of the objects being presented in the Graphical view are stored for editing. The tabular view contains individual pages with edit fields and tables for digitization points, river branches definitions and connections, hydraulic structures details and other data.

Network	
Points (255)	Branches (17)
Structures	
Weirs (8)	Culverts (0)
Pump (0)	Regulating (0)
Control Structures (0)	Dam Break Structures (0)
User defined (0)	Tabulated Structures (0)
Energy Loss (0)	Hydraulic Control (MIKE12) (0)
Routing	***Grid Points***
Kinematic routing method (0)	Grid Points (0)
Runoff / ground water links	
MIKE SHE links (0)	Rainfall – runoff links (29)

Table 17 – Property pages from MIKE 11 network tabular view in Vidaa River study

Routing is a simplified hydraulic calculation. Normally, simulation of how a flood wave or a hydrograph propagates along a branch is based on solving the St. Venant equations. Typically a routing element represents a reach of a river or a flood control device such as a reservoir or hydraulic control structure.

The Cross Section Editor (.XNS11)



VIDA2011.xns11

River name: VIDAA-OVR
Topo ID: TOPO-96
Chainage: 227.00
Cross section ID:
Section Type: Open
Radius Type: Resistance Radius
Datum: 0

Coordinates: ☐ Apply
Left: X 495.4470000, Y 0
Right: X 6089.785999, Y 0

Correction of X coor
☐ Apply
Angle: 0

Morphological Model: ☐ Divide Section
Level of Divide: 0

Resistance numbers
Transversal Distribution: Distributed
Resistance Type: Relative resistance

	X	Z	Resist.	Mark
1	0.000	5.090	1.000	1
2	3.520	5.010	1.000	
3	5.440	4.440	1.000	
4	6.500	3.690	1.000	
5	7.490	3.110	1.000	
6	8.010	2.730	1.000	
7	8.100	2.670	1.000	
8	8.400	2.580	1.000	
9	9.210	2.380	1.000	
10	10.440	2.160	1.000	
11	11.310	2.280	1.000	
12	12.470	2.220	1.000	

☑ Synchronize processed data
☑ Update processed data automatically

Figure 80 – The raw data from MIKE 11 Cross Section editor

The Cross Section Editor manages stores and display all model cross section information.

There are two types of cross section data; the raw survey data and the derived processed data. The raw data describes the shape of the cross section typically comes from a section survey of the river. The processed data is derived from the raw data and contains all information used by the computer model (e.g. level, cross section area, flow width, hydraulic/resistance radius). The processed data can be calculated by the cross section editor or entered manually.

Each cross section is uniquely identified by the following three keys:

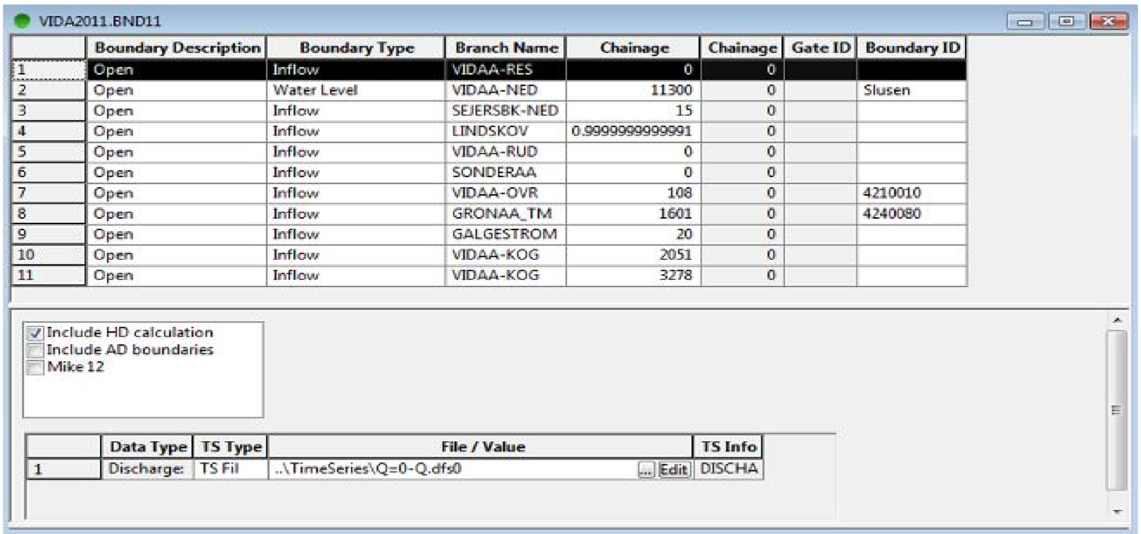
- ***River Name***: The name given to the river branch. String of any length.
- ***Topo ID***: Topographical identification name. String of any length.
- ***Chainage***: River chainage of cross section.

The raw data view is the default and is displayed whenever a cross section file is opened or created (see Figure 81).

The raw data editor is made up by three views plus a number of additional dialog boxes:

- ***Tree view***: Provides a list of all cross sections in the file. The list is displayed using a tree structure with three levels. The upper level contains river names, the second contains the Topo-IDs, and the third contains cross section chainage.
- ***Tabular view***: Selecting a cross section with the left mouse button will display the section information in the tabular view.
- ***Graphical view***: An *x-z*-plot of the cross sectional data with markers and vegetation zones indicated (the latter only for the quasi two dimensional steady state solver with vegetation, not in that study).

The Boundary Editor (.BND11)



	Boundary Description	Boundary Type	Branch Name	Chainage	Chainage	Gate ID	Boundary ID
1	Open	Inflow	VIDAA-RES	0	0		
2	Open	Water Level	VIDAA-NED	11300	0		Slusen
3	Open	Inflow	SEJERSBK-NED	15	0		
4	Open	Inflow	LINDSKOV	0.9999999999991	0		
5	Open	Inflow	VIDAA-RUD	0	0		
6	Open	Inflow	SONDERAA	0	0		
7	Open	Inflow	VIDAA-OVR	108	0		4210010
8	Open	Inflow	GRONAA_TM	1601	0		4240080
9	Open	Inflow	GALGESTROM	20	0		
10	Open	Inflow	VIDAA-KOG	2051	0		
11	Open	Inflow	VIDAA-KOG	3278	0		

☑ Include HD calculation
☐ Include AD boundaries
☐ Mike 12

	Data Type	TS Type	File / Value	TS Info
1	Discharge:	TS Fil	..\TimeSeries\Q=0-Q.dfs0	DISCHA

Figure 81 – Layout of the boundary editor from MIKE 11

The definition of a Boundary condition requires the following actions to be performed – in order as listed:

- Specify the location of the boundary point and the boundary description and type. A location is defined by the river name and the chainage. The boundary description is selected from a combo box. The boundary type is selected from the “Boundary Type” combo-box.
- After defining the location of boundary point, one must associate a time series to be applied at the boundary. The time series are kept in separate time series files (**.dfs0**) and it is required to browse and select a time series file for each boundary definition.

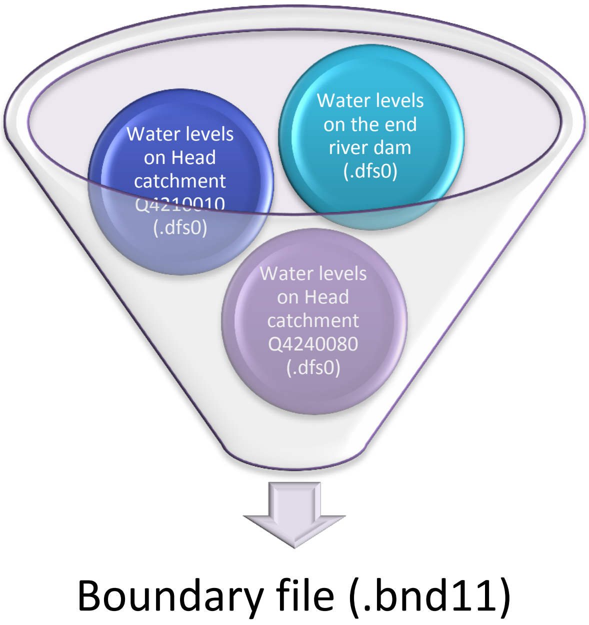


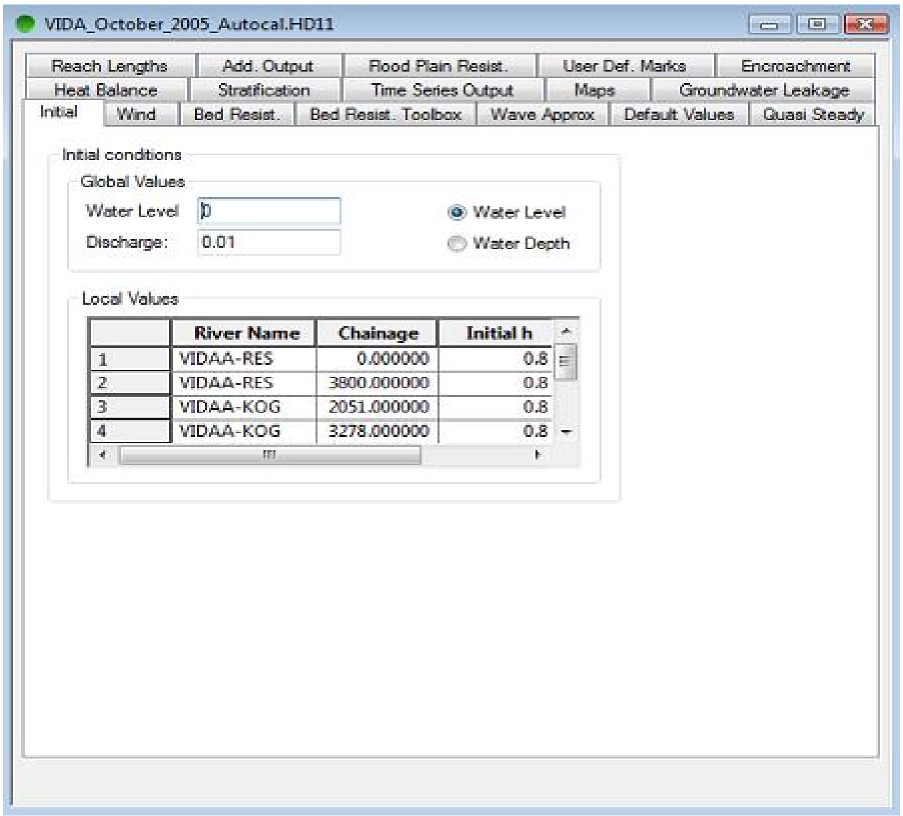
Figure 82 – Process to get the boundary file from the different Boundary conditions

The boundary editor is used to specify boundary conditions to a MIKE 11 Model. It is used not only to specify common boundary conditions such as water levels and inflows hydrographs but also for the specifications of lateral flows along river reaches, solute concentrations of the inflow hydrographs, various meteorological data and certain boundary conditions used in connection with structures applied in a MIKE 11 model.

The boundary editor consists of three split windows. The top split window contains the overall details of boundary conditions defined in the model. Each boundary condition is defined as one row in the Boundary Table and the table therefore, contains all boundaries included in a model set up. There is no limit to the number of boundaries that can be included in a model.

The view and contents of the second and the third split window depends on the specifications of the selected boundary identified by the highlighted row in the upper window in the Boundary Table. Additional information needed to specify the boundary conditions are entered in the second and third split windows.

The Hydrodynamic Parameters Editor (.HD11)



Water Level 0

Discharge: 0.01

● Water Level

○ Water Depth

	River Name	Chainage	Initial h
1	VIDAA-RES	0.000000	0.8
2	VIDAA-RES	3800.000000	0.8
3	VIDAA-KOG	2051.000000	0.8
4	VIDAA-KOG	3278.000000	0.8

Figure 83 – The Hydrodynamic Parameter Editor from MIKE 11 – opening view and tab-pages

To run a hydrodynamic (HD) computation it is required to create a HD Parameter file. The HD parameter editor offers a possibility of specifying user-defined values for a number of variables used during the HD computation.

Most of the parameters in this editor have default values and in most cases these values are sufficient for obtaining satisfactory simulation results. The HD parameters editor contains a number of tabs as present in Figure 84.

A list of the tab-page available in the Editor are presented below and described in the following paragraphs:

- ***Initial***
- ***Wind*** (not include)
- ***Bed Resistance***
- ***Bed Resistance toolbox*** (not include)
- ***Wave Approx.***
- ***Default Values*** (default values)
- ***Quasi Steady*** (default values)
- ***Heat Balance*** (not included
- ***Stratification*** (default values)
- ***Time Series Output***
- ***Maps***
- ***Groundwater Leakage*** (not included)
- ***Reach Lengths*** (not included)
- ***Add. Outputs***
- ***Flood Plain Resistance*** (default values)
- ***User Def. Marks*** (not included)
- ***Encroachment*** (default values)

Initial

Before starting a computation, the one must select how the initial conditions will be specified. MIKE 11 can automatically compute a steady-state profile in the river or the channel network compatible with the given boundary conditions at the specific computation start time in the simulation editor. Alternatively, the initial conditions may be obtained either from an existing result file or from manually specified initial conditions of corresponding values for Water levels and Discharges in the entire network at the start time of the computation.

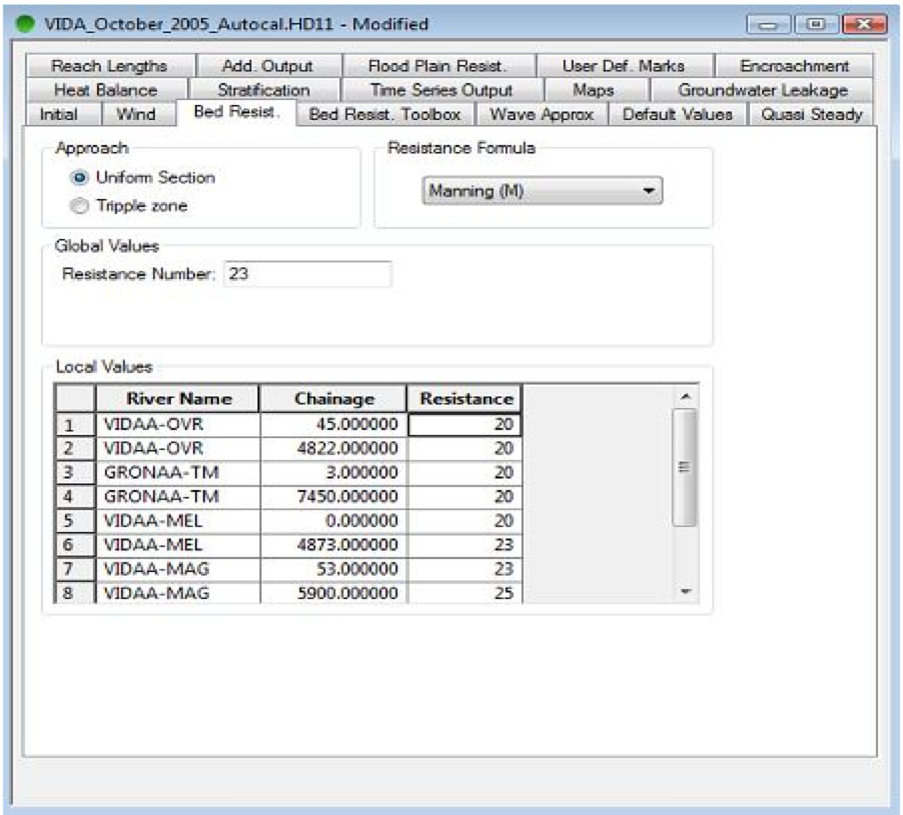
A global initial condition (water level and discharge) can be entered. This global condition is applied throughout the mode, unless otherwise specified. It is possible to specify a number of river reaches or channel reaches; “Local values”, where initial values of water level and discharge different from the global values are to be applied. The values entered for the initial water levels can also be interpreted as water depths by using the radio bottom.

Wind

If the user wishes to include Wind shear stress it is required that time variable boundary conditions for Wind Field are included in the simulation. The Wind Field boundary conditions consist of specifications for Wind direction (towards north) and the Wind velocity.

In the Wind page of the HD Parameter dialog, one can activate the usage of Wind field in the computation by activating the “Include Wind” check box (not in that study).

Bed Resistance



Approach
● Uniform Section
○ Tripple zone

Resistance Formula: Manning (M)

Global Values
Resistance Number: 23

Local Values

	River Name	Chainage	Resistance
1	VIDAA-OVR	45.000000	20
2	VIDAA-OVR	4822.000000	20
3	GRONAA-TM	3.000000	20
4	GRONAA-TM	7450.000000	20
5	VIDAA-MEL	0.000000	20
6	VIDAA-MEL	4873.000000	23
7	VIDAA-MAG	53.000000	23
8	VIDAA-MAG	5900.000000	25

Figure 84 – Bed Resistance tab from MIKE 11 HD Parameter editor

The resistance number must be specified in this page. The resistance number can have one of three different forms, of which Manning's M is default:

- Manning's *"n" (reciprocal of Manning's M; typical range: 0.010 – 0.100)*
- Manning's *"M" (M= 1/n; unit: $m^{1/3}/s$, typical range: 10 – 100)*
- Chezy number

After defining a resistance formula and the Global resistance and Local resistance values if required, the resulting bed resistance number applied in the simulation is the defined resistance numbers multiplied by the water level depending "Resistance factor" which is specified for the cross section editor (**.xns11** files).

Two approaches exist (See Figure 86): Uniform Section and Triple Zone. When the Uniform Section approach is selected the specified resistance number will be valid all over the section. If the Triple Zone approach is selected the cross sections are divided into three zones and a resistance number must be specified for each zone.

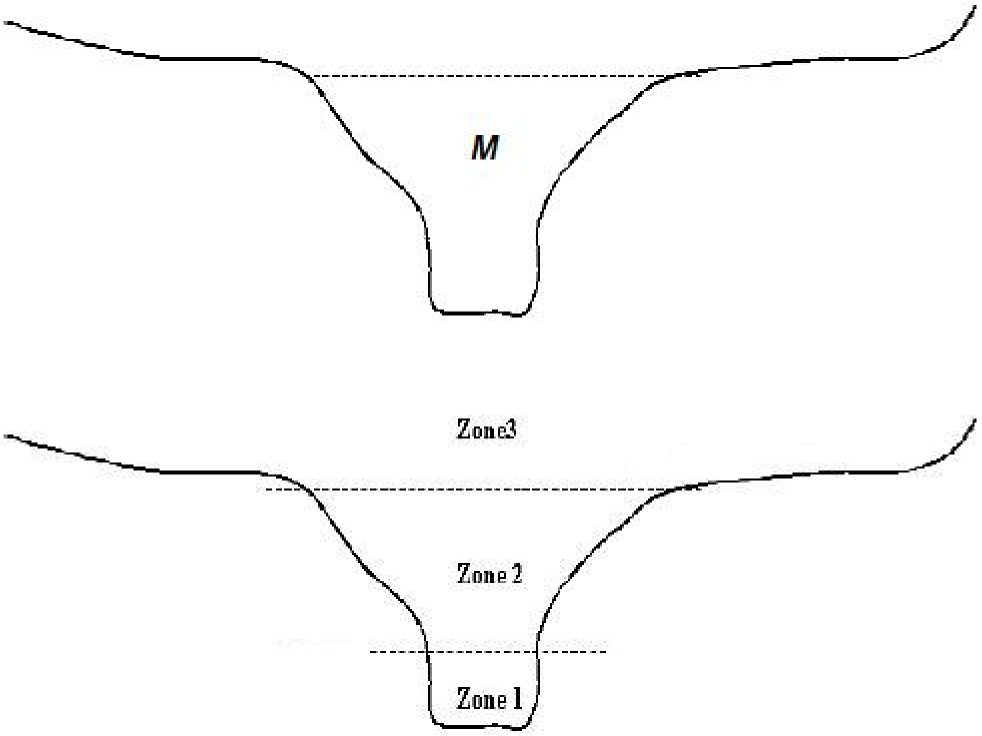


Figure 85 – Uniform Section and Triple Zone division of cross section

These zones represent the vegetation free zone in the bottom of the profile, a vegetation zone on banks etc. and a zone for description of flow over banks and flood plains etc. as indicated in Figure 86.

Global and local values for the resistance number can be defined. During a calibration exercise, typically, the resistance number is the most significant variable to adjust, and therefore, you will typically need to specify a number of local values to account for local variations in the topography, vegetation etc.

Bed Resistance Toolbox

The bed resistance toolbox offers a possibility to make the program calculate the bed resistance as a function of the hydraulic parameters during the computation by applying a Bed Resistance Equation. The Equations are designed to simulate the influence of vegetation on the resistance during varying flow conditions. In that study the bed resistance values used in the computation are those specified in the Bed Resistance page (Non Active Equation).

Wave Approximation

There are four possible flow descriptions available in MIKE 11. The flow description can be selected globally for the system and/or locally for individual branches. Locally specified flow descriptions must be specified for the whole branch.

It is possible to specified which wave approximation should be used in the computation choosing between Kinematic, Diffusive or one of two fully dynamic wave approximation. Default chooses is the dynamic wave.

Default Values

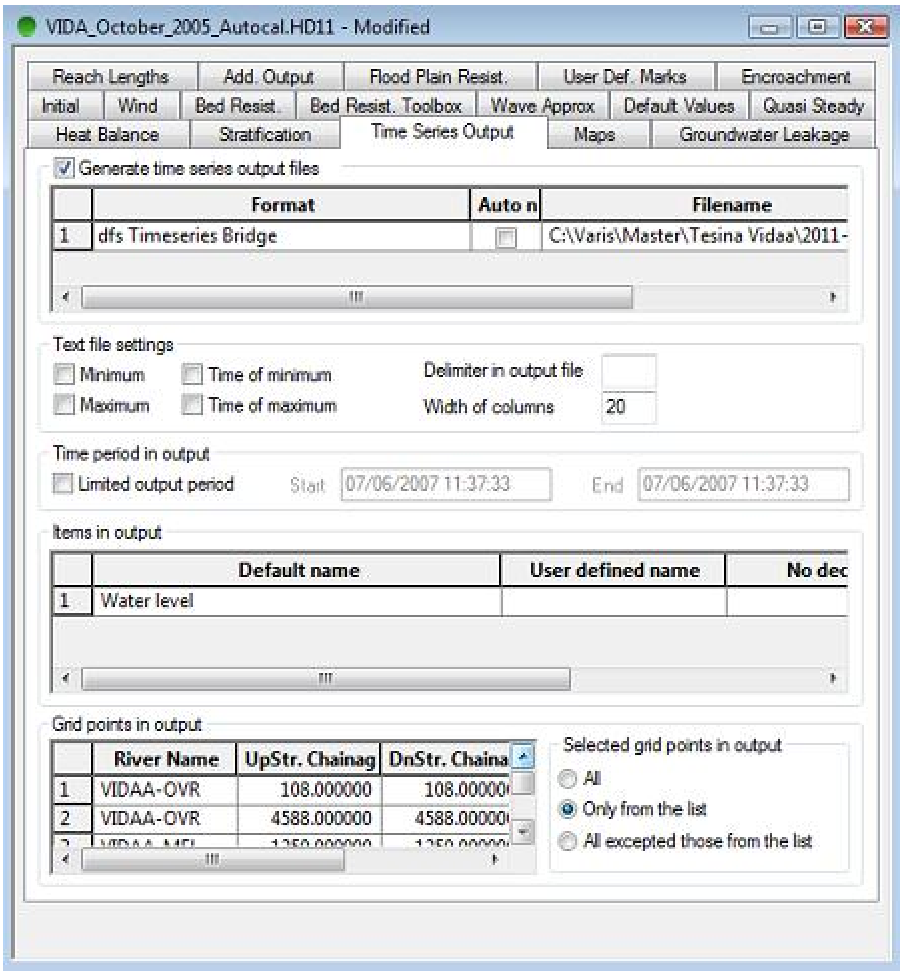
In this page it is possible to alter the value for a number of parameters connected to the hydrodynamic computations. Parameters should not be altered, unless the user is familiar with the effect on the results.

