Modeling erosion towards, and sediment transport within the unnavigable watercourses in Flanders, Belgium

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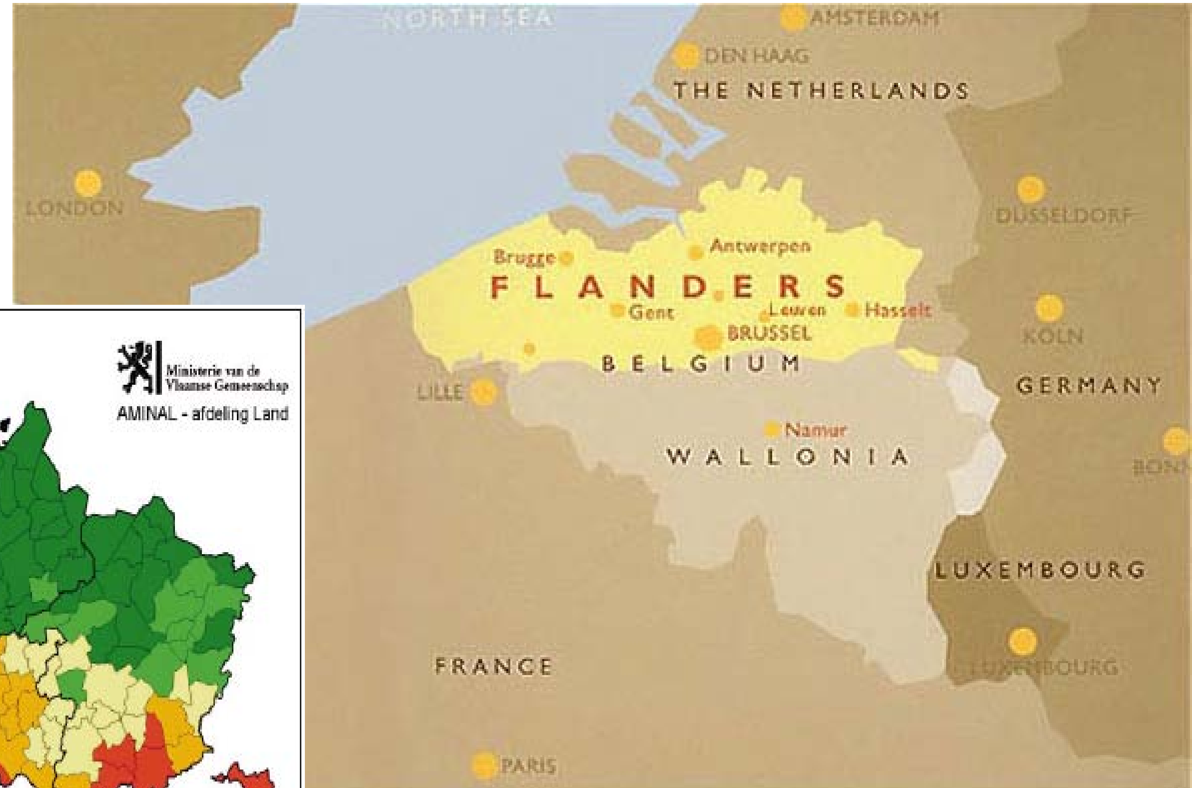
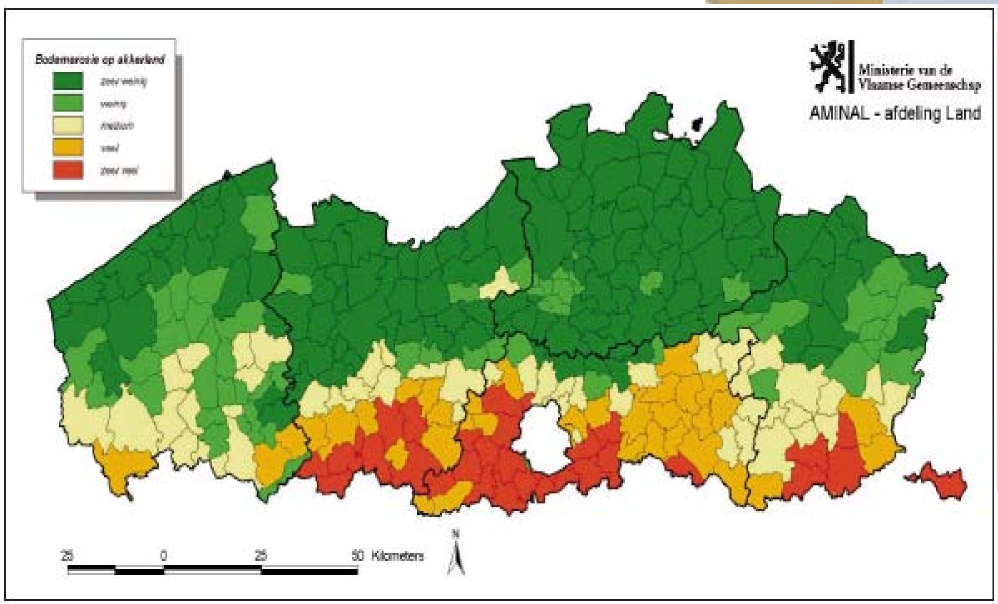
1. Introduction