Quasi Steady

A number of Quasi Steady Control parameters connected with the quasi steady computations are entered in this page.

- ***Relax***: Weighting parameter used in the quasi-steady solution. For single branches without bifurcation the value should be 1. In more complex systems the value should be less than 1 (0.75 in its study).
- ***Beta Limit***: Factor used to avoid underflow in horizontal branches (1e-008 in its study).
- ***Fac 0***: Factor used to control the stop criteria for the discharge convergence test (2.5 in its study).
- ***Qconv factor***: Q converge factor used in the stop criterion for the backwater computation iterations (0.0001 in its study).
- ***Hconv factor***: H convergence factor used in the stop criterion for the backwater computation iterations. (0.01 in its study).
- ***Min Hconv In Branch***: Minimum stop criterion to avoid underflow (1e-005 in its study).
- ***Q struc factor***: Q structure factor, used to determine the discharge at structures where a slot description is introduced due to zero flow conditions (0.005 in its study).
- ***H stop***: Stop criteria in the water level convergence test. Used also by the quasi two dimensional steady state solver with vegetation as the convergence criteria in the outer loop (0.0001 in its study).

Time Series Output



VIDA_October_2005_Autocal.HD11 - Modified

☑ Generate time series output files

	Format	Auto n	Filename
1	dfs Timeseries Bridge	☐	C:\Varis\Master\Tesina Vidaa\2011-

Text file settings

☐ Minimum ☐ Time of minimum

☐ Maximum ☐ Time of maximum

Delimiter in output file

Width of columns 20

Time period in output

☐ Limited output period Start 07/06/2007 11:37:33 End 07/06/2007 11:37:33

Items in output

	Default name	User defined name	No dec
1	Water level		

Grid points in output

	River Name	UpStr. Chainag	DnStr. Chaina
1	VIDAA-OVR	108.000000	108.00000
2	VIDAA-OVR	4588.000000	4588.00000

Selected grid points in output

○ All

● Only from the list

○ All excepted those from the list

Figure 86 – Time Series Output tab from MIKE 11 HD Parameter editor

On this property page request is made for time series output files to be generated during the simulation. This output is in addition to the regular and the additional **.res11** output file. Time series output can be saved in **.dfs0** or **ASCII** files.

Time series output files are typically requested instead of manually extracting time series data in selected grid points from the **.res11** file after the simulation has been completed. This is often useful for automatic or manual calibration or when running production simulations.

Maps

On this property page request is made for that MIKE 11 produces two dimensional maps based on the one-dimensional simulations. The maps are constructed through interpolation in space of grid point's results. Thus the maps constructed in this way should be viewed as a two dimensional interpretation of results from a one dimensional model.

Reach Lengths

This can only be used in connection with Quasi Steady simulations (is not that case).

Add. Outputs

Additional output can be produced upon request by the user. This extra facility is available as a supplement to the hydrodynamic result file. The additional output is stored in a file with a similar name as the HD result file name. Only difference is that an additional string "HDADD" is added to the filename of the HD result file name.

Flood Plain Resistance

Normally, the resistance numbers on flood plains are included through editing the relative resistance factors above "Level of Divide" in the Cross-section editor, Raw data specifications, Hence, it is possible to reduce the effective flow area as a function of the water level. Another possibility of changing flood plain resistance numbers is to edit the Resistance Factor in the Processed Data in the cross-section editor.

However, if the modeling task does not require a water level dependent resistance on flood plains, an overall Flood Plain Resistance number can be specified in this page.

A global resistance number on the flood plains in the model can be specified. This is applied on all flood plains unless local values are specified. Local specified values are linearly interpolated. Giving the value “-99” as a resistance number indicates that the flood plain resistance number should be calculated from the raw data in the Cross-section file (it happens in that study).

User Def. Marks

The User Defined Markers page offers a possibility for the user to define items in the modeling area, which they would like to present on a longitudinal profile from MIKE View.

Encroachment

The Encroachment module of MIKE 11 can be used to make analysis of the effect on making encroachment on floodplains.

Heat Balance

It is possible to include detailed descriptions of the heat exchange between the water and the atmosphere in MIKE 11.

Stratification

When one or more of the branches in the MIKE 11 set up have been selected as “Stratified” the data necessary to run the stratified model must be entered in that page.

MIKE View

The MIKE View program has been adopted as the result viewer for MIKE 11. MIKE View has not been integrated into MIKE 11 structure and therefore, must be started as a stand-alone program.

MIKE View offers a variety of functions and features for viewing and analysing simulation results produced by the MIKE 11 system. The main presentation features comprise:

- Colour plan plot of the river network
- Longitudinal profiles
- Time series plot (several events can be presented on the same plot)
- Animation of water level in cross sections
- Results from several result-files can be included for comparison
- Plot of Q-h relations
- Animation of user-specified result items (plan plot, longitudinal profiles and time series)
- Zoom facility in all windows
- Scanned images of background maps can be loaded
- Hard copy of all plots

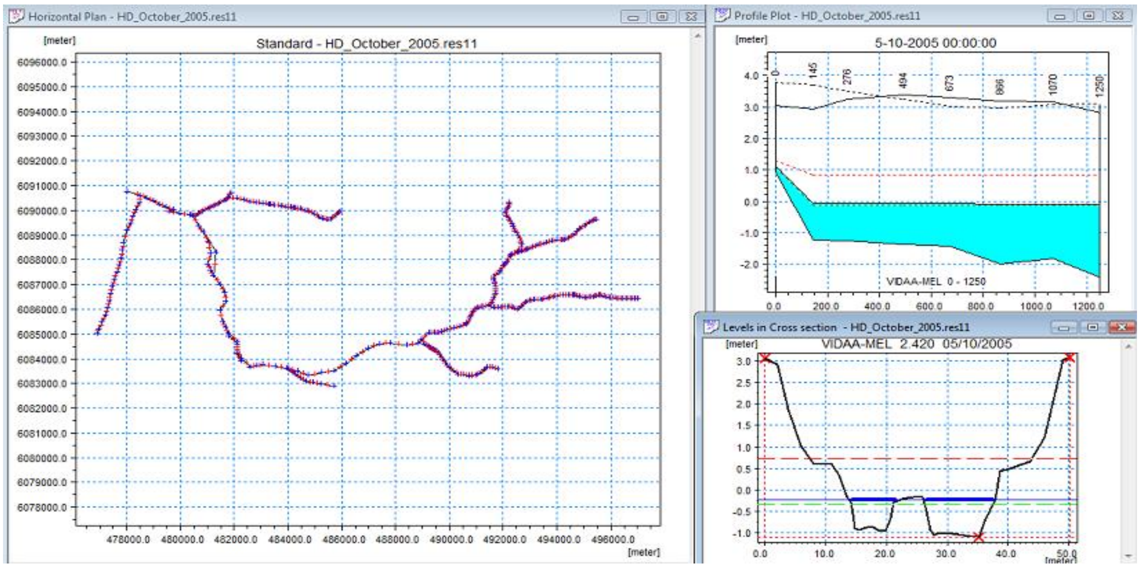
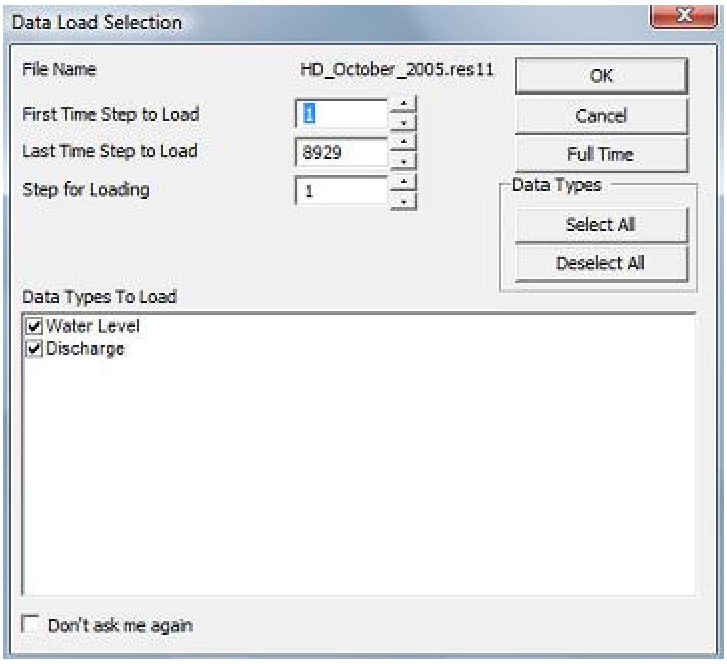


Figure 87 – Different types of views from MIKE View (network, longitudinal view, cross section view etc.)

One interesting option in MIKE View is the synchronized feature. This feature allows the user to play back the results of one or more simulations while viewing the results from several types of display windows, all fully synchronized. This option opens the possibility of:

- Viewing a plan view together with a longitudinal section, one or more time series and a Q-h relation plot, for a single simulation fully synchronised in time.
- Viewing two sets of plan views, time series etc. for two alternative simulations, shown together and fully synchronised

By default, MIKE View selects all available information saved in the result file. One can reduce the amount of data to be loaded by excluding some of the available data types, by truncating the time period to be presented (choosing the appropriate first and last time step), or by increasing the “Step for loading” factor to an integer value larger than one (see Figure 31).



File Name HD_October_2005.res11
First Time Step to Load 1
Last Time Step to Load 8929
Step for Loading 1

Data Types To Load
☑ Water Level
☑ Discharge

☐ Don't ask me again

Figure 88 – Example of the Data Load Selection view for a MIKE result file

When the user opens MIKE View, the software opens two windows on the screen:

- Horizontal Plan window
- Plan Overview window.

The Horizontal Plan window dominates MIKE View. It displays the layout of the sewer network. If the user select the Horizontal Plan window it becomes the active window, and the Horizontal Plan toolbar appears under the main menu.

When the user moves the cursor within the Horizontal Plan window, the co-ordinates of the current position are displayed in the status bar, located in the bottom left corner. The status bar also provides useful information on the program mode, help text, etc.

The Overview Plan window contains an outline of the network Horizontal Plan. It makes it easier to see where in the network you are while zooming.

The Horizontal Plan Options allows the user to try different options from the Plan Type group. The user selects one of the drawing models featuring the system information. One can choose between (see Figure 89 below):

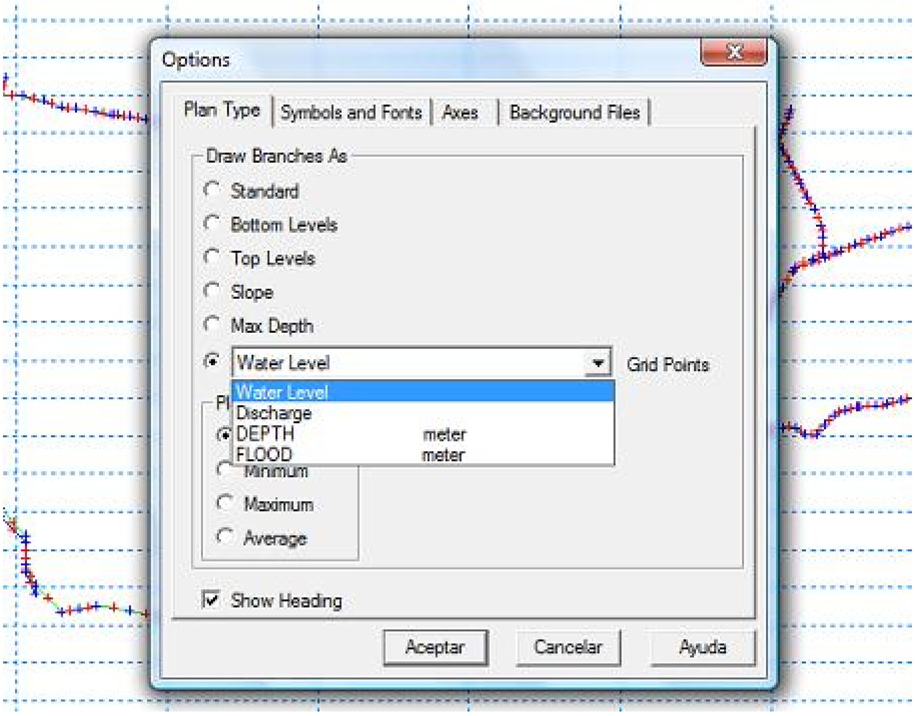


Figure 89 – Options Plan Type group from MIKE View

The user also can choose between what kinds of plot type prefer selecting Animation, Minimum, Maximum and Average. First of them, Animation, allows the user display dynamically the selected variable as a replay of the simulation through time. If the user selects one of the other three options, the program will show him the option value chosen (minimum values, maximum values or average values).

Auto Calibration

Autocal is a generic tool for performing automatic calibration, parameter optimisation, sensitivity analysis and scenario management of the numerical modelling engines under MIKE Zero PFS (parameters files system) format for model input and the DFS (data file system) format for model output.

The core of the Autocal tool consists of the following steps:

- Provision of a set of model parameter values to the numerical model to be used in a specific model run.
- Execution of the simulation model using the specified set of model parameter values.
- Calculation of statistical performance measures of the model output.

The model parameter interface is made via so-called template file. This file is simply a replica of the model input file in which parameter identification tags are placed at the locations where the numerical values of model parameters are given. Thus, when Autocal has to provide a new set of model parameters to the model, the parameter identification tags in a template file are substituted by the numerical values and saved in the model input file to be used when running the model. It is possible to manipulate model parameters in different model input files. For each model input fila a corresponding template is defined.

Autocal allows parameters to be defined as functions of other parameters that are manipulated in the Autocal run. In this case general equations can be specified that defines the relations between the dependent model parameter and the other parameters. Autocal provides the set of independent parameter values and the dependent parameters are then calculated automatically from these values using the defined equations. Both dependent and independent parameter values are then substituting their corresponding parameter identification tags in the template files.

A parameter may also be defined as a constant. In this case the constant value defined in Autocal is substituting the corresponding parameter identification tag in the template file. This feature is especially useful when a sensitivity analysis is performed prior to the parameter optimisation. In this case the sensitivity analysis typically includes a long list of parameters. From the results of the sensitivity analysis the most sensitive parameters are retained in the subsequent parameter optimisation. Instead of making a new Autocal setup, the same setup as used in the sensitivity analysis can be applied simply by setting the insensitive parameters to constant values.

Whether Autocal is used for parameter optimisation, sensitivity analysis or scenario management, the performance of the model simulation given the specified parameter set should be assessed. This is done by calculating statistical performance measures. These measures are typically comparison statistics that compare measurements or, in general, target values with corresponding simulated values.

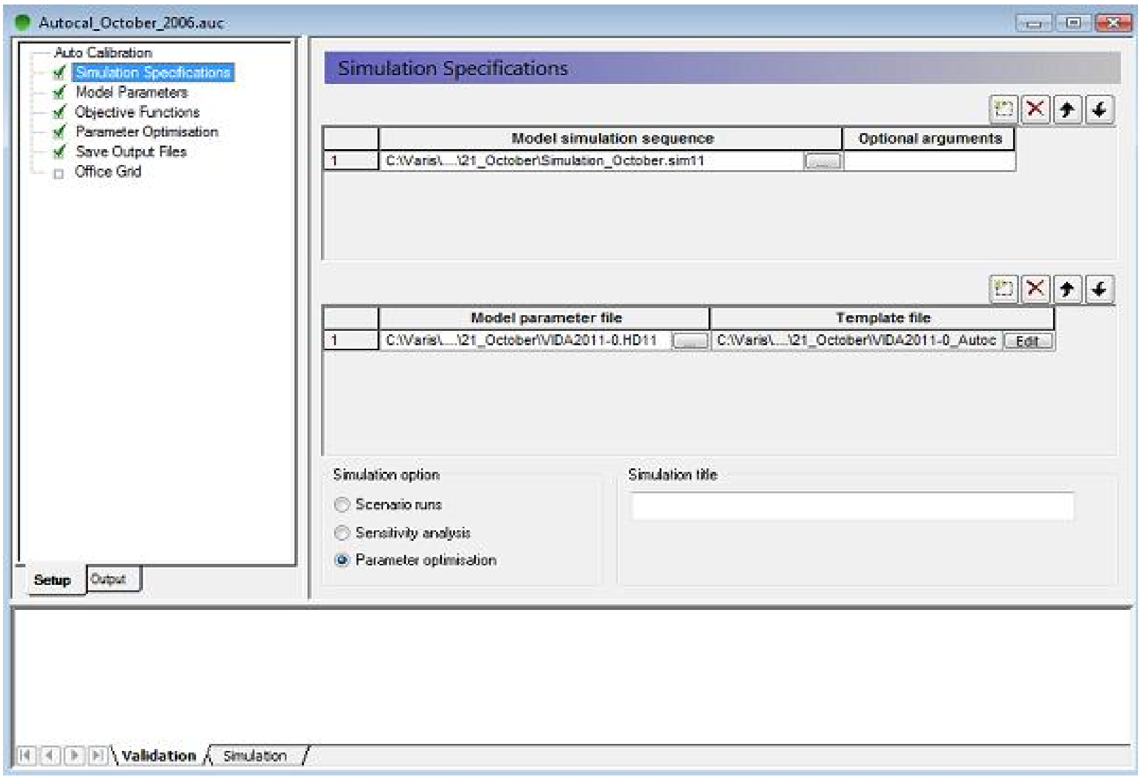
For calculating the comparison statistics Autocal requires that simulation results and corresponding observations are given as time series in DFS0 files. If the output from a model engine is not explicitly given in DFS0 format, a processing of simulation results is required to transform the simulation results at measurement locations into DFS0 format.

Before setting up Autocal, the simulation model should be properly tested. At least one model run should be performed to create the output files that are needed in the Autocal setup.

Autocal follows the next sequence:

- Simulation Specifications
- Model Parameters
- Objective Functions
- Simulation Options
    - Scenario Runs
    - Sensitivity Analysis
    - Parameter Optimisation
- Save Output Files
- Office Grid

Simulation Specifications



	Model simulation sequence	Optional arguments
1	C:\Varis\....\21_October\Simulation_October.sim11	

	Model parameter file	Template file
1	C:\Varis\....\21_October\VIDA2011-0.HD11	C:\Varis\....\21_October\VIDA2011-0_Autoc

Simulation option
○ Scenario runs
○ Sensitivity analysis
● Parameter optimisation

Simulation title

Figure 90 – Simulation Specifications view page from Autocal

On the Simulation Specification page, the model simulation sequence, the model parameter files, and the simulation option are specified.

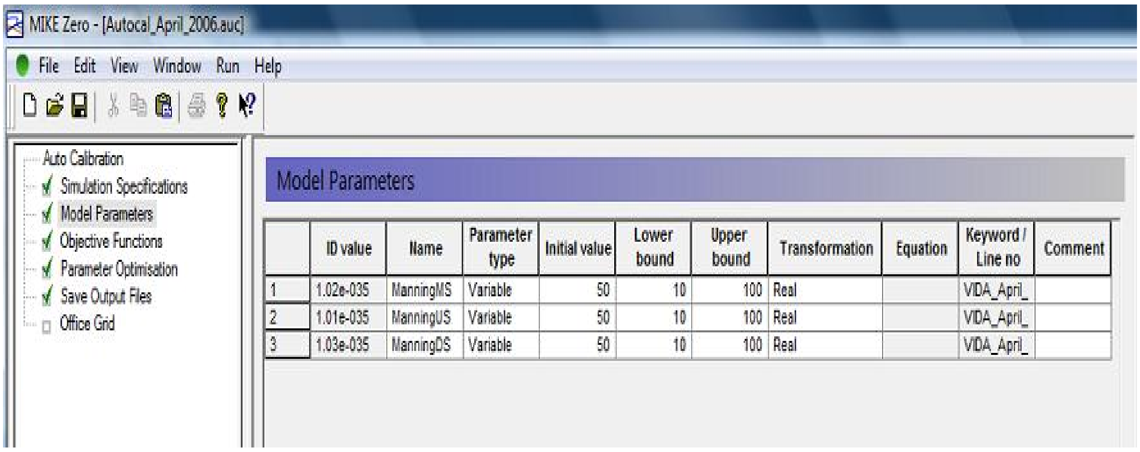
A ***model simulation*** in Autocal can be defined as a sequence of individual model runs. For example, a modelling sequence may consist of a hydrodynamic (HD) model simulation followed by an advection dispersion (AD) model simulation that uses the HD outputs.

In the ***model parameter files*** table, the names of the files containing the model parameters to be manipulated by Autocal are specified.

Autocal supports three different ***simulation options***: Scenario runs, Sensitivity analysis and Parameter optimisation. Depending on the choice a corresponding property page is shown in the tree view.

Optionally a simulation title can be specified.

Model Parameters



Model Parameters

	ID value	Name	Parameter type	Initial value	Lower bound	Upper bound	Transformation	Equation	Keyword / Line no	Comment
1	1.02e-035	ManningMS	Variable	50	10	100	Real		VIDA_April_	
2	1.01e-035	ManningUS	Variable	50	10	100	Real		VIDA_April_	
3	1.03e-035	ManningDS	Variable	50	10	100	Real		VIDA_April_	

Figure 91 – Model Parameters view page from Autocal

On the Model Parameter page the properties of the model parameters that are defined in the model parameter files are specified. The parameter table is automatically created by Autocal based on the specifications given in the template files on the Simulation Specifications page.

The following properties are specified in the table: ID Value, Keyword/Line nº, Name, Parameter type, Initial value, Lower value, Upper value, Transformation and Equation.

The ***ID value*** is the identification tag value given for the parameter in the template file.

Ones must specify a unique ***Name*** for each parameter. This name must not include white spaces. In addition, if the parameter is included as an independent parameter in an equation, arithmetic symbols and function names used by the equation parser must not be used as a part of the parameter name.

The ***Parameter type*** may be defined as a *Variable* parameter, a *Constant* parameter or a *Dependent* parameter. A variable parameter is a parameter that is changed by Autocal according to the chosen simulation option. For a variable parameter the ***Initial value, Lower bound and Upper bound*** need to be defined. A constant parameter is set to the value defined in the ***Initial value*** field. A dependent parameter is defined as a function of the others parameters. In this case the ***Equation*** must be specified.

The ***Initial value*** is the value used by Autocal for performing a single scenario run. If the *Local sensitivity analysis* option is chosen, the sensitivity coefficients are evaluated around the initial parameter set.

The ***Lower bound*** specifies the lower limit of the feasible parameter values in the parameter optimisation.