- 1.8 mln tonnes of sediment enter Flemish rivers yearly
- 1.1 mln tonnes from upstream & North Sea
- 0.4 mln tonnes from soil erosion

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1. Introduction

- Need for tool to estimate soil erosion towards and sediment transport within (unnavigable) watercourses
  - Hydrological sediment export (erosion) model: SEM
    - *Spatially distributed: 20x20 m²*
    - *On event and yearly base*
    - *Implementation of Erosion Control Measures (ECM)*
  - Hydraulic sediment transport model: STM
    - *Per VHA segment*
    - *Implementation of river engineering measures*
  - Application for 7 river catchments (< 100 km²)
  - Simplified version for 11 river basins (500-2000 km²)

2. Sediment Export Model

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2. Sediment Export Model

Combination of 2 empirical methods:

- Spatially and temporally distributed Curve Number (CN) technique:
  - USDA (1954), revision by Van Oost (2003)
  - Runoff hydrograms and spatial runoff patterns
  - Limited input requirements
- Water and Tillage Erosion Model/Sediment Delivery Model WATEM/SEDEM (WS):
  - Van Oost et al. (2000), Van Rompaey et al. (2001)
  - Sediment load
  - Succesful applications and calibrations in Flanders
  - Expertise KUL

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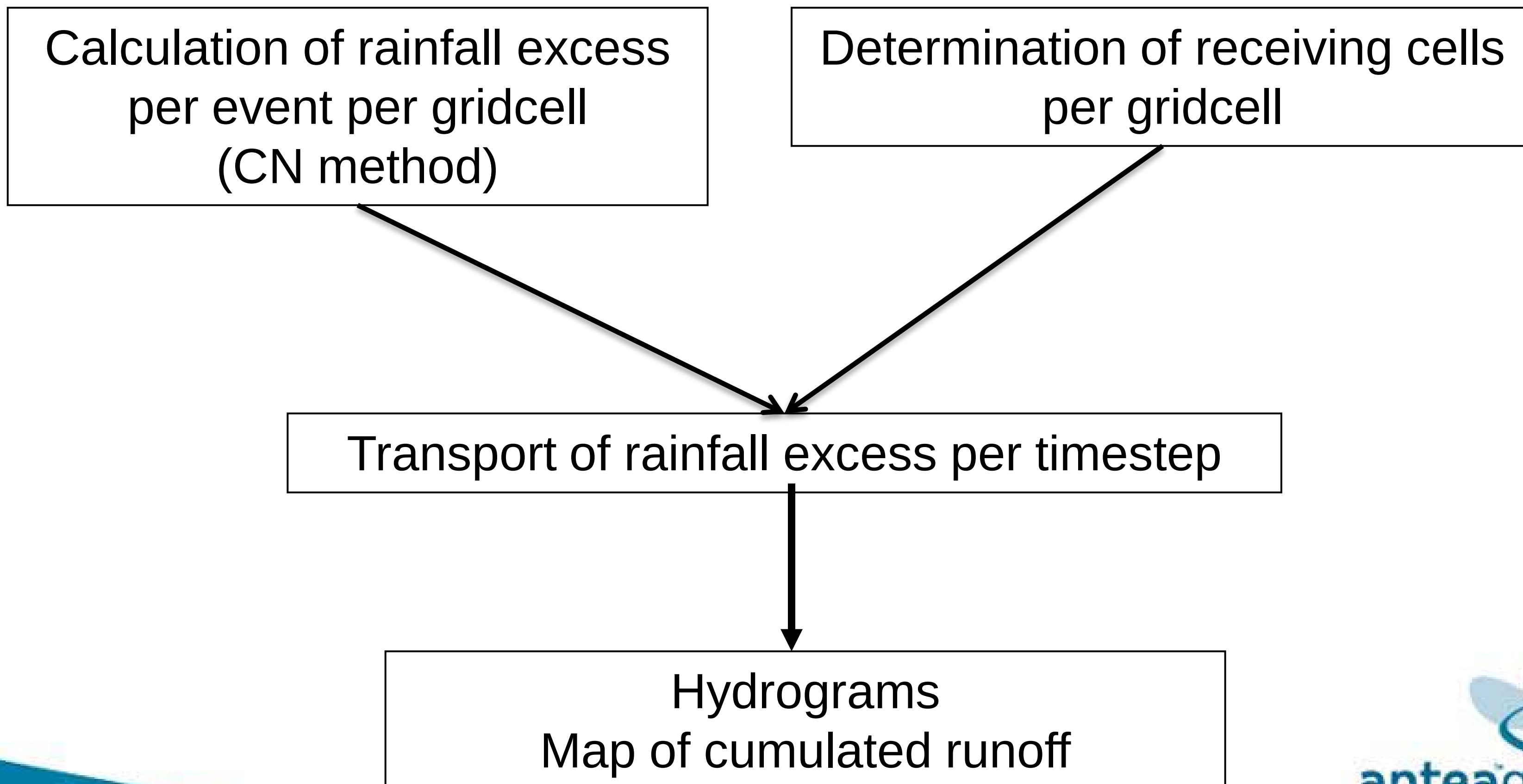
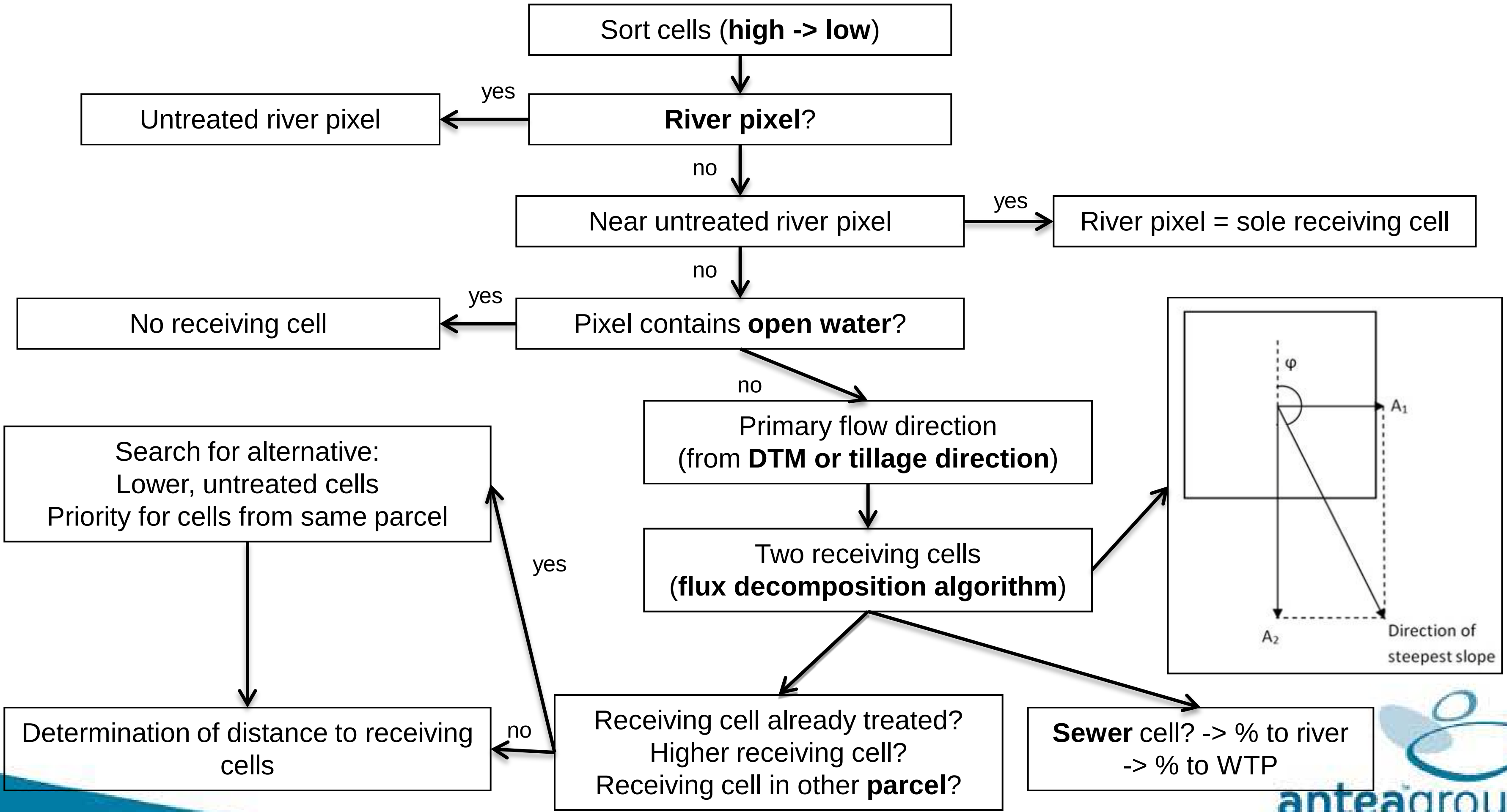
2. Sediment Export Model