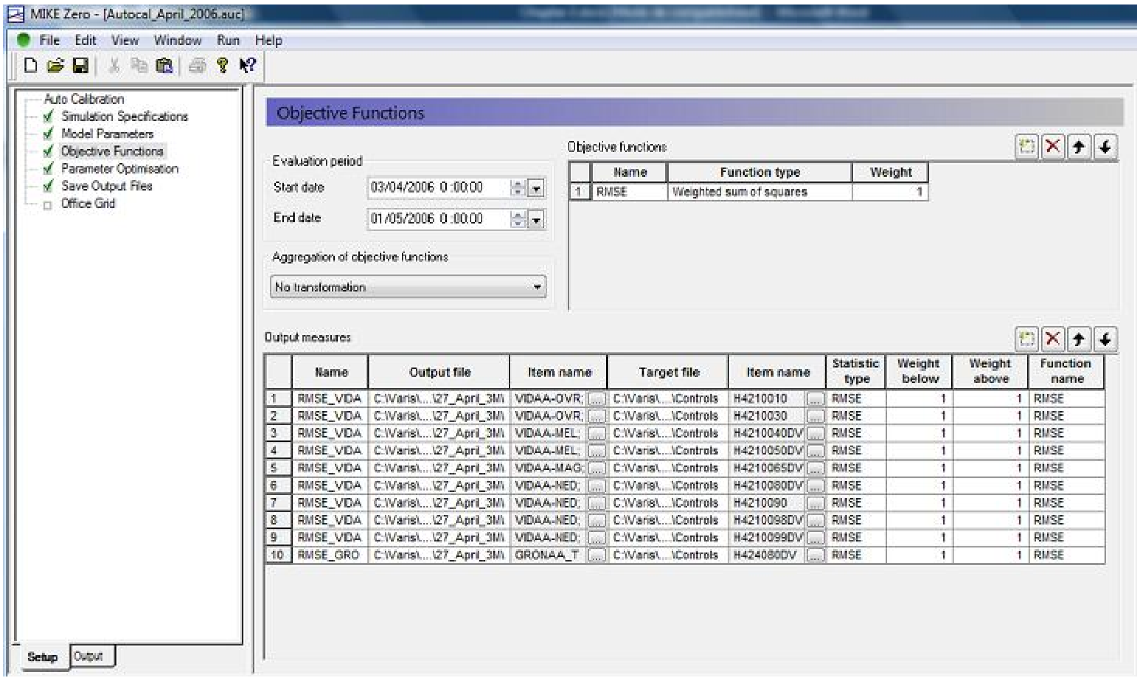
The ***Upper bound*** specifies the upper limit of the feasible parameter values in the parameter optimisation.

The parameter may be used in Autocal as its native value by setting the ***transformation*** field to ***Real*** or as its logarithmic transformed value by setting the ***transformation*** field to ***Logarithmic***. A logarithmic transformation is generally recommended if the feasible range of parameter varies over orders of magnitude.

If a parameter is defined as a dependent parameter, an ***equation*** must be given to define the parameter as a function of the available variable parameters. Autocal uses an equation parser that supports the general arithmetic operators (+, -, *, /) as well as a number of mathematical functions.

The ***Keyword*** is an identification string that shows the location of the parameter in the PFS model input file. The first part of the string is the name of the template file. This is followed by the hierarchy of PFS sections separated by dots. The last part of the string is the PFS keyword. Id the parameter file is not a MIKE Zero PFS file; the Line No. where the parameter is located is shown.

Objective Functions



Objective Functions

Evaluation period

Start date 03/04/2006 0:00:00

End date 01/05/2006 0:00:00

Aggregation of objective functions

No transformation

Objective functions

	Name	Function type	Weight
1	RMSE	Weighted sum of squares	1

Output measures

	Name	Output file	Item name	Target file	Item name	Statistic type	Weight below	Weight above	Function name
1	RMSE_VIDA	C:\Varis\...\27_April_3M\	VIDAA-OVR;	C:\Varis\...\Controls	H4210010	RMSE	1	1	RMSE
2	RMSE_VIDA	C:\Varis\...\27_April_3M\	VIDAA-OVR;	C:\Varis\...\Controls	H4210030	RMSE	1	1	RMSE
3	RMSE_VIDA	C:\Varis\...\27_April_3M\	VIDAA-MEL;	C:\Varis\...\Controls	H4210040DV	RMSE	1	1	RMSE
4	RMSE_VIDA	C:\Varis\...\27_April_3M\	VIDAA-MEL;	C:\Varis\...\Controls	H4210050DV	RMSE	1	1	RMSE
5	RMSE_VIDA	C:\Varis\...\27_April_3M\	VIDAA-MAG;	C:\Varis\...\Controls	H4210065DV	RMSE	1	1	RMSE
6	RMSE_VIDA	C:\Varis\...\27_April_3M\	VIDAA-NED;	C:\Varis\...\Controls	H4210080DV	RMSE	1	1	RMSE
7	RMSE_VIDA	C:\Varis\...\27_April_3M\	VIDAA-NED;	C:\Varis\...\Controls	H4210090	RMSE	1	1	RMSE
8	RMSE_VIDA	C:\Varis\...\27_April_3M\	VIDAA-NED;	C:\Varis\...\Controls	H4210098DV	RMSE	1	1	RMSE
9	RMSE_VIDA	C:\Varis\...\27_April_3M\	VIDAA-NED;	C:\Varis\...\Controls	H4210099DV	RMSE	1	1	RMSE
10	RMSE_GRO	C:\Varis\...\27_April_3M\	GRONAA_T	C:\Varis\...\Controls	H424080DV	RMSE	1	1	RMSE

Figure 92 – Objective Functions view page from Autocal

On the Objective Functions page the properties for calculation of comparison statistics are specified. The basic statistics used by Autocal are the *Output Measures* that include a single comparison statistics between an observed and a simulated time series. These basic measures can then be aggregated into different *Objective Functions*, for instance according to spatial location, type of variable, or type of statistic. Finally, the defined objective functions are aggregated into a single statistic that is used by the optimisation algorithm.

Output Measures

One has to give a ***Name*** of the output measure. The ***output file and item name*** are the file names and corresponding item name of the time series of the simulation results at the observation points. The ***observation files and item name*** are the file names and corresponding item name of the observation time series.

Autocal includes three basic comparison statistics:

- Average error (*Avg. Error*)

$$AE = \frac{1}{N}\sum_{i=1}^{N}(OBS_i - SIM_i)$$

- Root mean square error (*RMSE*)

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(OBS_i - SIM_i)^2}$$

- Standard deviation of residuals (*St. Dev.*)

$$STD = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(OBS_i - SIM_i - AE)^2}$$

Where the OBS_i and SIM_i, i=1, …, N are the observed and the corresponding simulated time series, respectively. Before calculation of the statistics, the time series are synchronised; that is, simulated values are extracted at the same time instants as the available observation using linear interpolation.

The three statistics are linked via the equation:

$$RMSE^2 = AE^2 + STD^2$$

The statistics ***AE*** is a measure of the general offset between measurements and simulations (bias), whereas ***STD*** is a measure of the dynamical correspondence. ***RMSE*** is an aggregated measure that includes both bias and dynamical correspondence.

Objective Functions

One has to give a ***Name*** of the objective function. Autocal uses three different functions for aggregation of the defined output measures:

- Weighted sum

$$F_{pool,i} = \sum_{j=1}^{n} w_j F_j$$

- Weighted sum of absolute values

$$F_{pool,i} = \sum_{j=1}^{n} w_j |F_j|$$

- Weighted sum of squares

$$F_{pool,i} = \sum_{j=1}^{n} w_j F_j^2$$

Where $\boldsymbol{F_j}$ is the output measure, $\boldsymbol{w_j}$, j = 1, 2, ..., n are the weights given to each measure, and $\boldsymbol{n}$ is the number of measures that are pooled.

Typically, output measures within a certain area that measure the same statistic for the same physical variable are pooled to evaluate the average model performance for that variable in the specified area with respect to bias (*Avg. Error*), dynamical behaviour (*St. Dev.*) or an overall goodness-of-fit (*RMSE*). The event-based statistics are typically pooled into an aggregate error of maximum and minimum values, respectively.

Evaluation Period

One has to indicate the start date of the time series for which the output measures are calculated. It is generally recommended to set the start date after the start date of the model simulation in order to include a certain warm-up period in the simulation to minimise the influence from the initial conditions in the calculation of the output measures.

The end date of the time series has to be indicating for which the output measures are calculated. This is usually set to the end date of the model simulation.

Aggregation of Objective Functions

The defined objective functions are aggregated into one measure:

$$F = \sum_{i=1}^{M} w_i g_i(F_{pool,i})$$

Where ***M*** is the number of objective functions that are aggregated, ***w_i***, i= 1, 2, ..., M are the weights, and ***g_i(.)***, i=1, 2, …,M are transformation functions assigned to each objective function.

Three different transformations are available:

- No transformation

$$g_i(F_{pool,i}) = F_{pool,i}$$

- Transformation to a common distance scale:

$$g_i(F_{pool,i}) = \frac{F_{pool,i}}{\sigma_i} + \varepsilon_i$$

Where σ_i is the standard deviation of the i'th objective function of the initial population used in the Shuffled Complex Evolution or Population Simplex Evolution optimisation algorithm and ε_i is a transformation constant given by:

$$\varepsilon_i = max\left\{min\left\{\frac{F_j}{\sigma_j}, j = 1,2,\dots,M\right\}\right\} - min\left\{\frac{F_j}{\sigma_j}\right\}$$

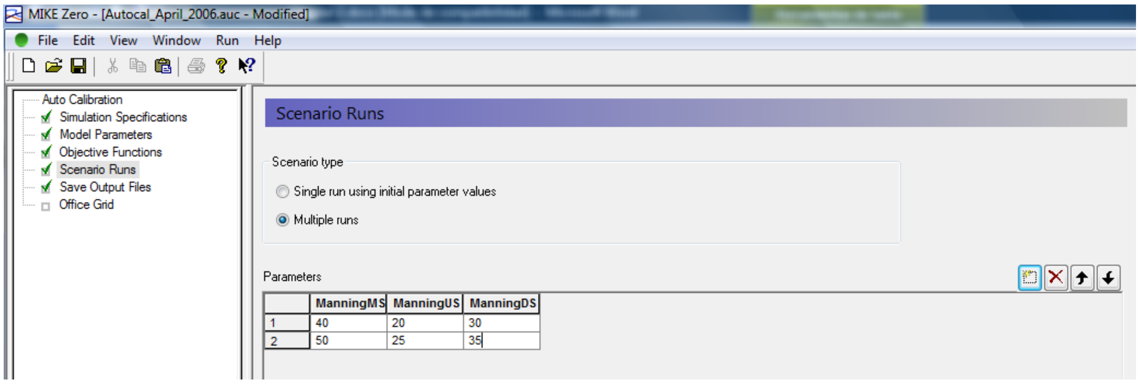
- Transformation to a common probability scale

$$g_i(F_{pool,i}) = \varphi\left(\frac{F_{pool,i} - \mu_i}{\sigma_i}\right)$$

Where ϕ_i is the cumulative distribution function of the standard normal distribution, and μ_i and σ_i are the mean and the standard deviation of the i'th objective function of the initial population.

The transformation functions that are applied in the transformation to a common distance scale and a common probability scale are introduced to compensate for differences in the magnitudes of the different measures so that all $g_i(.)$ have about the same influence on the aggregated objective function near the optimum.

Scenario Runs



Scenario type

○ Single run using initial parameter values

● Multiple runs

Parameters

	ManningMS	ManningUS	ManningDS
1	40	20	30
2	50	25	35

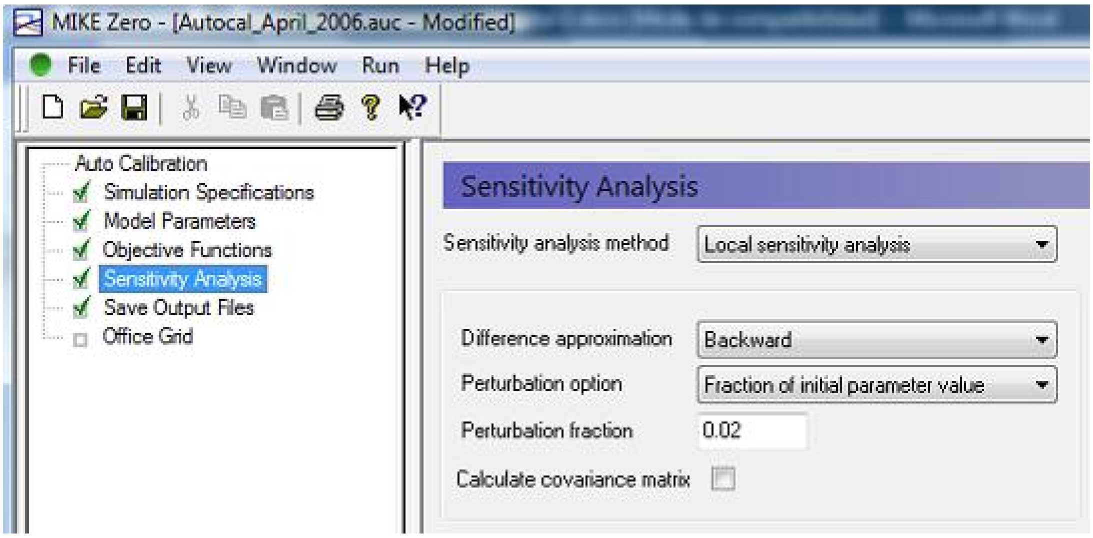
Figure 93 – Scenario Runs view page from Autocal

If the Scenario Runs option has been chosen, the scenario run properties must be specified. Autocal include two different options for performing scenario analysis:

- Single run using initial parameter values. In this case a single model run is performed using the initial parameter values given in the table on the ***Model Parameters*** page. When the model parameters and the objective functions have been specified, it is recommended to carry out a single run in order to check the setup.
- Multiple runs. In this case multiple model runs are performed using the parameters values given in the parameters table.

In the parameters table the set of variable parameters to be used in the scenario runs are specified.

Sensitivity Analysis



Sensitivity analysis method: Local sensitivity analysis

Difference approximation: Backward

Perturbation option: Fraction of initial parameter value

Perturbation fraction: 0.02

Calculate covariance matrix ☐

Figure 94 – Sensitivity Analysis view page from Autocal

If the Sensitivity Analysis option has been chosen, the properties must be specified on the page. Sensitivity analysis is often done as a first step in a model calibration to identify the most important model parameters to be fine-tuned in the succeeding parameter optimisation.

The present version of Autocal includes one sensitivity analysis method: ***Local sensitivity analysis***. Local sensitivity analysis provides the sensitivity of the model parameters around specified parameters set, and hence gives information about the importance of the parameters only at that location in parameter space. If the simulation model is highly non-linear in its parameter-output interactions, sensitivity measures may vary considerably in the parameter space. Thus, parameters that are intensitive for certain parameter sets may be highly sensitive for other parameter set and vice versa.

The local sensitivity analysis measures are calculated around the initial parameter set specified on the ***Model Parameters*** page.

The sensitivity of a parameter with respect to a model response (output measure) is defined as:

$$S_i = \frac{\partial F}{\partial \theta_i}$$

Where F is the output measure and θ_i is the considered model parameter. The sensitivity measure is evaluated around a specified parameter set ($\theta_1, \theta_2, \ldots, \theta_n$).

In Autocal a finite difference approximation is used to evaluate the sensitivity coefficient. Three different options are available:

- Forward difference approximation

$$S_i = \frac{F(\theta_1, \theta_2, \ldots, \theta_i + \Delta\theta_i, \ldots, \theta_n) - F(\theta_1, \theta_2, \ldots, \theta_n)}{\Delta\theta_i}$$

- Backward difference approximation

$$S_i = \frac{F(\theta_1, \theta_2, \ldots, \theta_n) - F(\theta_1, \theta_2, \ldots, \theta_i - \Delta\theta_i, \ldots, \theta_n)}{\Delta\theta_i}$$

- Central difference approximation

$$S_i = \frac{F(\theta_1, \theta_2, \ldots, \theta_i + \Delta\theta_i, \ldots, \theta_n) - F(\theta_1, \theta_2, \ldots, \theta_i - \Delta\theta_i, \ldots, \theta_n)}{2\Delta\theta_i}$$

Where $\Delta\theta_i$is the parameter perturbation. The calculation of the sensitivity coefficients require n+1 model evaluations in the case of forward and backward difference approximations, and 2n+1 model evaluations when the central difference approximation is applied. The parameter perturbation can be calculated as:

- A fraction of the initial parameter value

$$\Delta\theta_i = f_c\theta_i$$

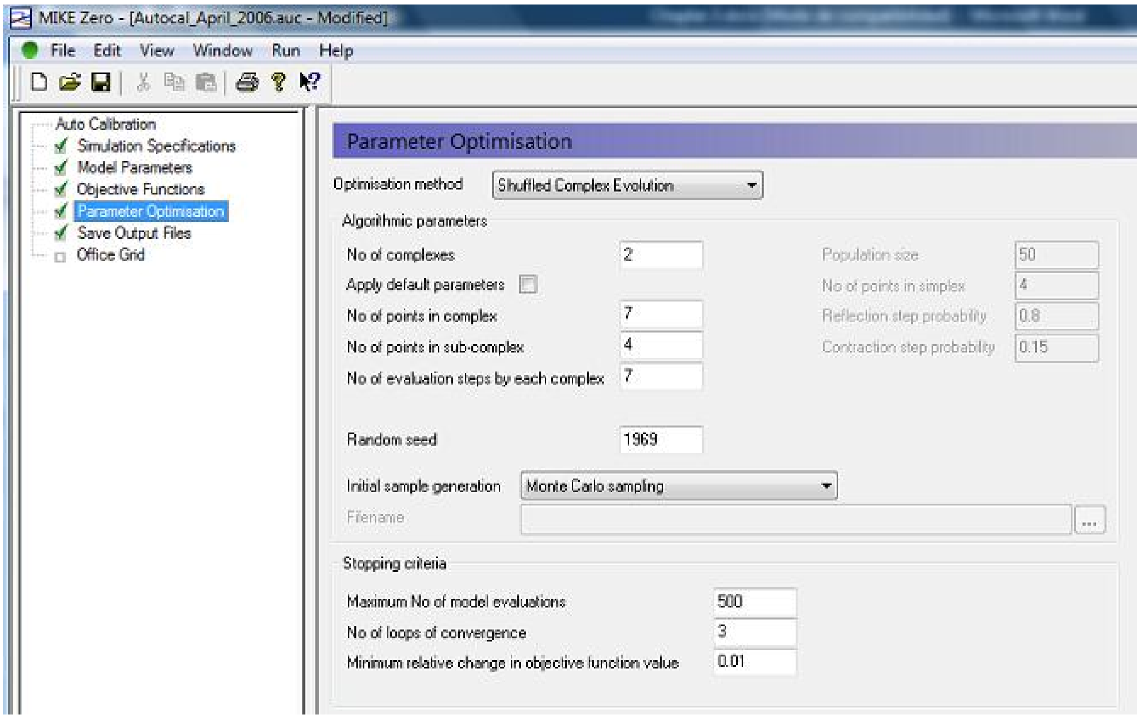
- A fraction of the parameter interval

$$\Delta\theta_i = f_c\left(\theta_{i,upper} - \theta_{i,lower}\right)$$

Where $\theta_{i,upper}$ and $\theta_{i,lower}$ are the specified upper and lower limits of the parameter. The perturbation fraction is the fraction f_c of the initial parameter value or the parameter interval depending on the choice of parameter perturbation.

If the option of calculate covariance matrix is selected, the matrix of the parameters evaluated around the initial parameter set is calculated. This matrix is derived based on the sensitivities of the simulated values corresponding to each of the measurements with respect to each of the parameters. The matrix can only be calculated in the case a weighted least square aggregated objective function is specified.

Parameter Optimisation



Parameter Optimisation

Optimisation method: Shuffled Complex Evolution

Algorithmic parameters

No of complexes: 2
Apply default parameters: ☐
No of points in complex: 7
No of points in sub-complex: 4
No of evaluation steps by each complex: 7
Population size: 50
No of points in simplex: 4
Reflection step probability: 0.8
Contraction step probability: 0.15
Random seed: 1969
Initial sample generation: Monte Carlo sampling
Filename:

Stopping criteria

Maximum No of model evaluations: 500
No of loops of convergence: 3
Minimum relative change in objective function value: 0.01

Figure 95 – Parameter Optimisation view page from Autocal

If the Parameter Optimisation has been chosen, the properties must be specified in the present page.

Autocal include two parameter optimisation methods: ***Shuffled Complex Evolution*** and ***Population Simplex Evolution***.

The ***Shuffled Complex Evolution*** (***SCE***) method is a global optimisation algorithm that combines various search strategies, including:

- Competitive evolution
- Controlled random search
- The simplex method
- Complex shuffling

The ***SCE*** algorithm includes the following steps:

1. ***Initialisation***. An initial sample of parameters sets θ_i are randomly generated from the feasible parameter space defined by lower and upper limits of each parameter on the ***Model Parameters*** page. For each parameter set the objective function value $F_i=F(\theta_i)$ is calculated. The initial sample has the size $s=pm$ where p is the number of complexes and m is the number of points in each complex.
2. ***Partitioning into complexes***. The s points are ranked in order of increasing objective function value ($F(1) < F(2) < \ldots < F(s)$). The s points are partitioned into p complexes, such that points corresponding to function values $\{F(1), F(p+1), \ldots, F((s-1)p+2)\}$ form the 2nd complex, etc.
3. ***Evolution***. A sub-complex of size q is formed from the complex by randomly choosing q points from the p points in the complex. A triangular probability distribution is used for assigning the probability of a point to be include in the sub-complex (i.e. larger probability for points with smaller objective function value). The sub-complex is evolved (offspring generation) according to the simplex algorithm. Each complex is evolved β times.
4. ***Complex shuffling***. The new sample of s points is shuffled, cf. step 2.
5. Steps 2-4 are repeated until a stopping criterion is met.

The algorithmic parameters of the ***SCE*** algorithm, their feasible range and recommended values are shown in the below table:

Parameter	**Description**	**Range**	**Recommended value**
p	No. of complexes	$p \geq 1$	-
m	No. of points in a complex	$m \geq 2$	$2n + 1$
q	No. of points in a sub-complex	$2 \leq q \leq m$	$n + 1$
β	No. of evolutions steps taken by each complex before shuffling	$\beta \geq 1$	$2n + 1$

Table 18 - Algorithmic parameters for the SCE algorithm (n = No. of calibration parameters), their range and recommended values

If one complex is chosen in SCE and the numbers of points in the complex as well as the sub-complex are set equal to n + 1, the local search simplex method is obtained as a special case.

Number of complexes *p* applied in the ***SCE*** algorithm. This is the most important parameter of the ***SCE*** algorithm. Sensitivity tests show that the dimensionality of the calibration problem (No. of calibration parameters) is the primary factor determining the proper choice of *p*. In general, the larger value of *p* is chosen the higher the probability of converging into the global optimum but at the expense of a larger number of model simulations (the number of model simulations is virtually proportional to *p*), and vice versa. One should choose *p* to balance the trade-off between the robustness of the algorithm and the computing time.

Random seed used in the optimisation can be set to any positive integer value. Since the ***SCE*** method is a probabilistic search procedure, different optimisation results will be obtained by using different random seeds.

Three different options are available for generation of the initial sample in the ***SCE*** algorithm:

- ***Monte Carlo sampling***. In this case the initial parameter sets are randomly generated within the feasible parameter range specified on the ***Model Parameters*** page assuming a uniform distribution.
- ***Latin hypercube sampling***. In this case the individual parameters are sampled according to a stratified sampling scheme where the feasible parameter interval is divided into *s* equal intervals (*s* being the sample size) and a point is then randomly selected within each interval.
- ***Initial sample from previous optimisation run***. This option allows continuing the optimisation from the last iteration loop of a previous optimisation run.

Three stopping criteria are defined:

- ***Maximum number of model evaluations***.
- ***Convergence in objective function space***. In this case the optimisation terminates if the objective function of the best parameter set has not changed more than a user-defined minimum value in a given number of shuffling loops.
- ***Convergence in parameter space***. In this case the optimisation terminates if the range of parameter values of the entire population in the parameter space is less than a given value (not user-defined).

The search ends when one of these criteria is met.

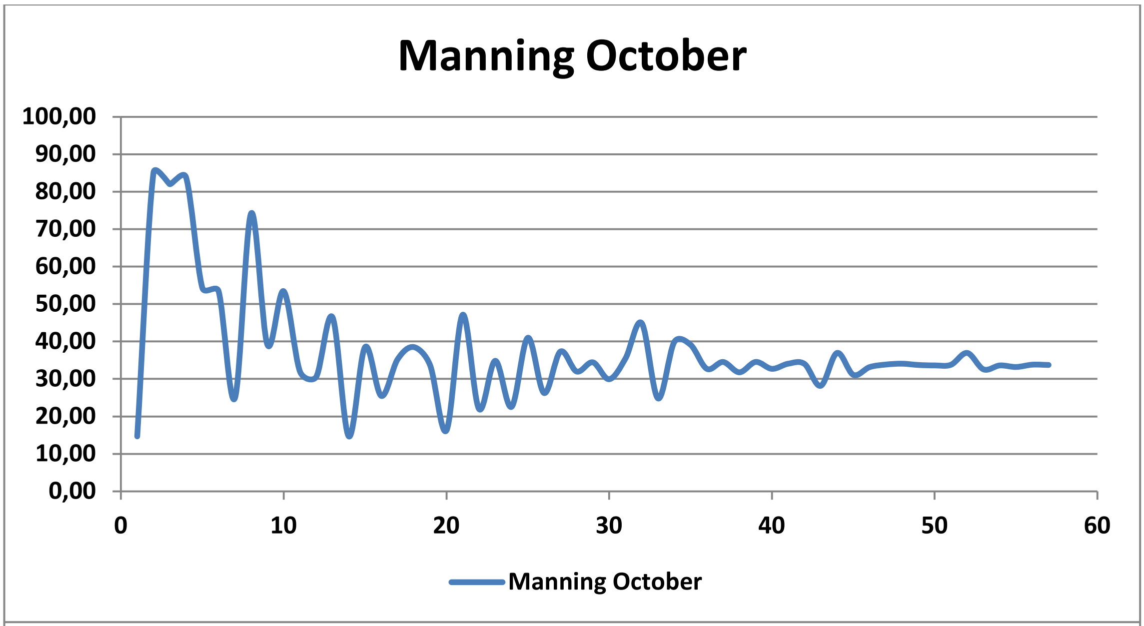
The ***Population Simplex Evolution (PSE)*** method is a global optimisation algorithm that is especially suited for parallel execution using the Office Grid facility in Autocal. The method evolves a population of points using the reflection and contraction operators included in the simplex method. In addition a mutation component is added to minimise the risk of premature convergence.

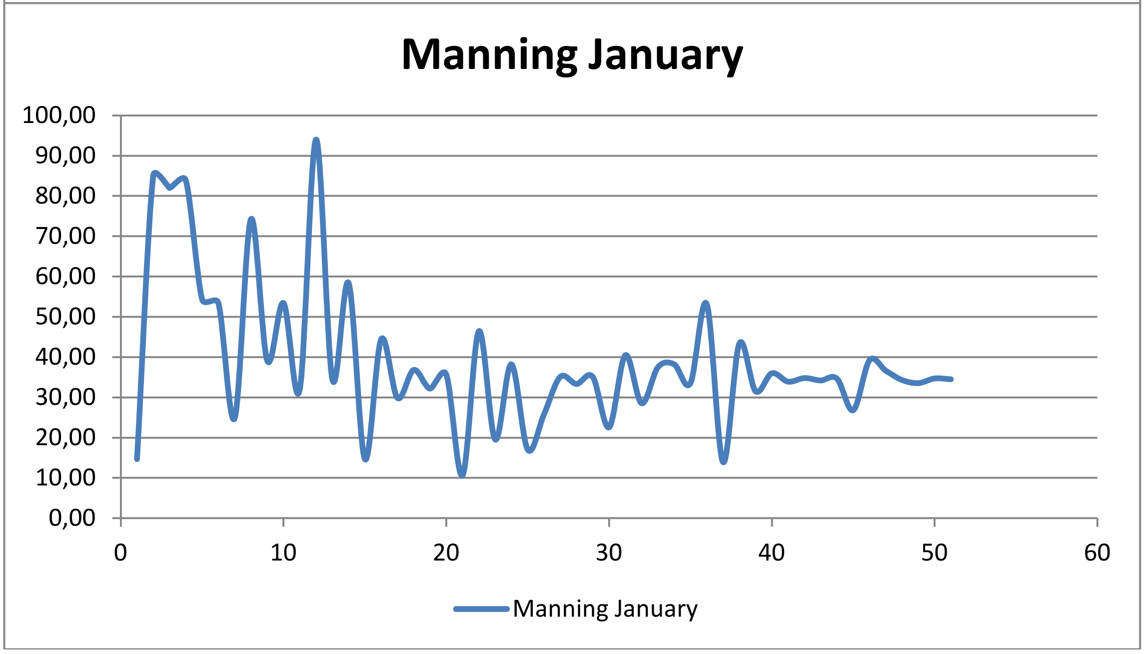
Appendix 2

Control Station	***Vidaa stream (chainage)***
H4210030	Vidaa OVR 4588
H4210040	Vidaa MEL 1250
H4210050	Vidaa MEL 3744
H4210065	Vidaa MAG 4670
H4210080	Vidaa NED 5117
H4210090	Vidaa NED 9400
H4210098	Vidaa NED 10800
H4240080	Gronaa_TM 3072

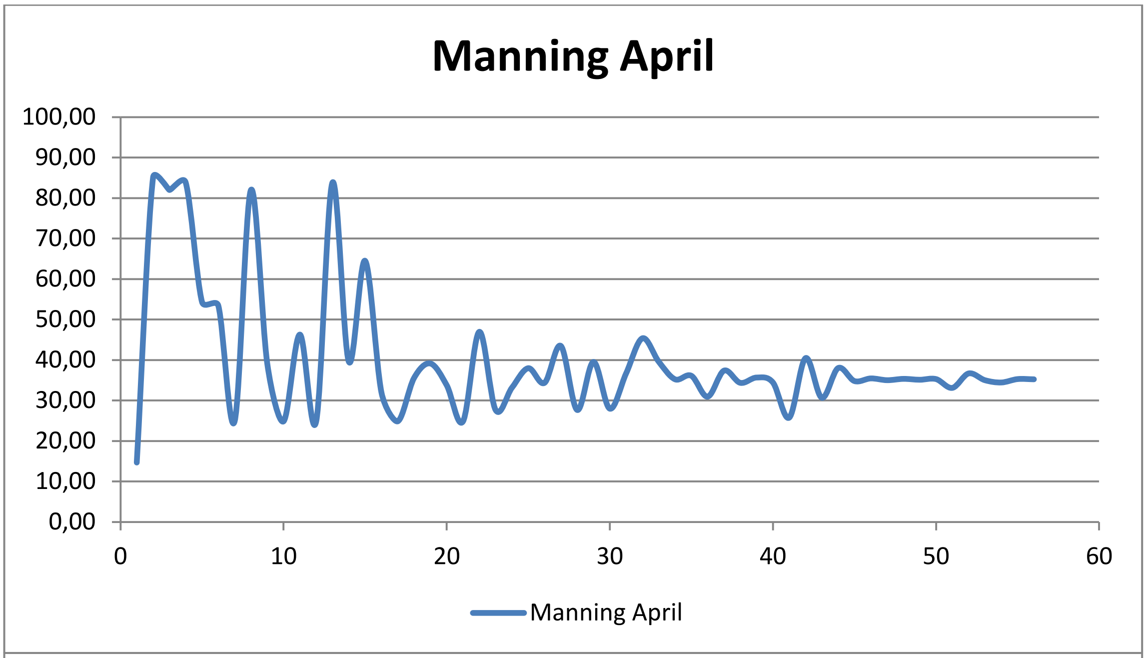
Appendix 3

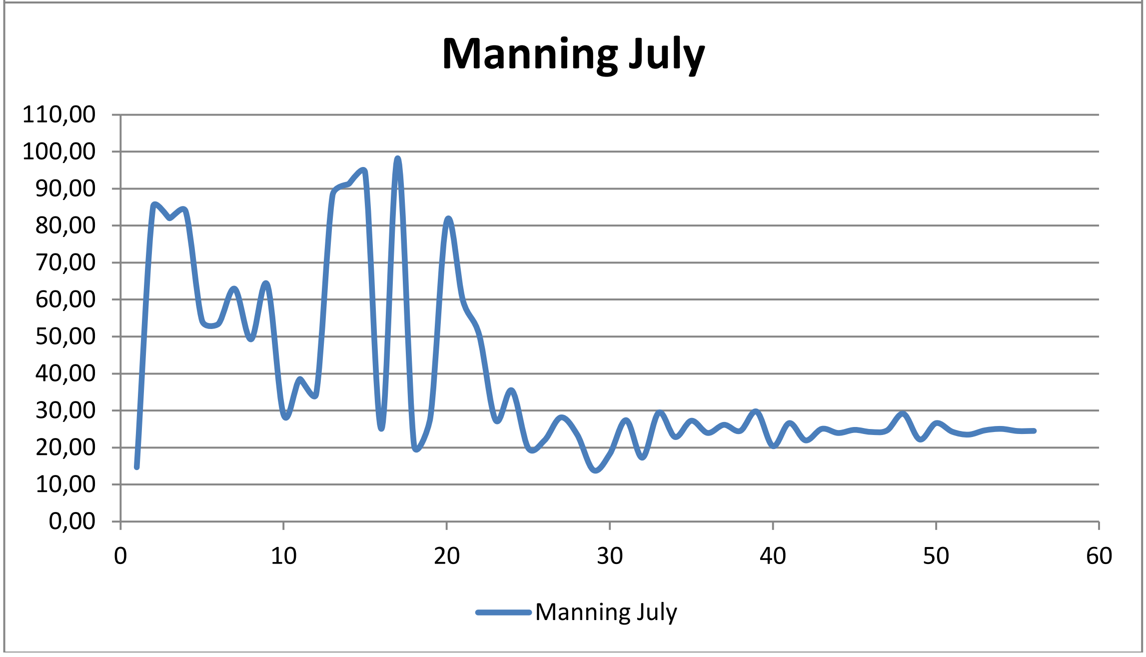
Parameter Optimisation October-January for a Manning Varying on time.



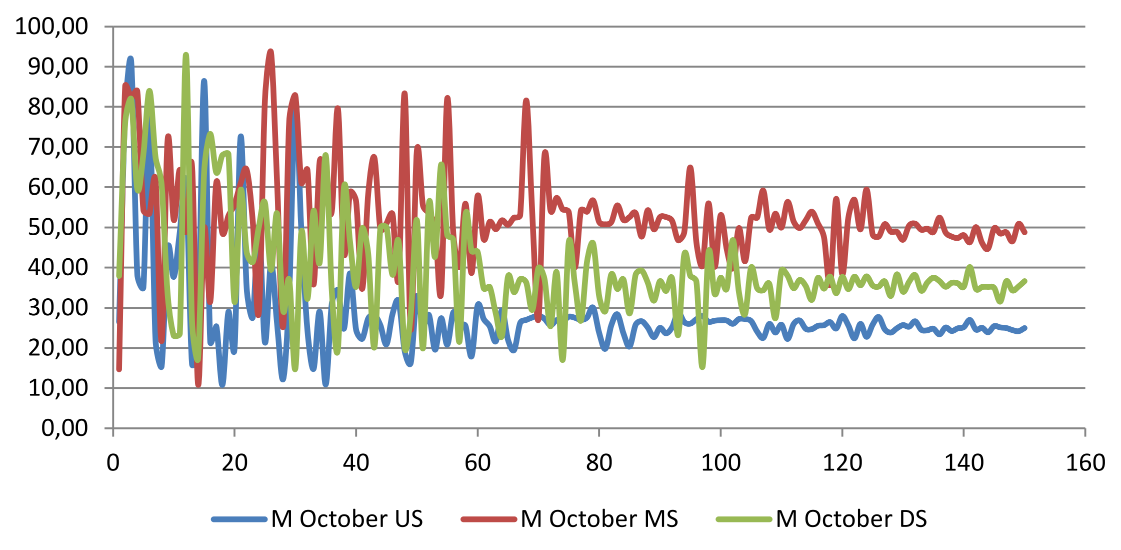


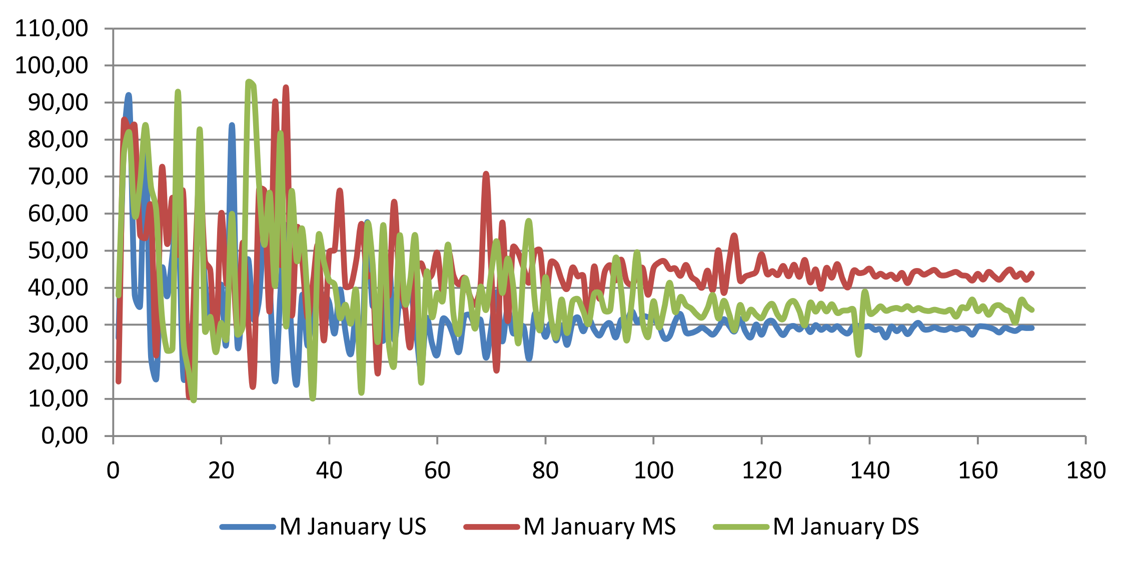
Parameter Optimisation April-July for a Manning Varying on time.



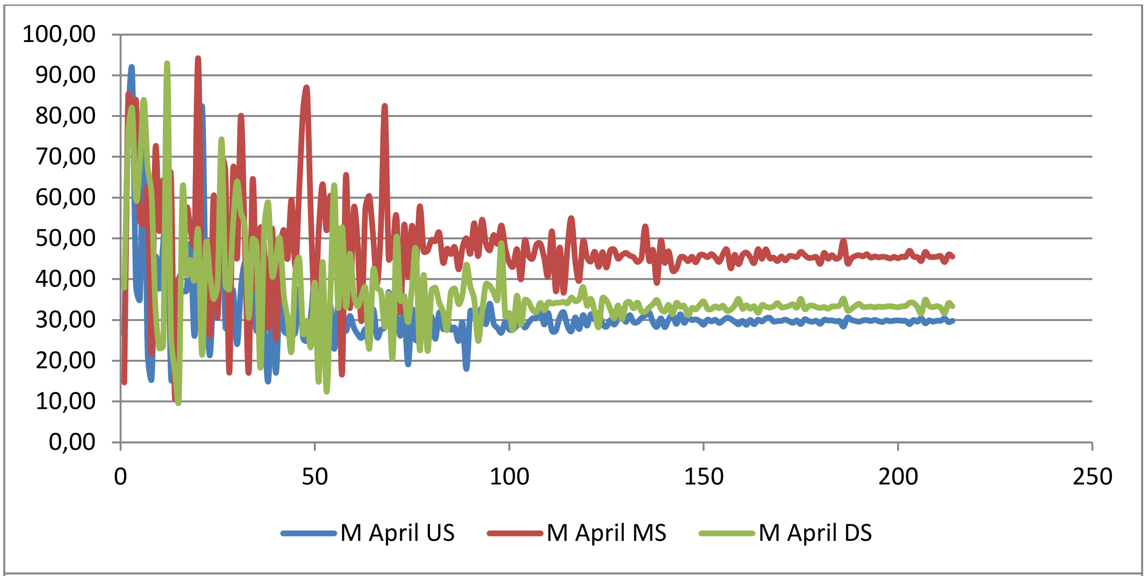


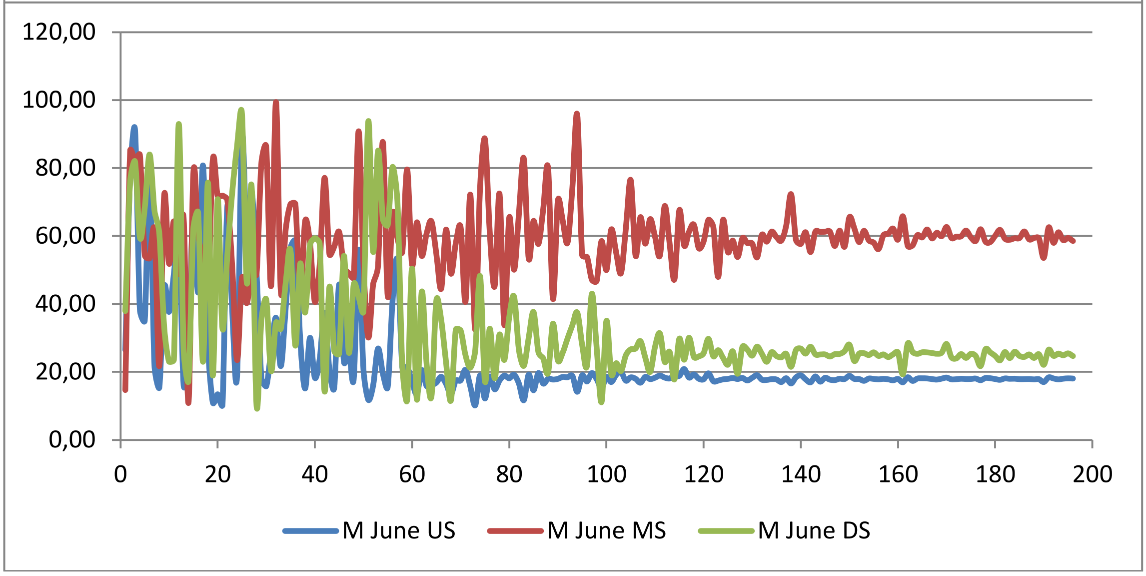
Parameter Optimisation October-January for a Manning Varying on time and length.





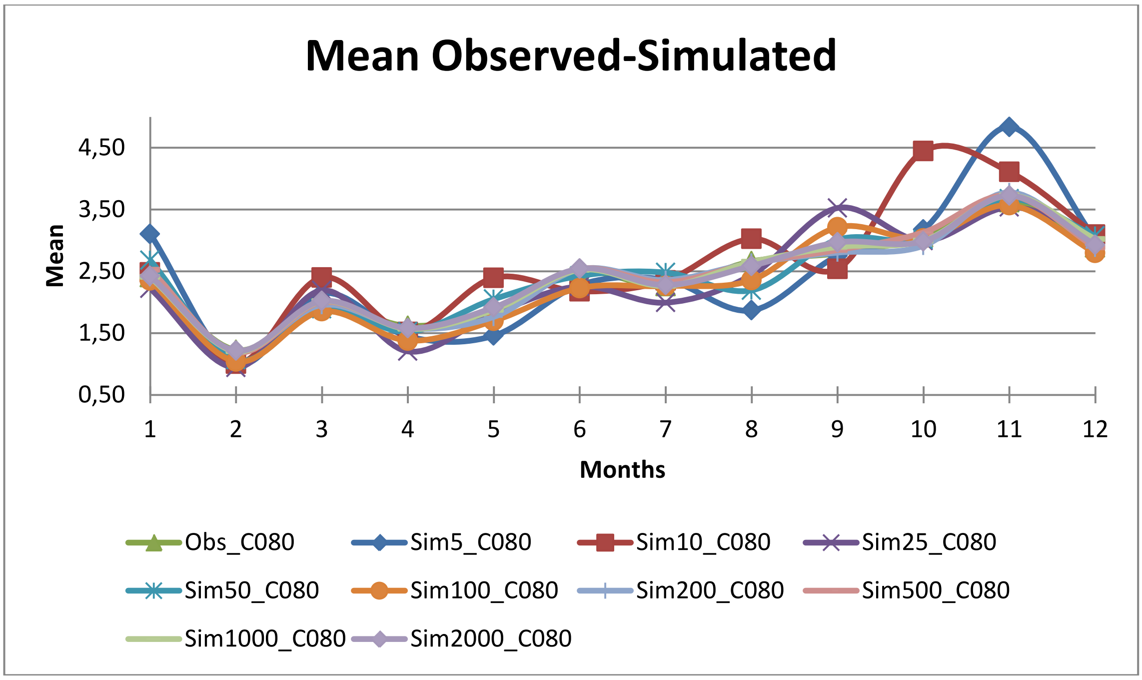
Parameter Optimisation April-July for a Manning Varying on time and length.