Adjusted Curve Number model



2. Sediment Export Model

Determination of receiving cells



2. Sediment Export Model

Calculation of **rainfall excess per event per gridcell**

$$CN = CN_{max} - \left(\left(\frac{Cc}{100}\right) * c_1\right) + \left(\left(\frac{Cr}{5}\right) * c_2\right)$$

CNmax (landuse and soil type) (USDA, 2010),

Cc = crop coverage (Ruysschaert, 2005)

Cr = soil degradation (Evrard et al., 2008)

$$S = \frac{25400}{CN} - 254$$

$$I_a = \lambda * S$$

($\lambda = 0{,}2$)

Rainfall (P) > Initial abstration (I_a)
=> Runoff

$$R^* = \frac{(P - I_a)^2}{(P - I_a) + S}$$

$$R = (R^* * \left(\frac{I_{10}}{10}\right)^{\alpha}) + (AR5 * \beta)$$

Rainfall (P) < Initial abstration (I_a)
=> Infiltration

$$R = (P - I_a) * \left(\frac{D}{1440}\right)$$

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2. Sediment Export Model

Transport of rainfall excess throughout the catchment:

Add fraction of rainfall excess to each cell (based on rainfall distribution) per timestep

↓

Calculation of runoff per cell

$$R = R_{tot} * \left(\frac{v * \Delta t}{x}\right)$$

↓

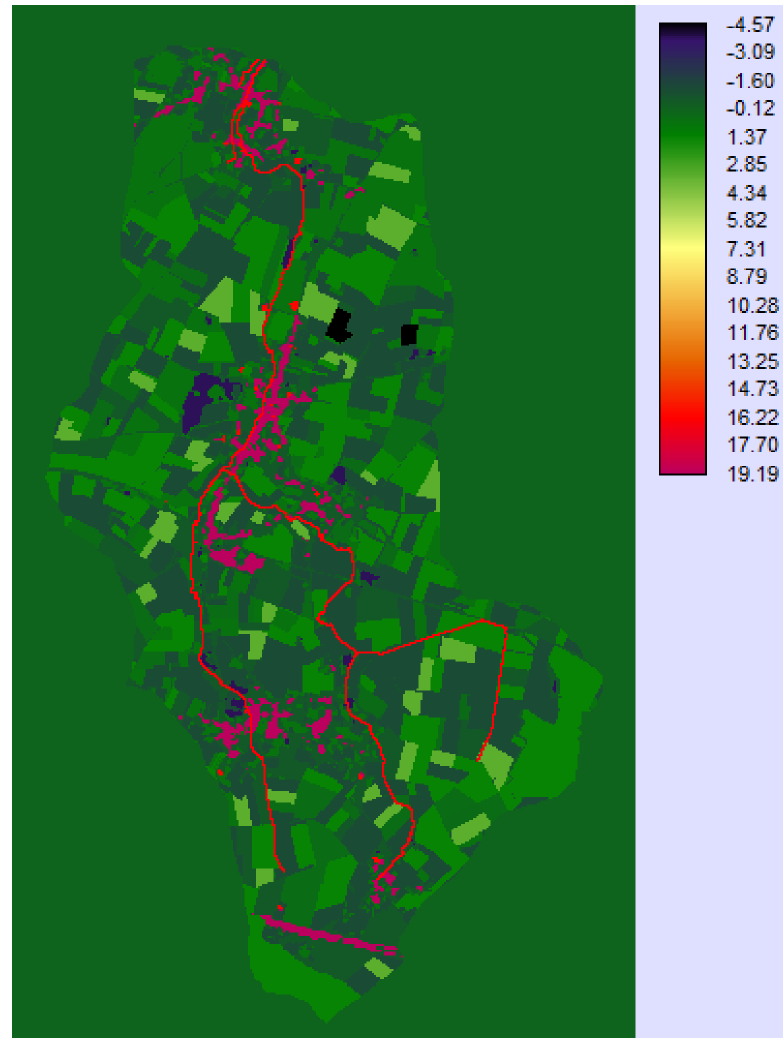
Subtract runoff from water in source cell

↓

Add runoff to receiving cell(s):
If possible, re-infiltration before runoff

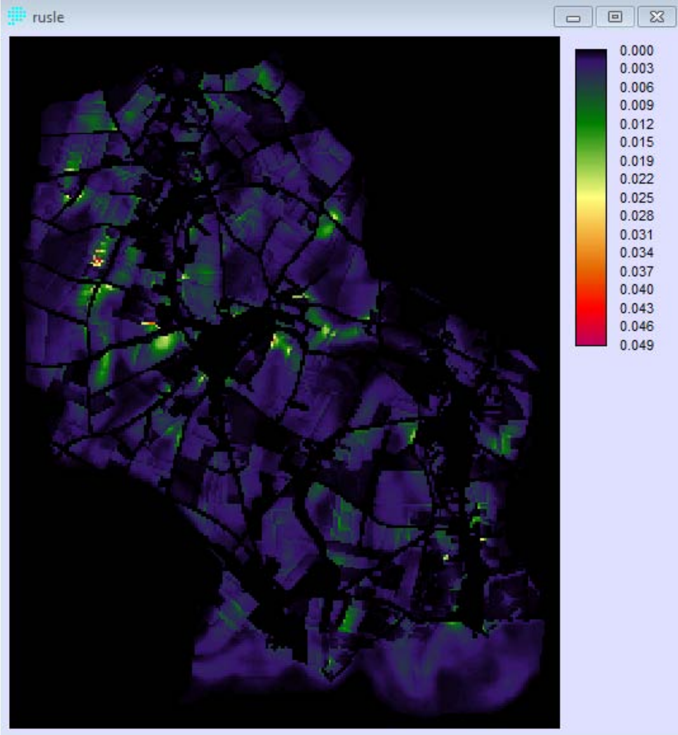
↓

Hydrogram at outlet/segment



2. Sedimentation Export Model

3. WATEM/SEDEM model



RUSLE equation: $A = R * K * LS * C * P$

A = soil loss due to water erosion (rill & interrill) (kg m^{-2})

R = rainfall erosivity factor (MJ mm m^{-2} h^{-1})

-> calculated by means of rainfall intensity and kinetic energy (Verstraeten et al., 2006)

$$R = \frac{E * I_{30}}{10^{-6}}$$

K = soil erosivity factor (kg h MJ^{-1} mm^{-1})

-> Input (based on soil map and Notebaert el al., 2006)

LS = topographic slope and length factor (-)

$$S = -1{,}5 + \frac{17}{1 + 2{,}718281828^{2{,}3-(6{,}1*\sin(Sl))}}$$

-> calculated by means of slope, slope direction and upstream area (Desmet & Govers, 1996)

$$L = \frac{(A + res^{2})^{exp+1} - A^{exp+1}}{X^{exp} * res^{exp+2} * 22{,}13^{exp}}$$