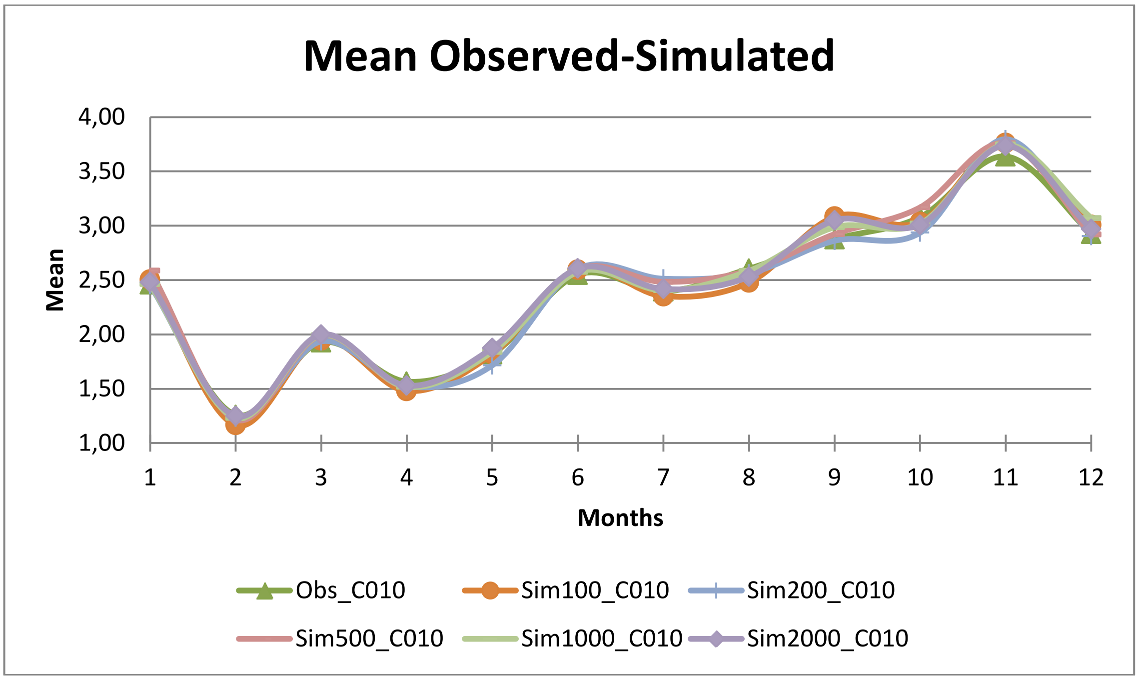




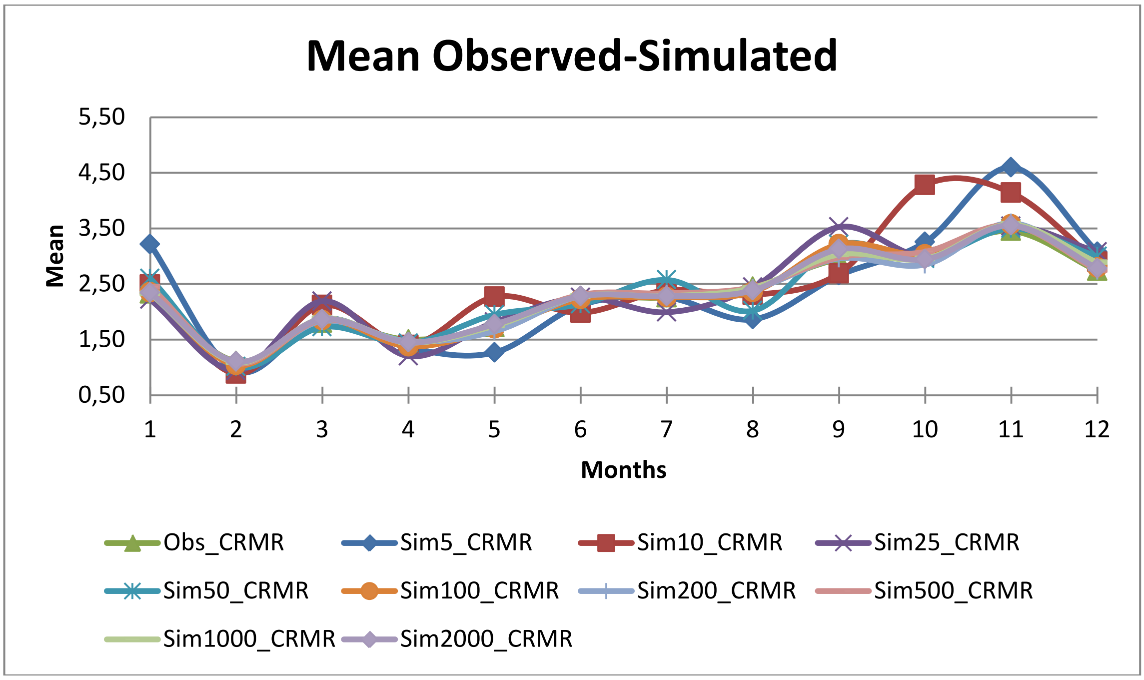
Appendix 4

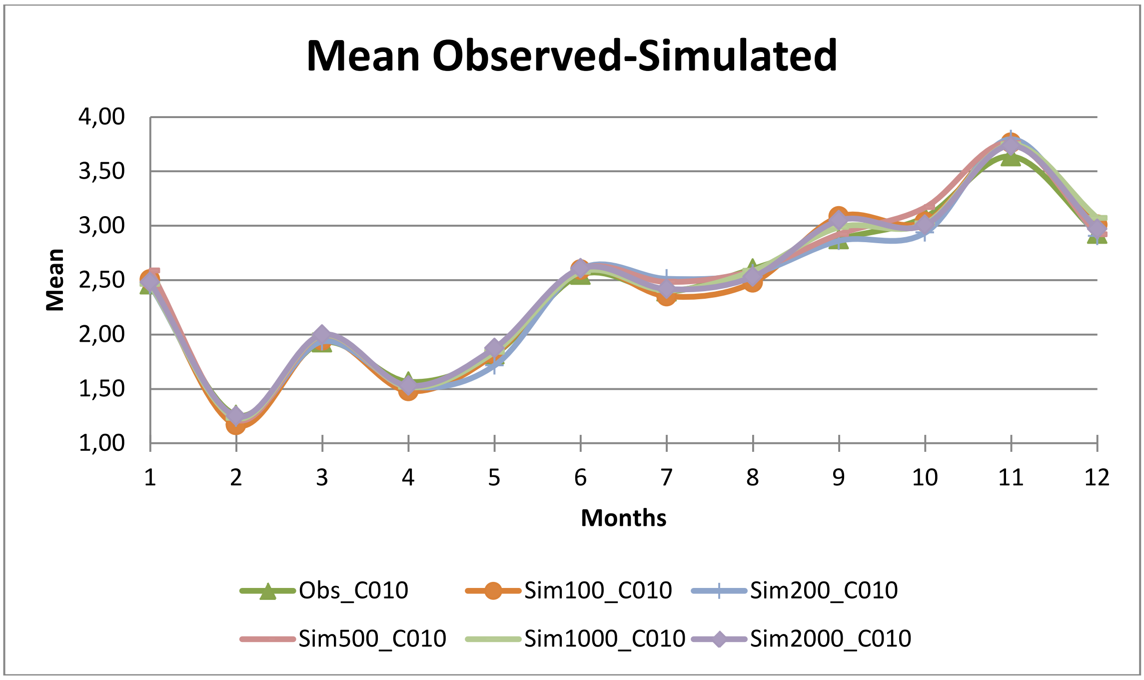
Mean precipitation at Gronaa head catchment station.



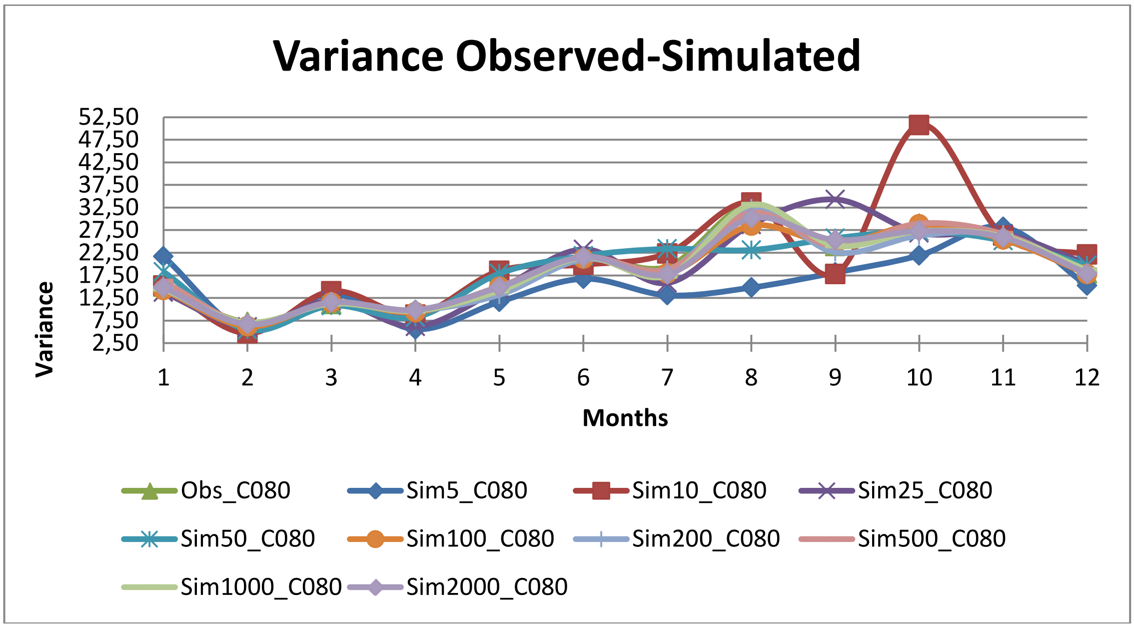


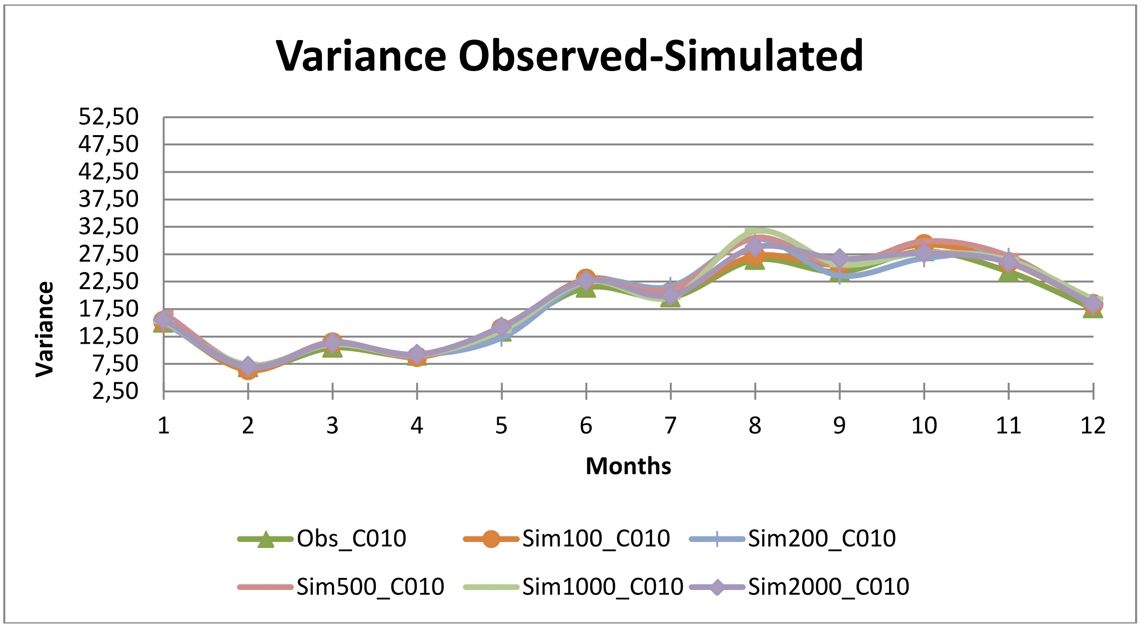
Mean precipitation at Høje station.



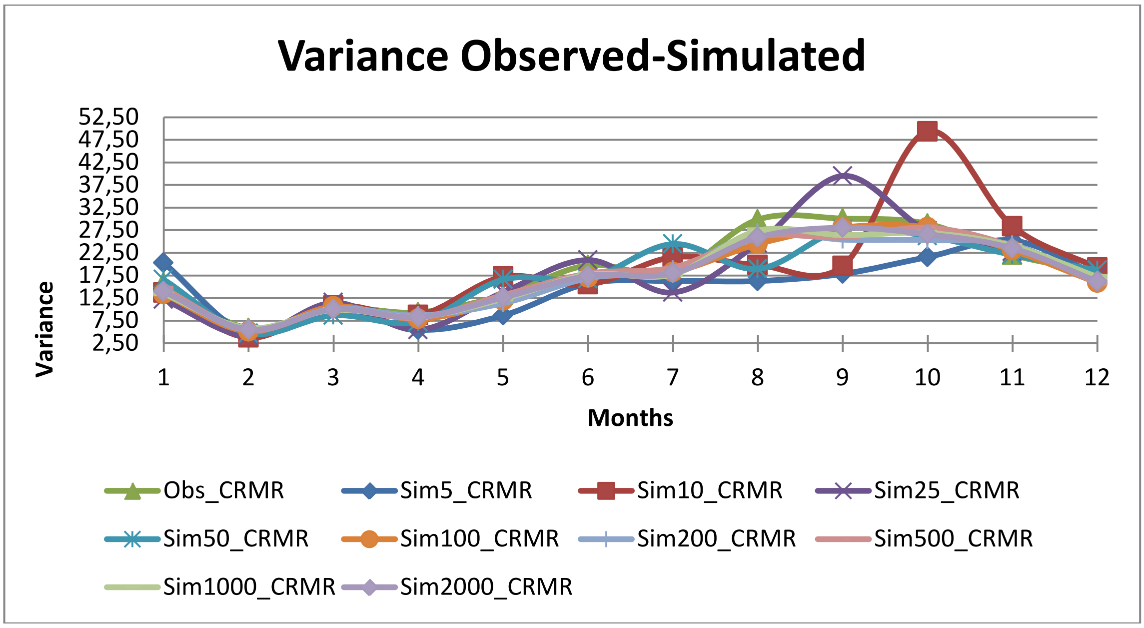


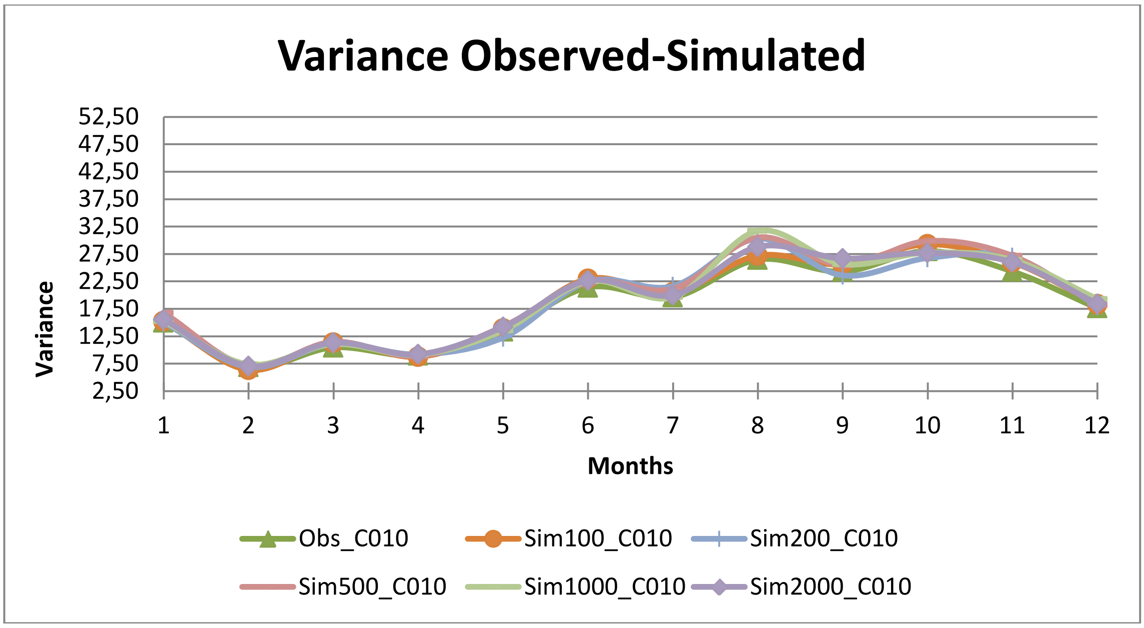
Variance at Gronaa head catchment station.



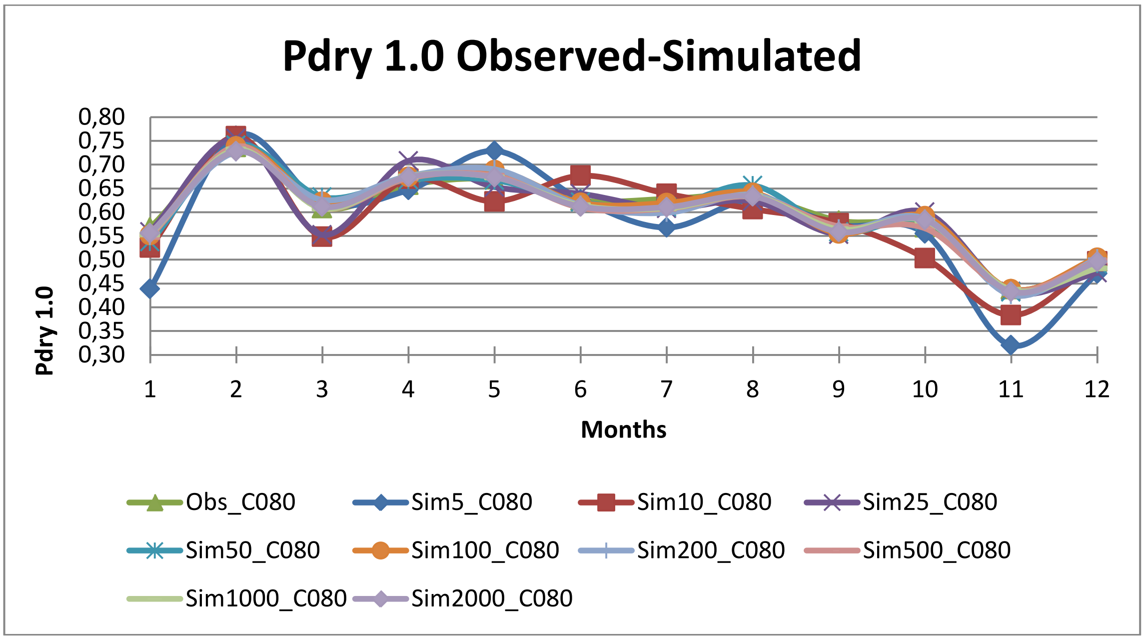


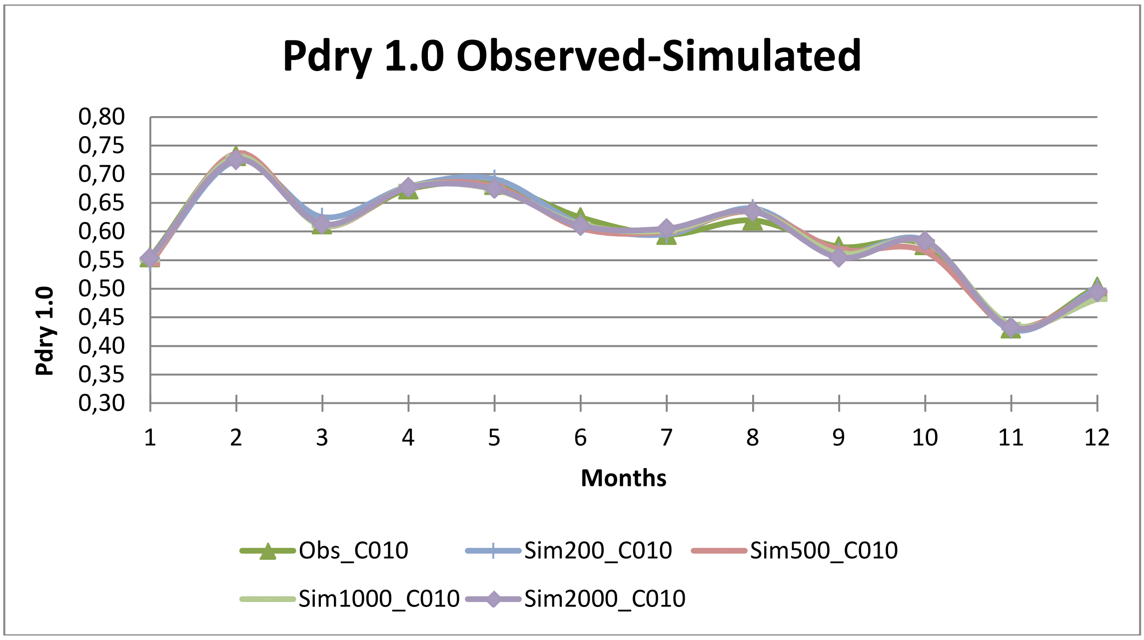
Variance at Høje station.



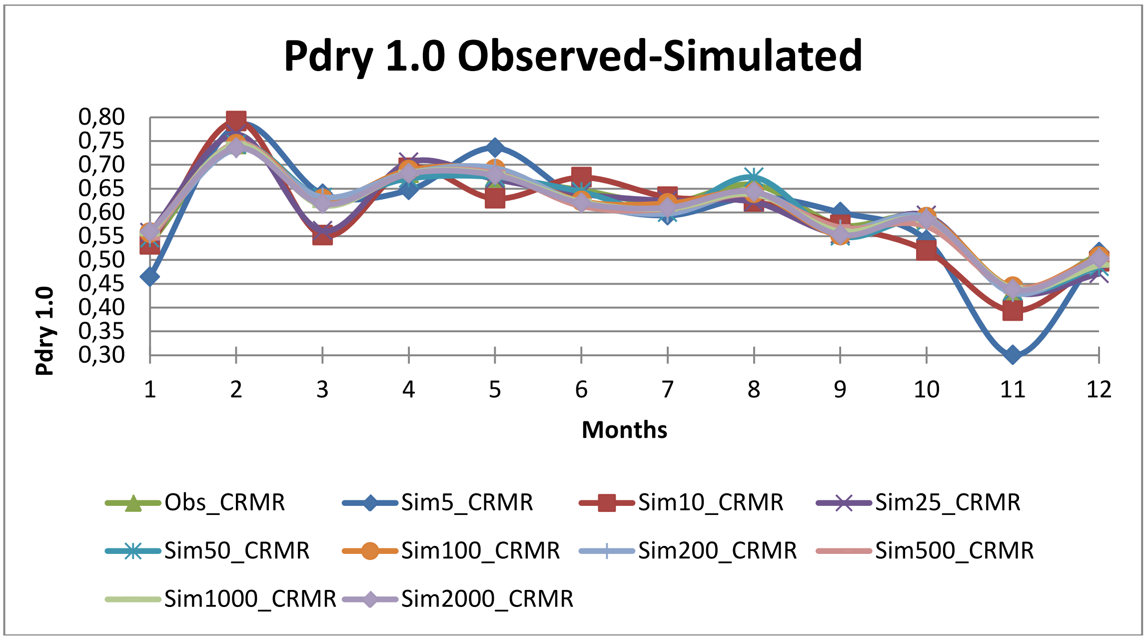


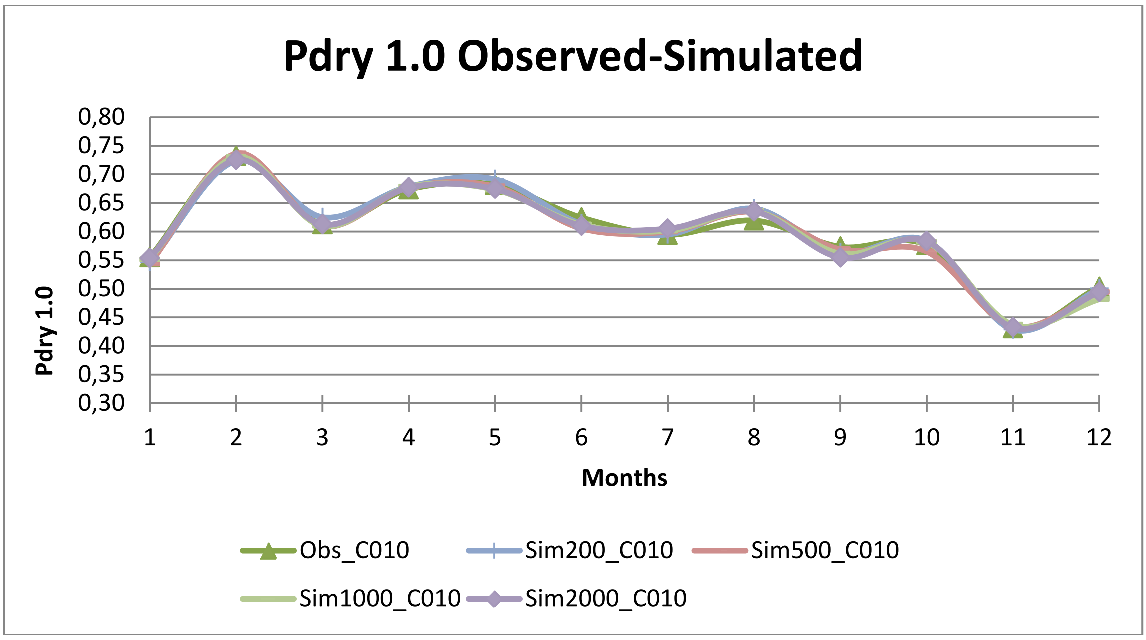
Probability of dry days at Gronaa head catchment station.



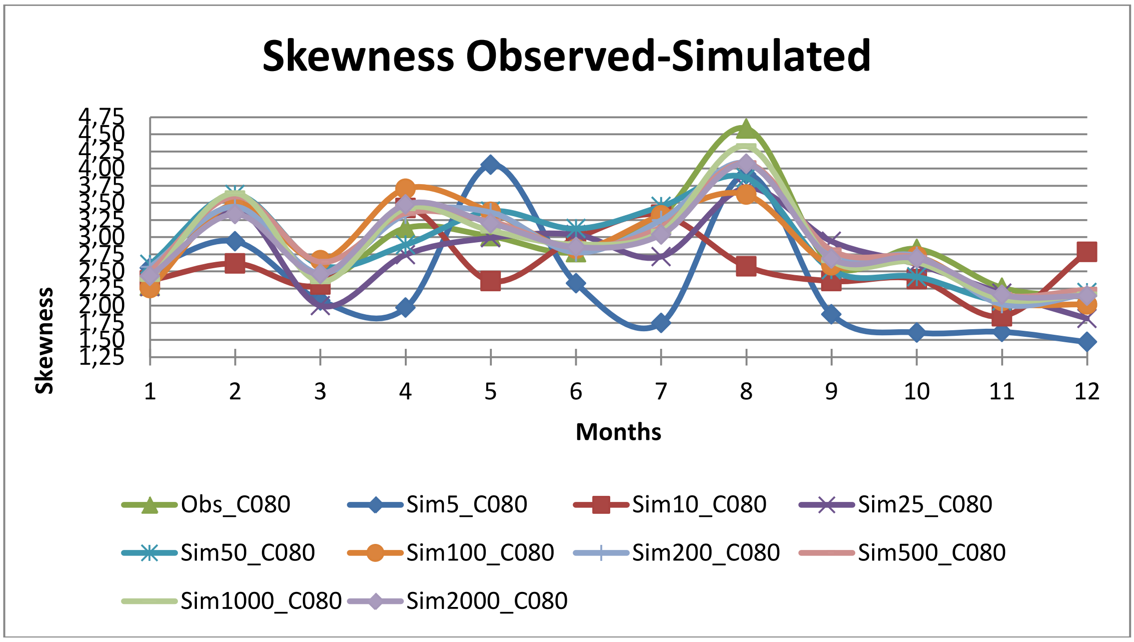


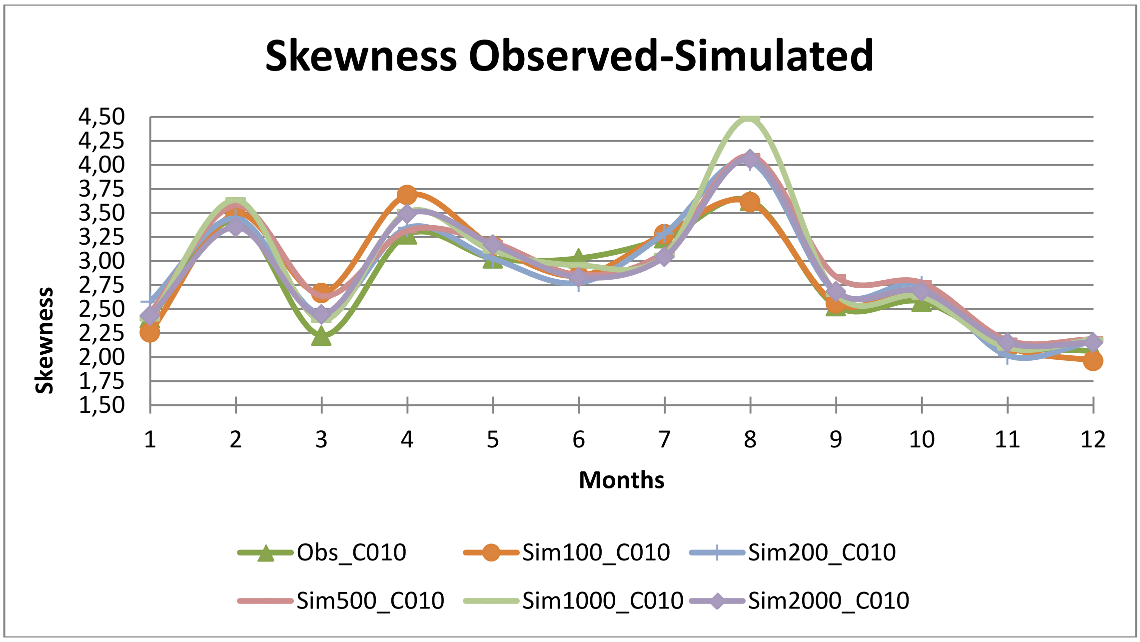
Probability of dry days at Høje station.



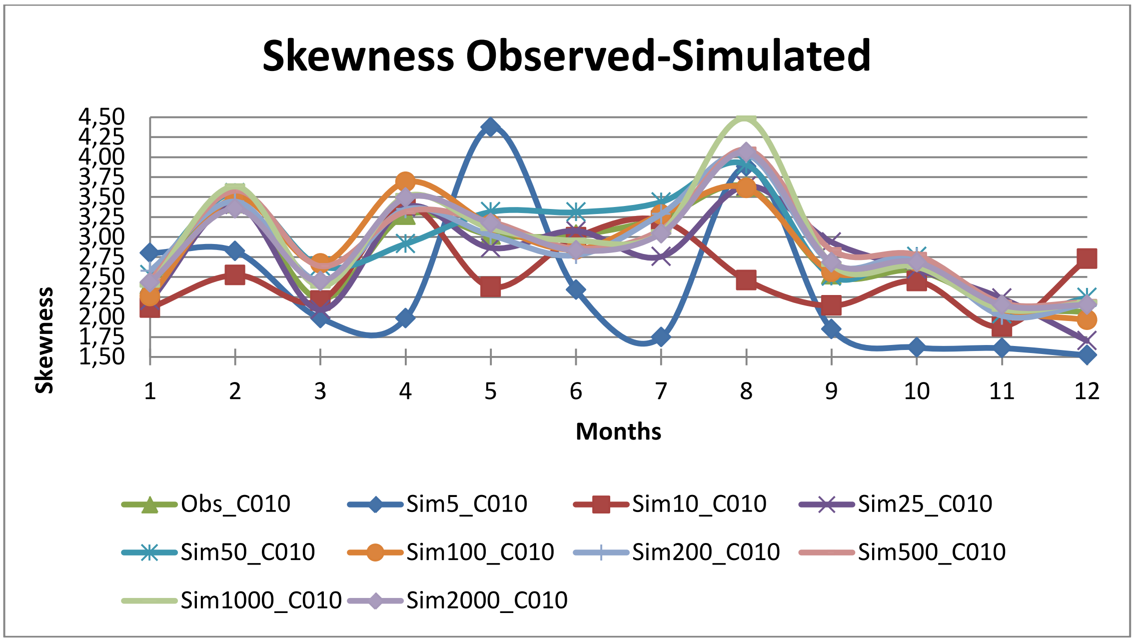


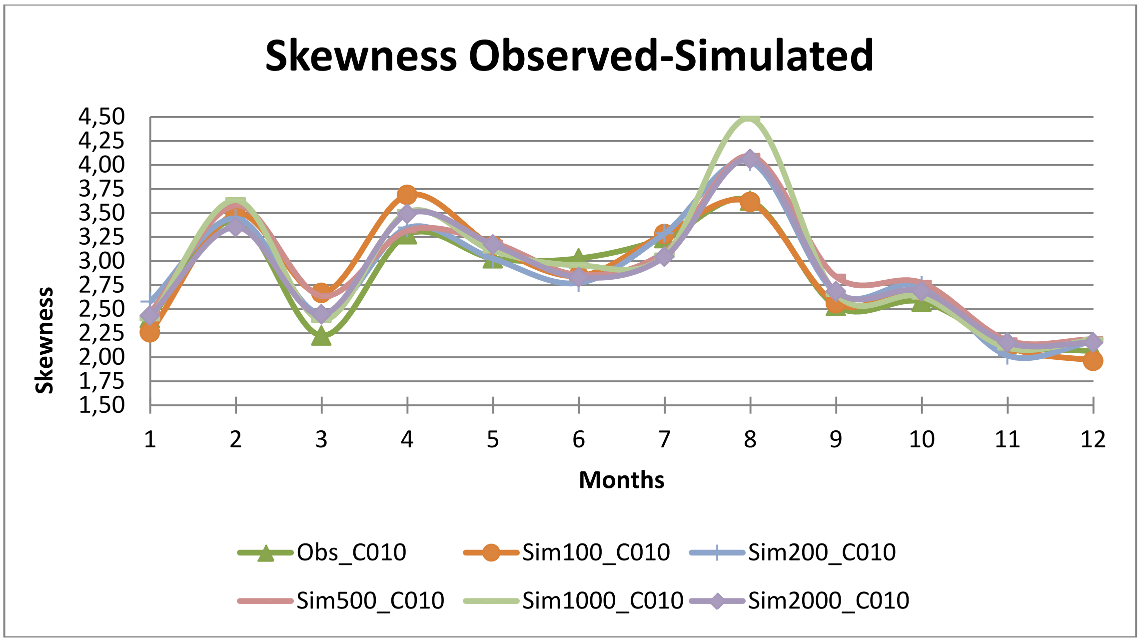
Skewness at Gronaa head catchment station.



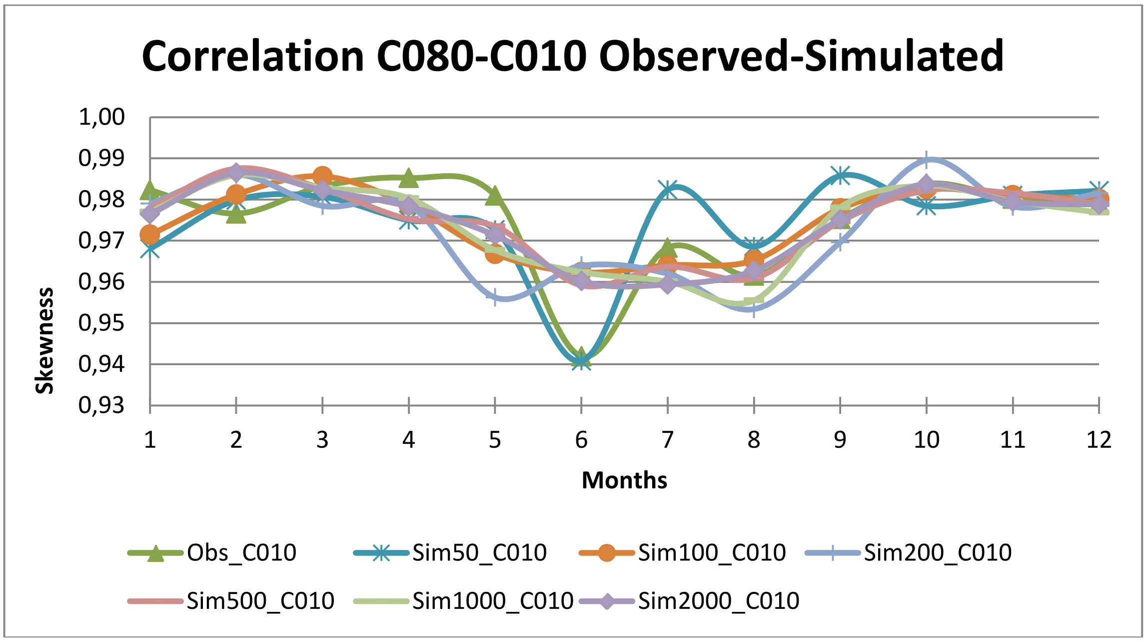


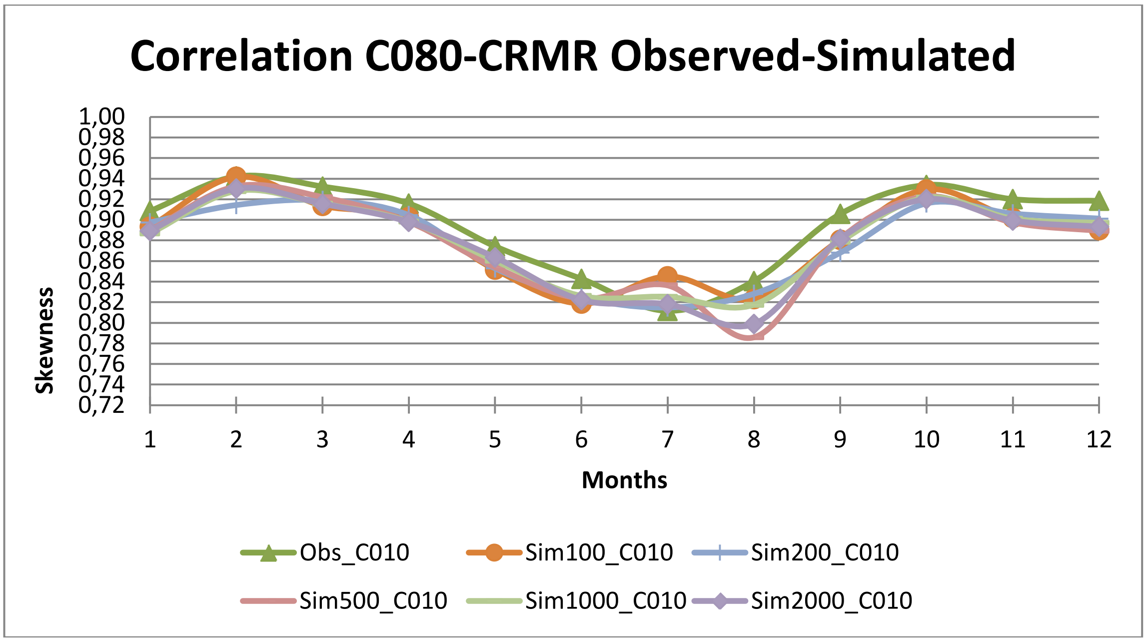
Skewness at Høje station.



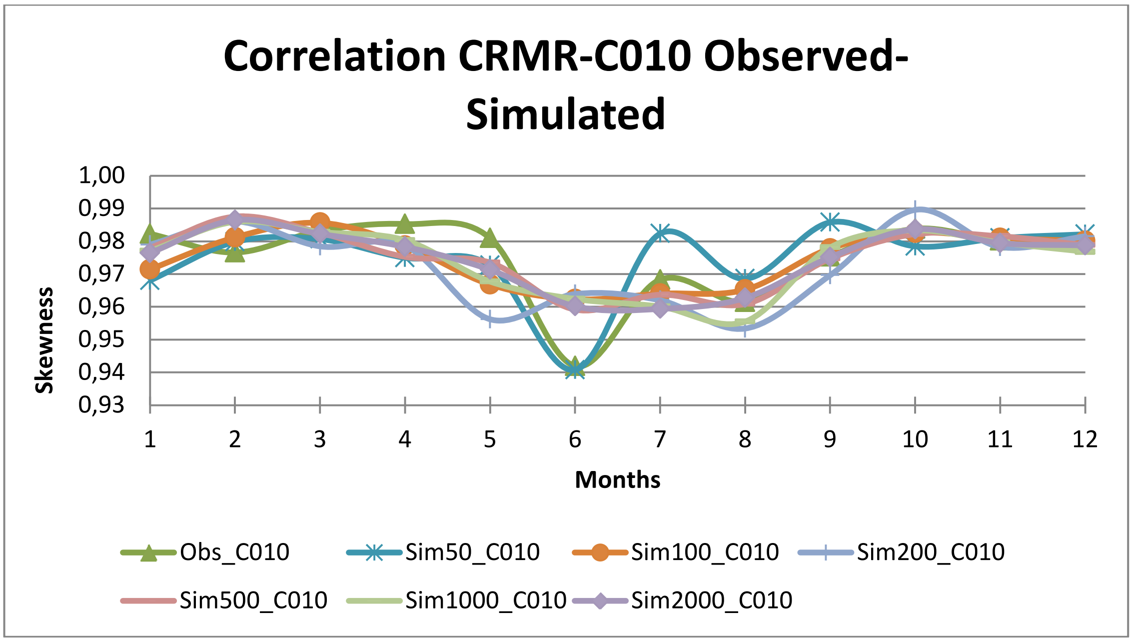


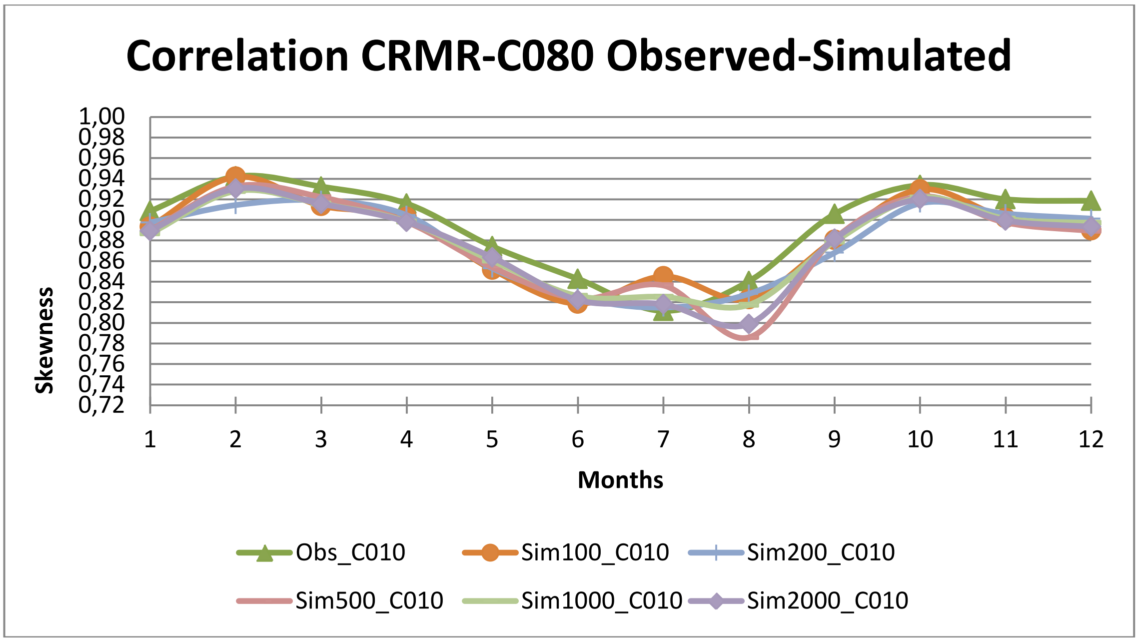
Autocorrelation lag-1 at Gronaa head catchment station.



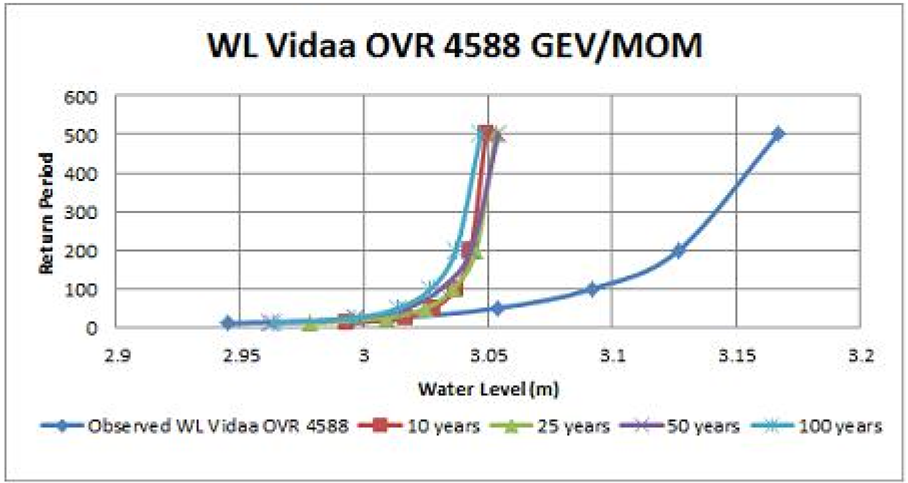


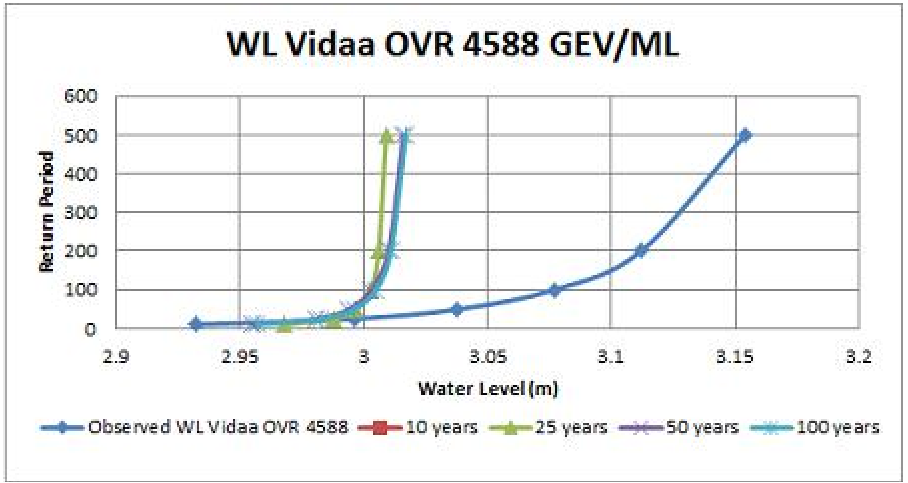
Autocorrelation lag-1 at Høje station.

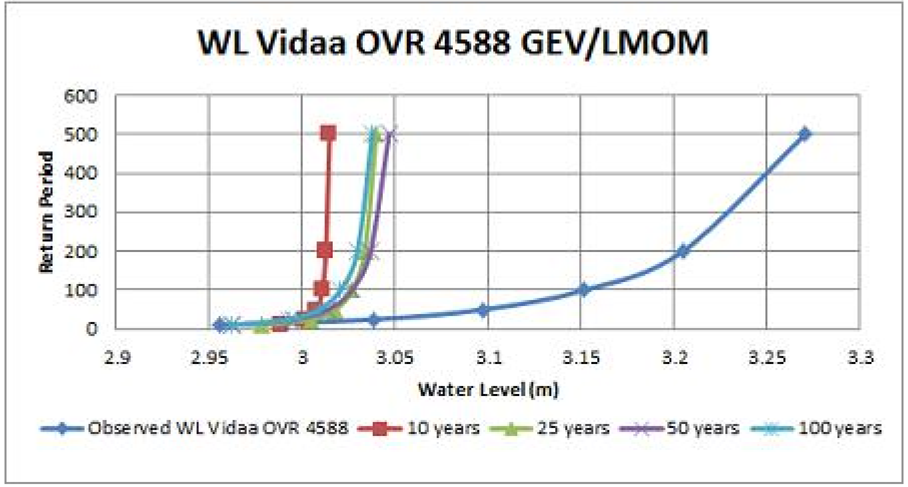


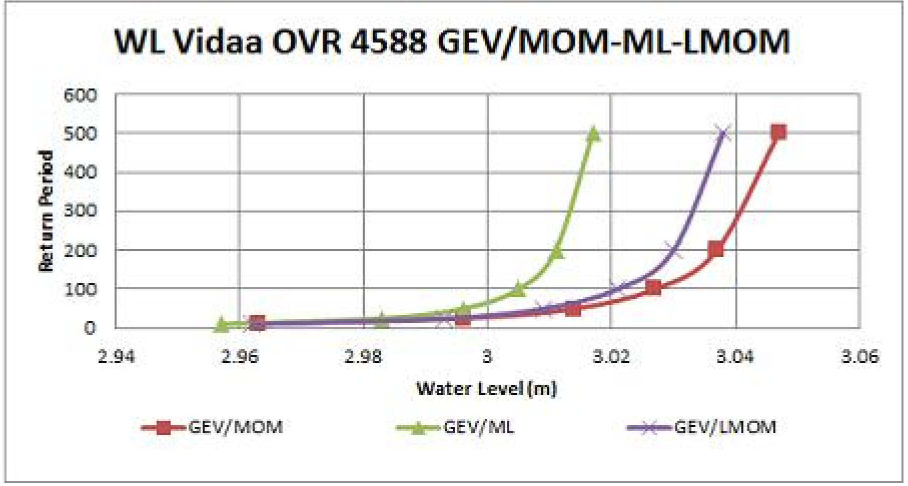


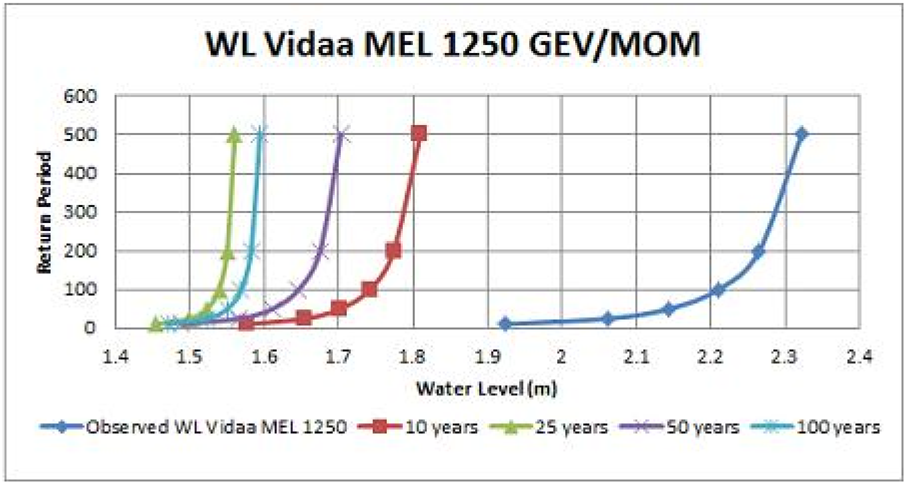
Appendix 5


WL Vidaa OVR 4588 GEV/MOM

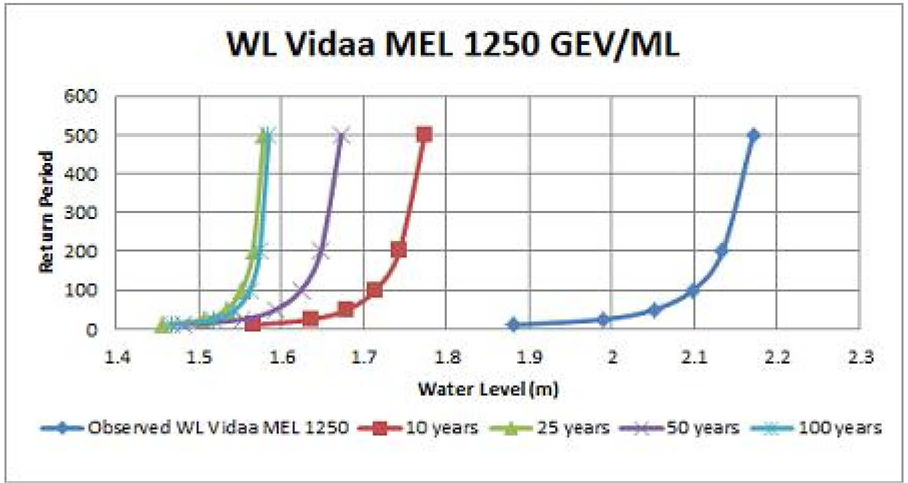

WL Vidaa OVR 4588 GEV/ML


WL Vidaa OVR 4588 GEV/LMOM

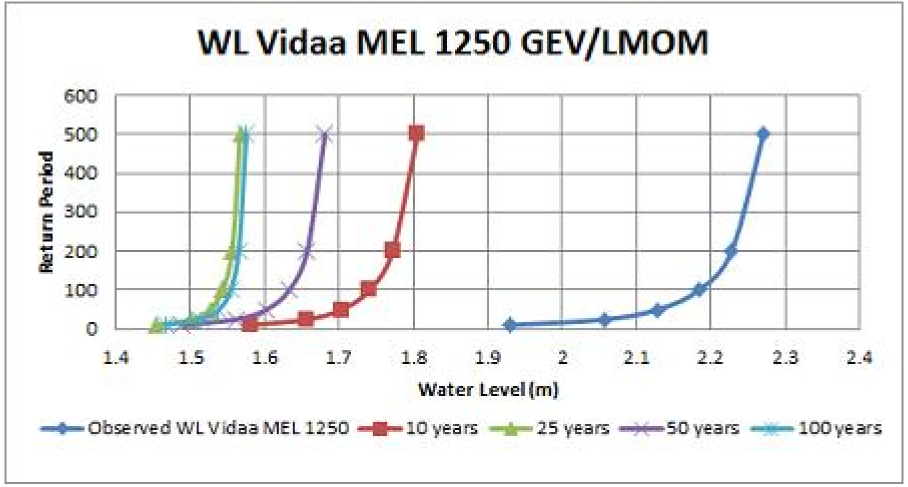

WL Vidaa OVR 4588 GEV/MOM-ML-LMOM



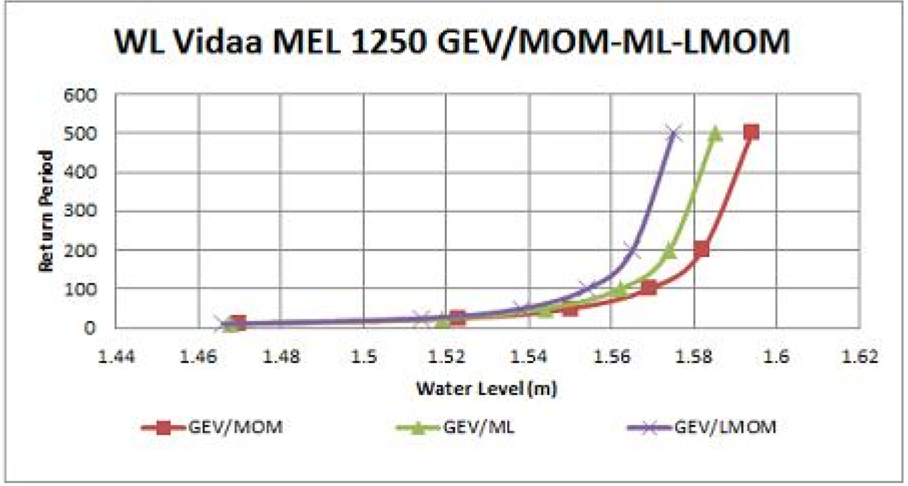
WL Vidaa MEL 1250 GEV/MOM



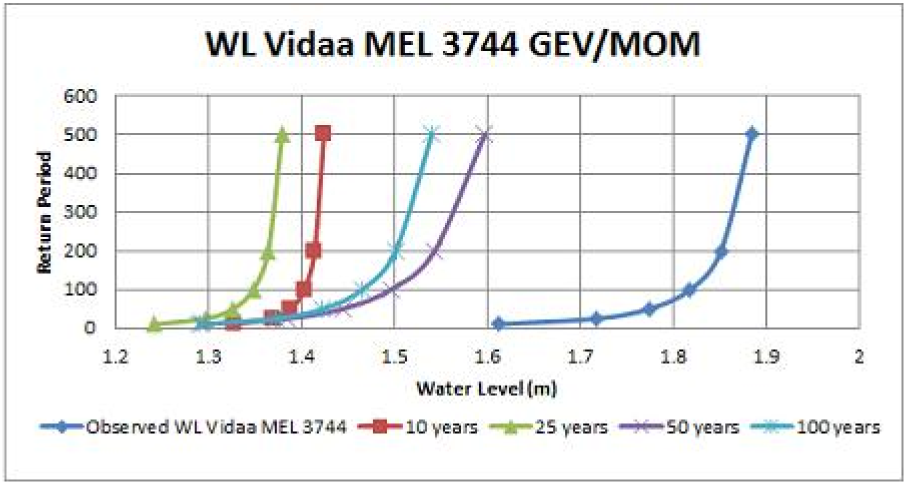
WL Vidaa MEL 1250 GEV/ML

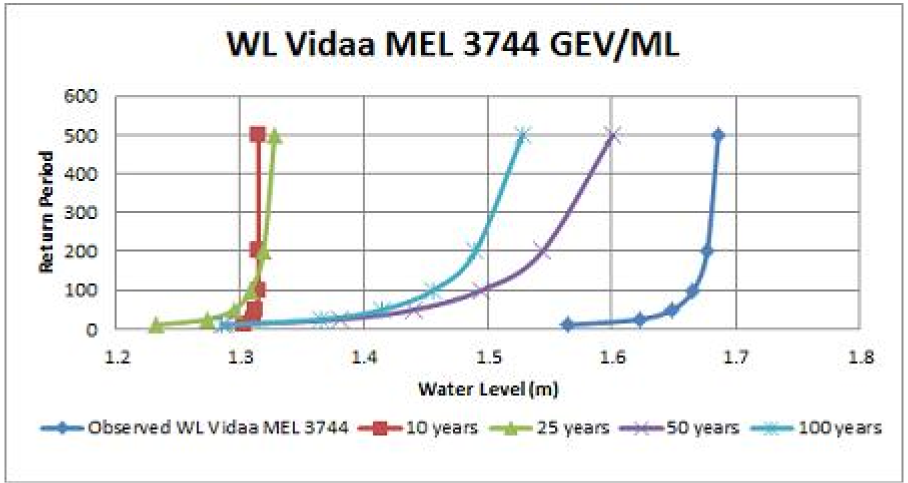


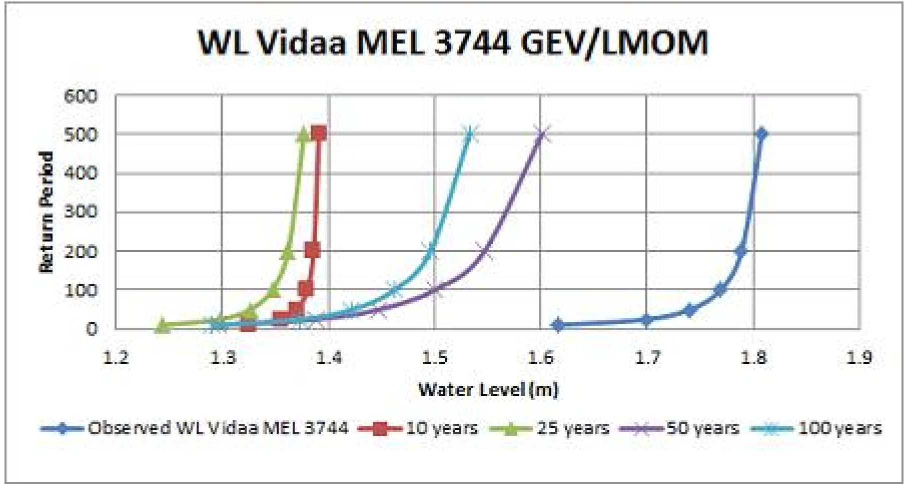
WL Vidaa MEL 1250 GEV/LMOM

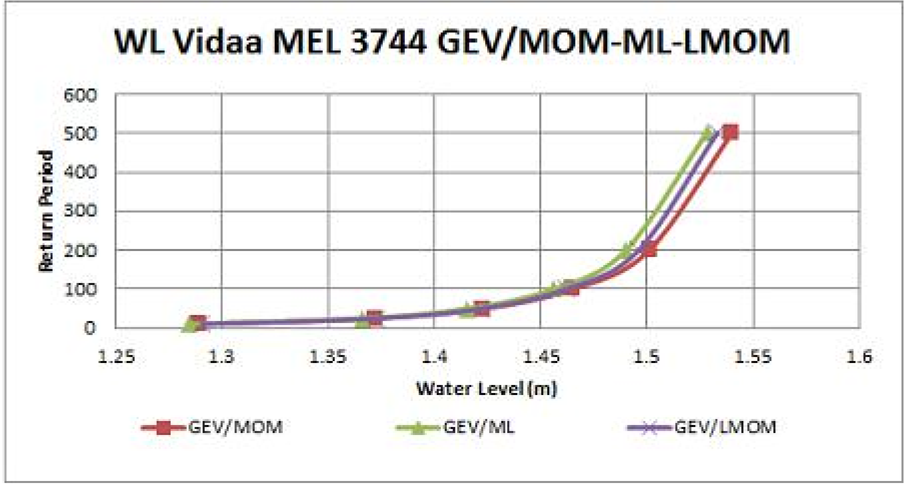


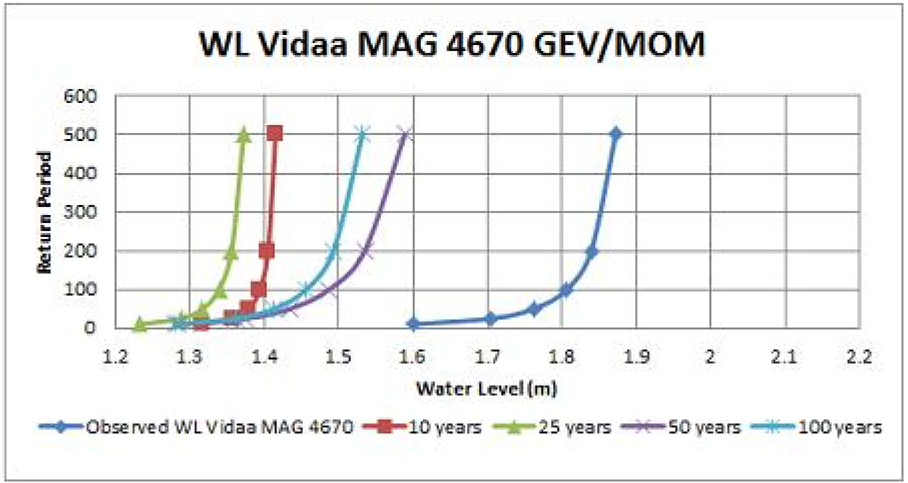
WL Vidaa MEL 1250 GEV/MOM-ML-LMOM

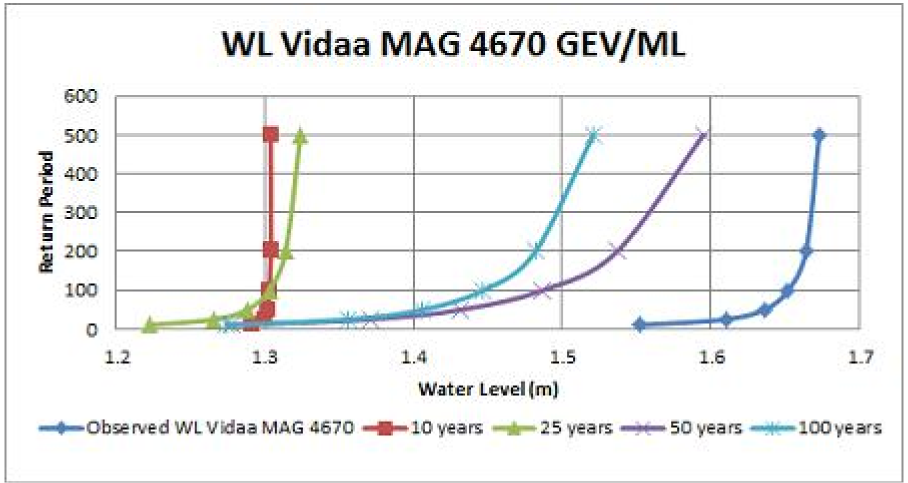

WL Vidaa MEL 3744 GEV/MOM
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
Water Level (m)
Observed WL Vidaa MEL 3744
10 years
25 years
50 years
100 years

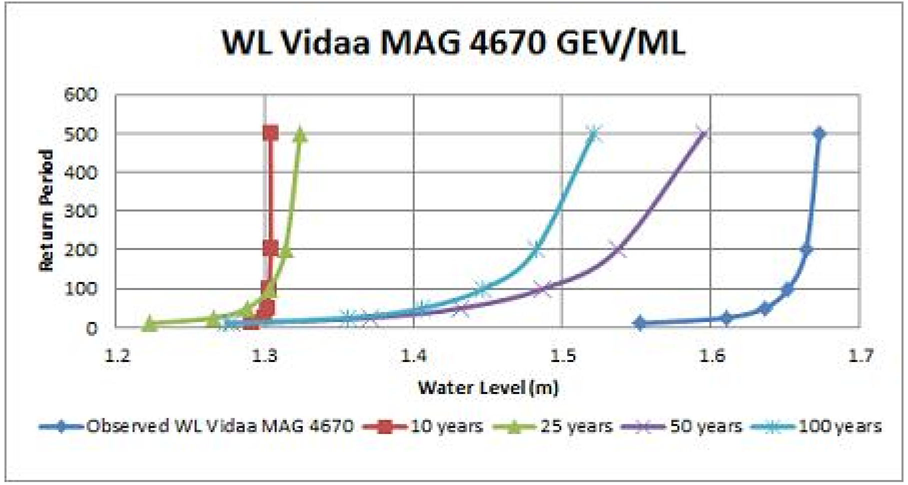

WL Vidaa MEL 3744 GEV/ML
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Water Level (m)
Observed WL Vidaa MEL 3744
10 years
25 years
50 years
100 years

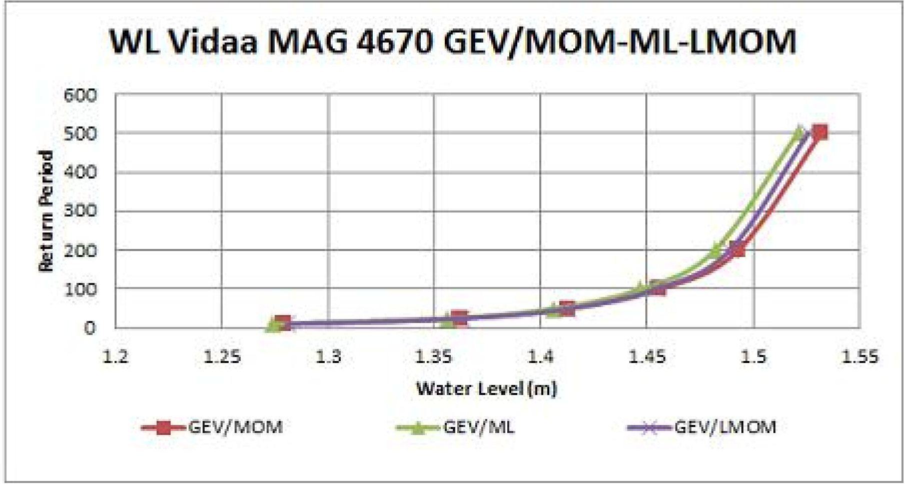

WL Vidaa MEL 3744 GEV/LMOM
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
Water Level (m)
Observed WL Vidaa MEL 3744
10 years
25 years
50 years
100 years

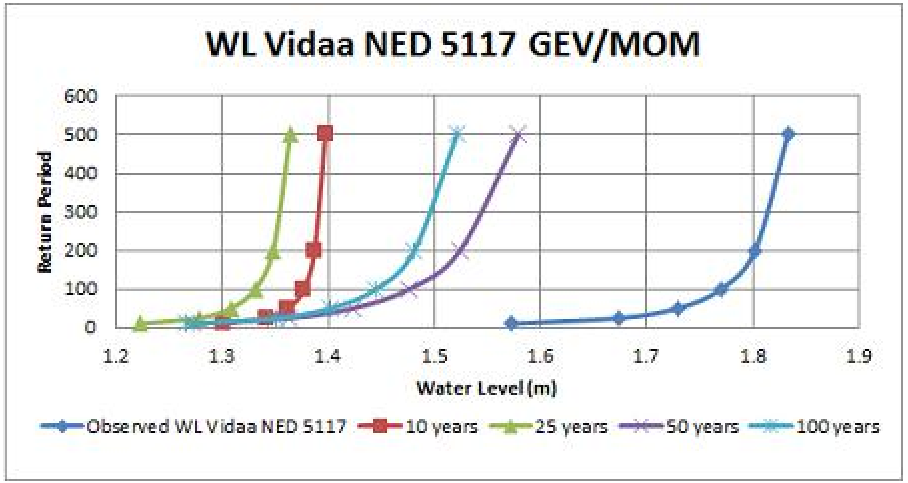

WL Vidaa MEL 3744 GEV/MOM-ML-LMOM
Return Period
600
500
400
300
200
100
0
1.25
1.3
1.35
1.4
1.45
1.5
1.55
1.6
Water Level (m)
GEV/MOM
GEV/ML
GEV/LMOM

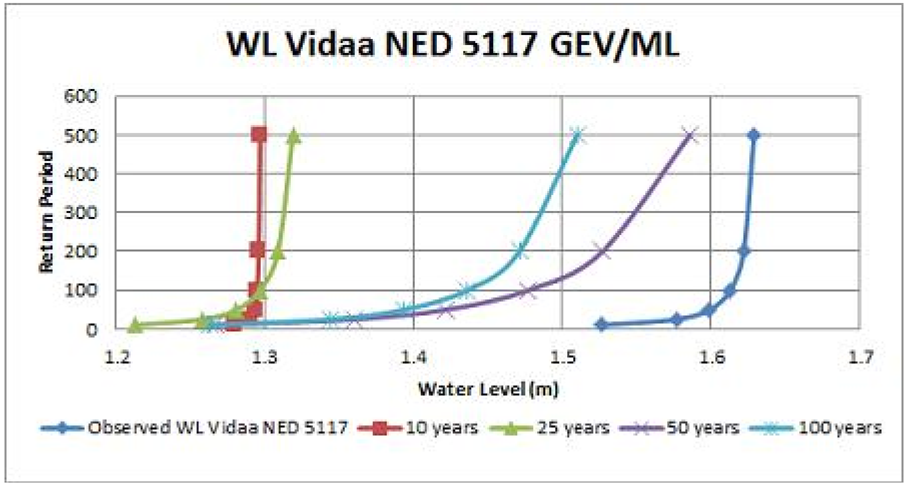

WL Vidaa MAG 4670 GEV/MOM
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
2.2
Water Level (m)
Observed WL Vidaa MAG 4670
10 years
25 years
50 years
100 years

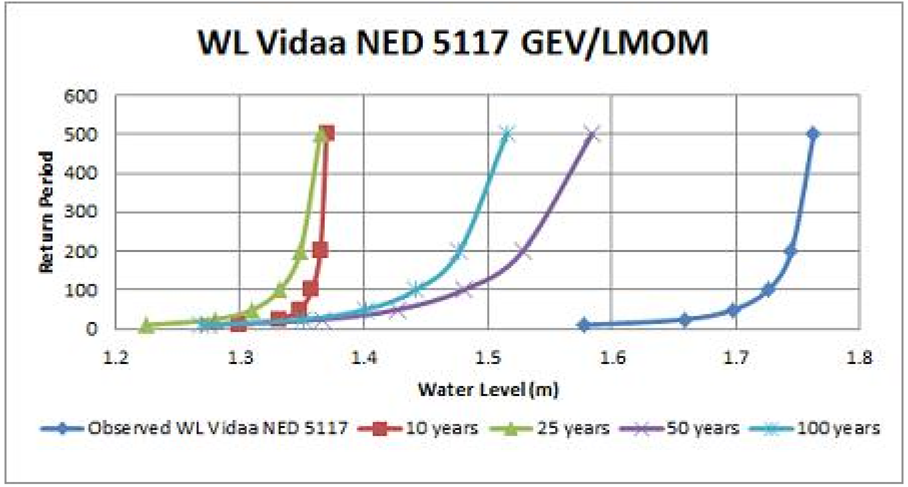

WL Vidaa MAG 4670 GEV/ML
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
Water Level (m)
Observed WL Vidaa MAG 4670
10 years
25 years
50 years
100 years

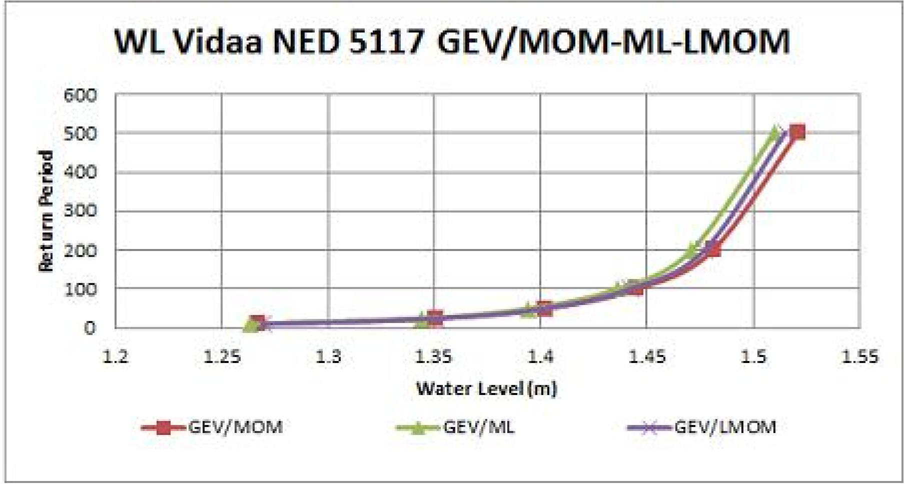

WL Vidaa MAG 4670 GEV/ML
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
Water Level (m)
Observed WL Vidaa MAG 4670
10 years
25 years
50 years
100 years

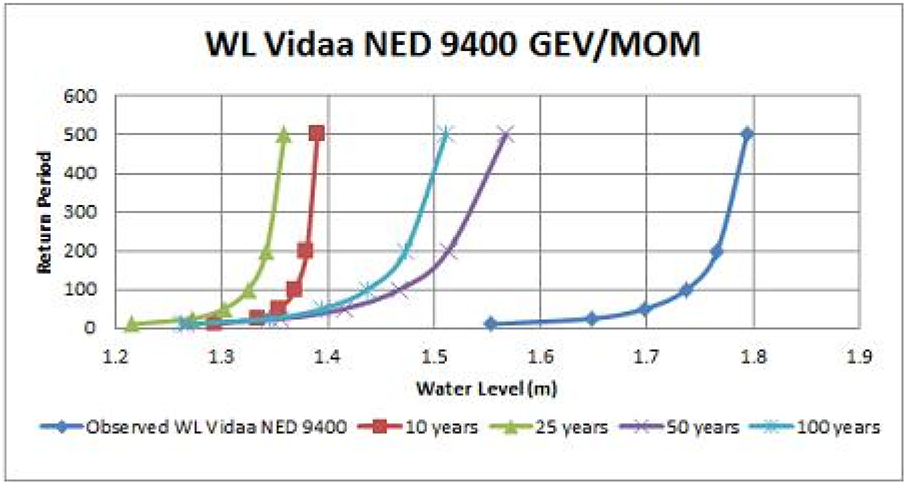

WL Vidaa MAG 4670 GEV/MOM-ML-LMOM
Return Period
600
500
400
300
200
100
0
1.2
1.25
1.3
1.35
1.4
1.45
1.5
1.55
Water Level (m)
GEV/MOM
GEV/ML
GEV/LMOM


WL Vidaa NED 5117 GEV/MOM
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
Water Level (m)
Observed WL Vidaa NED 5117
10 years
25 years
50 years
100 years

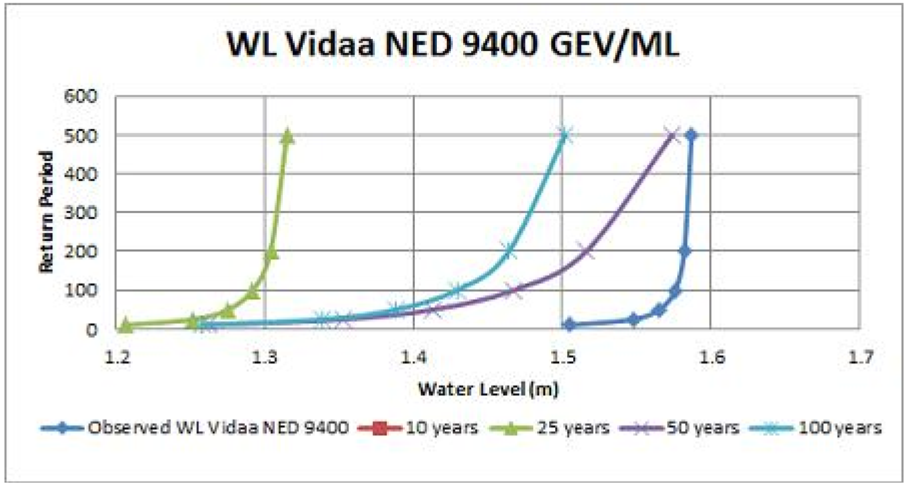

WL Vidaa NED 5117 GEV/ML
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
Water Level (m)
Observed WL Vidaa NED 5117
10 years
25 years
50 years
100 years


WL Vidaa NED 5117 GEV/LMOM
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Water Level (m)
Observed WL Vidaa NED 5117
10 years
25 years
50 years
100 years

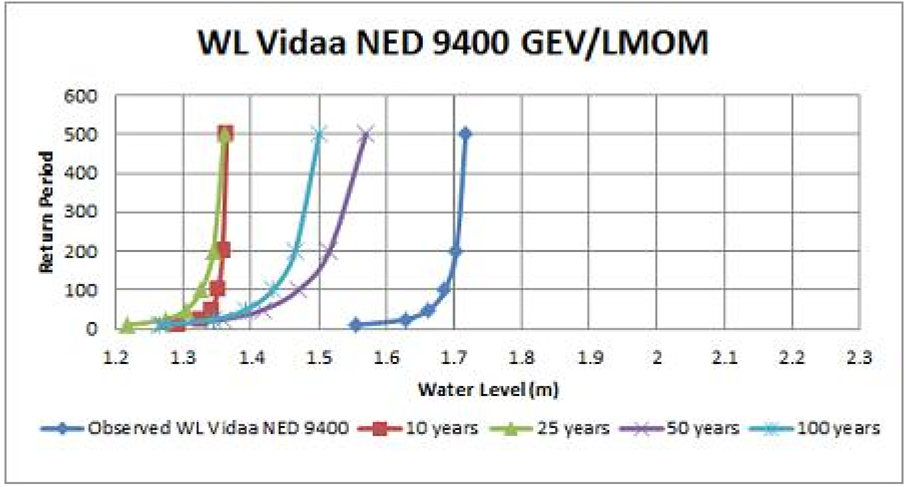

WL Vidaa NED 5117 GEV/MOM-ML-LMOM
Return Period
600
500
400
300
200
100
0
1.2
1.25
1.3
1.35
1.4
1.45
1.5
1.55
Water Level (m)
GEV/MOM
GEV/ML
GEV/LMOM



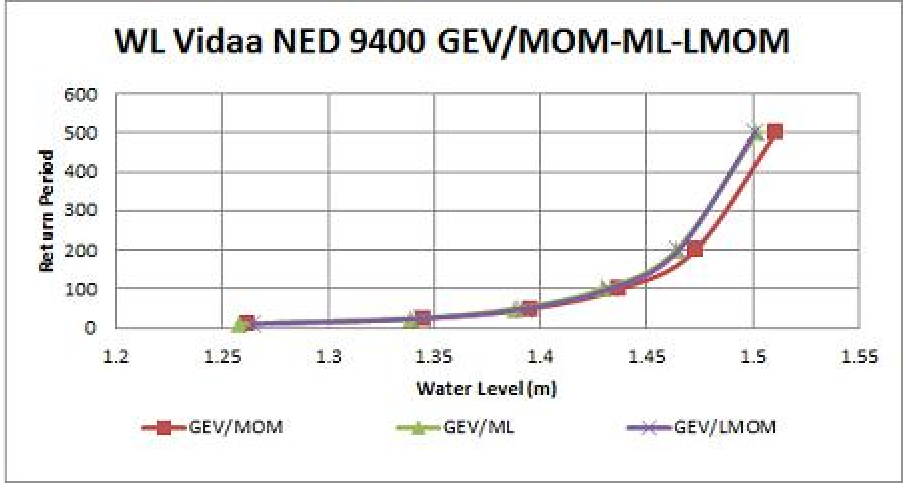
WL Vidaa NED 9400 GEV/MOM



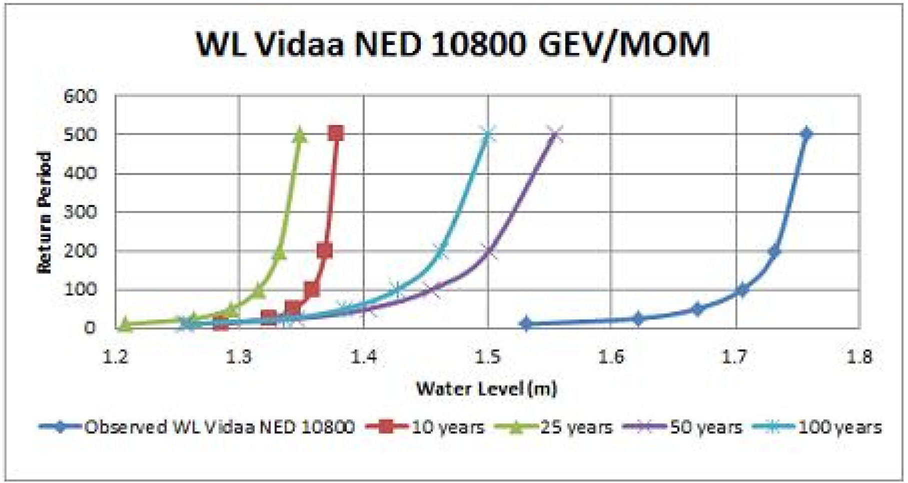
WL Vidaa NED 9400 GEV/ML

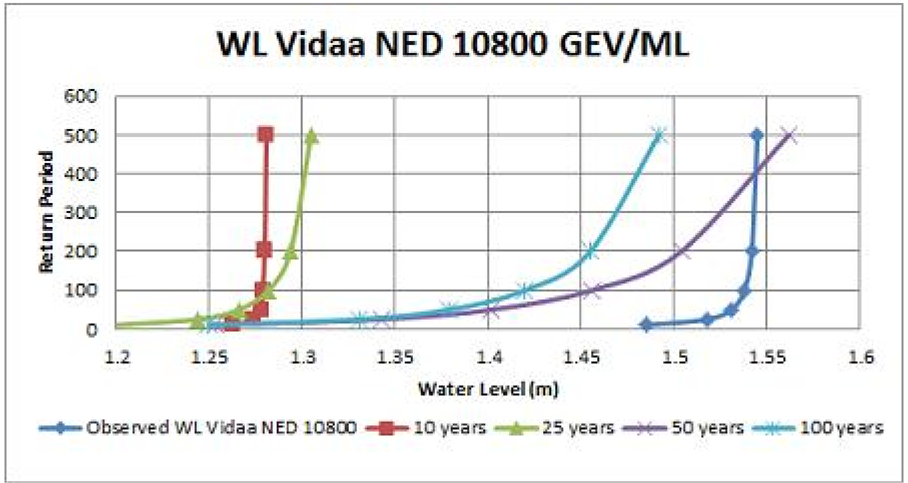


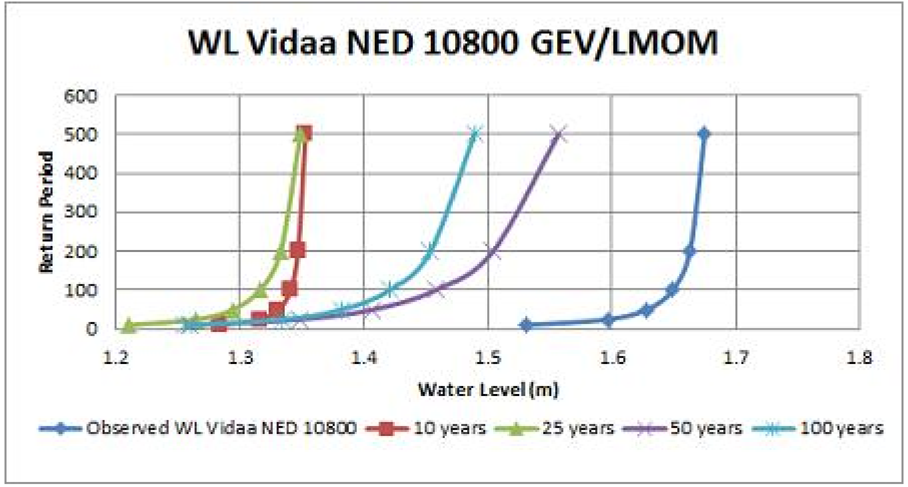
WL Vidaa NED 9400 GEV/LMOM

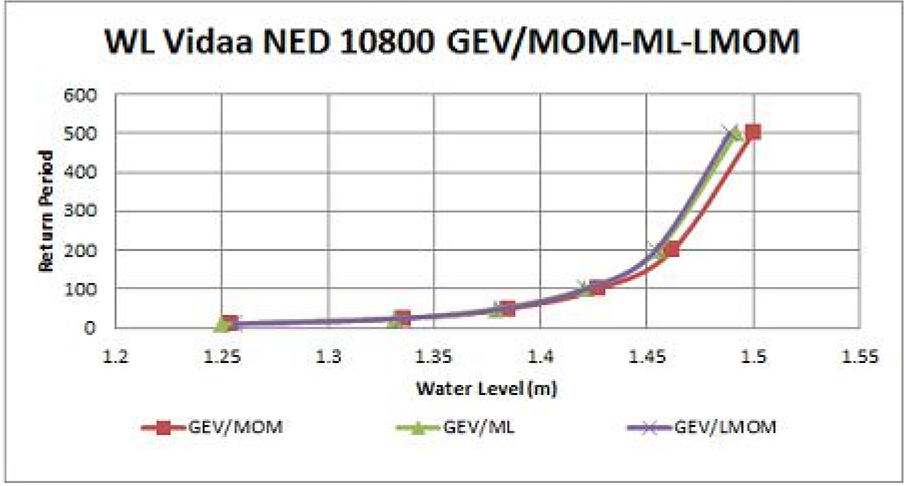


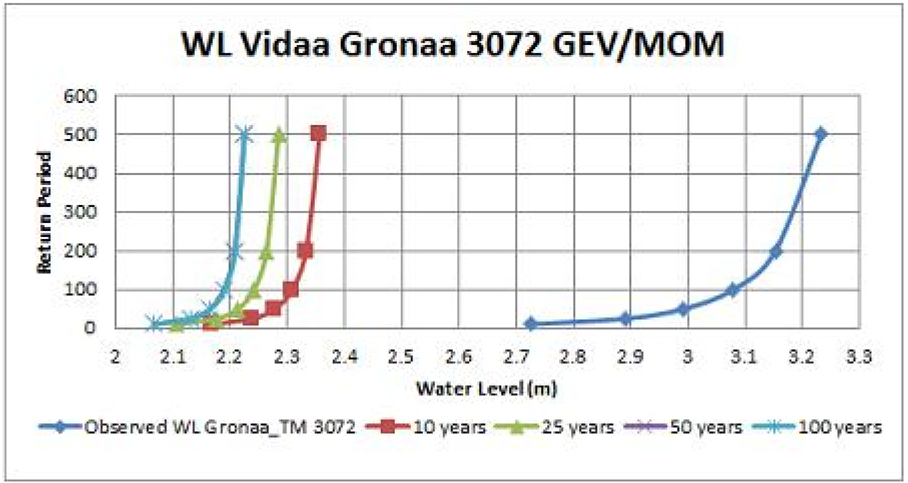
WL Vidaa NED 9400 GEV/MOM-ML-LMOM

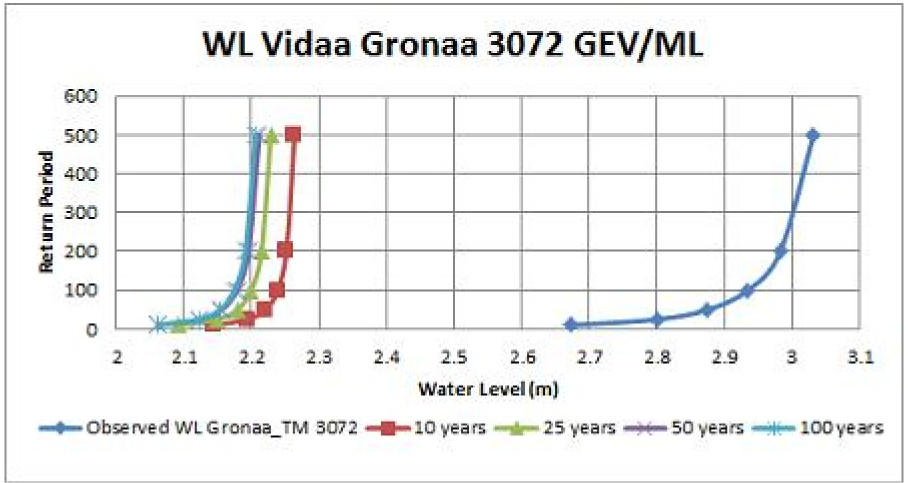

WL Vidaa NED 10800 GEV/MOM
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Water Level (m)
Observed WL Vidaa NED 10800
10 years
25 years
50 years
100 years

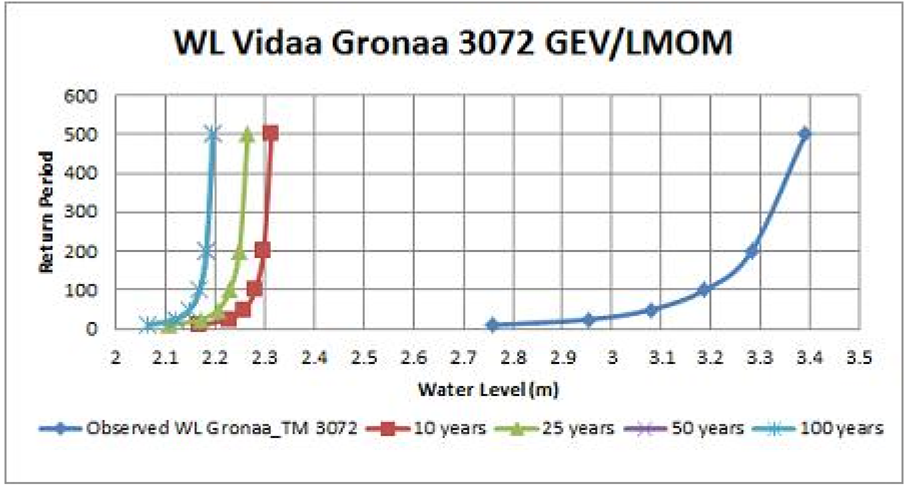

WL Vidaa NED 10800 GEV/ML
Return Period
600
500
400
300
200
100
0
1.2
1.25
1.3
1.35
1.4
1.45
1.5
1.55
1.6
Water Level (m)
Observed WL Vidaa NED 10800
10 years
25 years
50 years
100 years

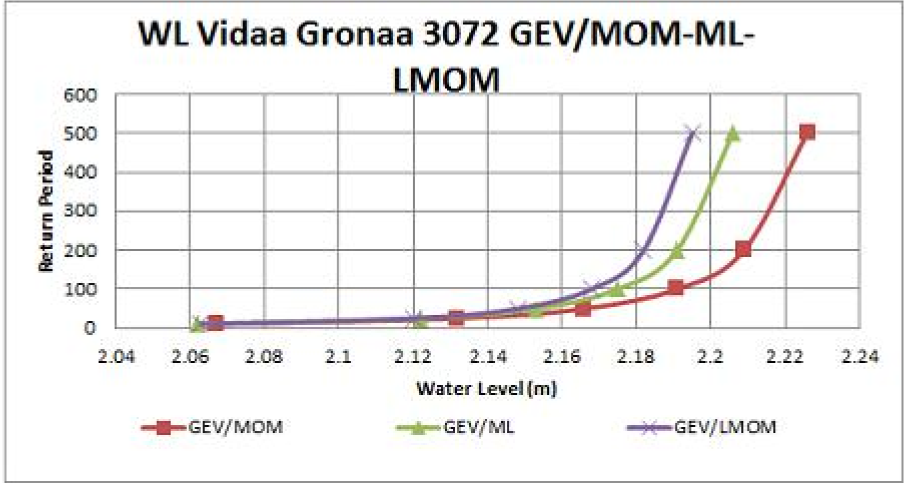

WL Vidaa NED 10800 GEV/LMOM
Return Period
600
500
400
300
200
100
0
1.2
1.3
1.4
1.5
1.6
1.7
1.8
Water Level (m)
Observed WL Vidaa NED 10800
10 years
25 years
50 years
100 years


WL Vidaa NED 10800 GEV/MOM-ML-LMOM
Return Period
600
500
400
300
200
100
0
1.2
1.25
1.3
1.35
1.4
1.45
1.5
1.55
Water Level (m)
GEV/MOM
GEV/ML
GEV/LMOM


WL Vidaa Gronaa 3072 GEV/MOM


WL Vidaa Gronaa 3072 GEV/ML


WL Vidaa Gronaa 3072 GEV/LMOM


WL Vidaa Gronaa 3072 GEV/MOM-ML-LMOM