C = crop-management factor (-)

-> Input (ALBON tables)

P = erosion control factor (-)

= 1

2. Sediment Export Model

Each gridcell is treated once (high to low, idem as CN model):

- Total amount of sediment in cell
  = incoming sediment from higher cells + potential soil loss (RUSLE)

- Calculation of transportcapacity:
  Tc = A * kTc * c (kTc = 6m forest/grass, 10m crop field, 0 open water, 9999 rivers)

Total sediment > transportcapacity	**Total sediment < transportcapacity**
Transport = transportcapacity Sedimentation of sediment excess	Transport = total amount of sediment Erosion = potential soil loss

- Result = sediment load at outlet(s)

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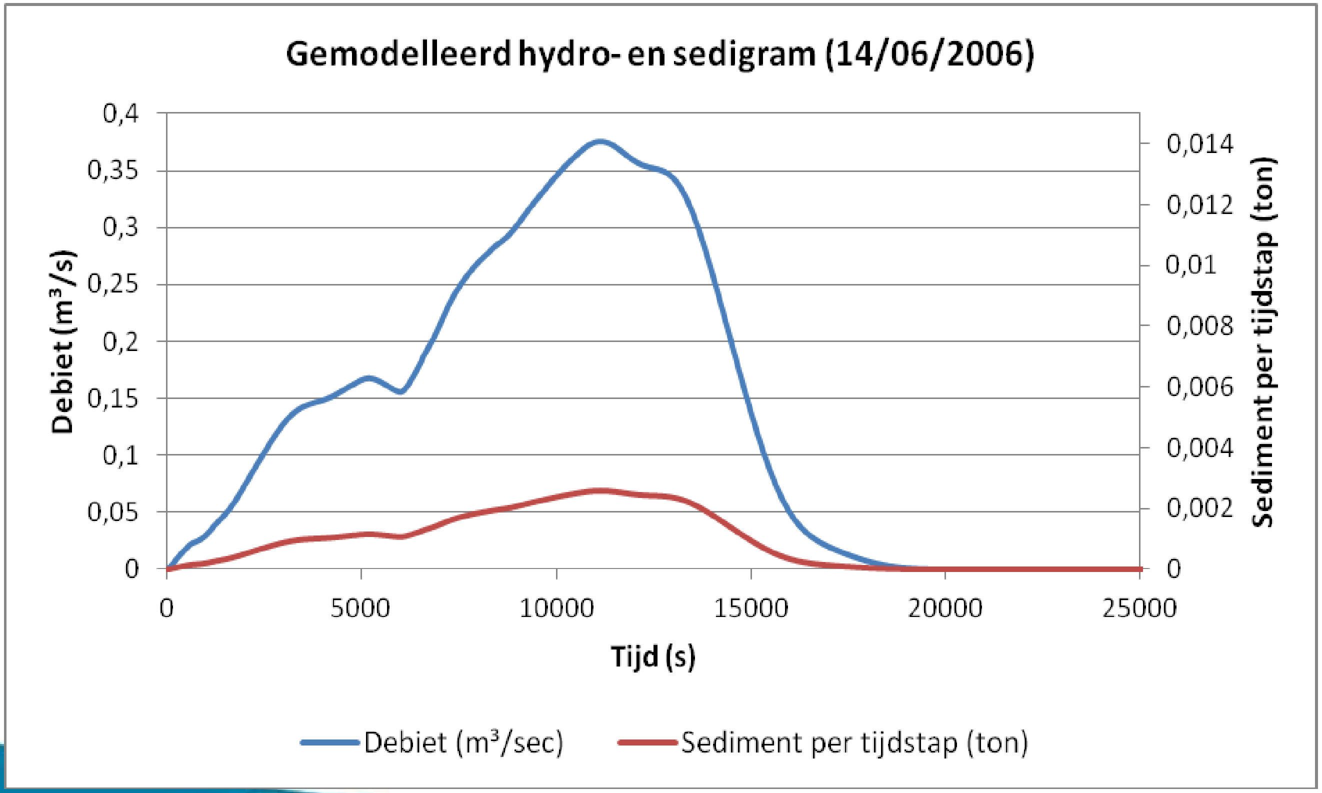
2. Sediment Export Model

Distribution sediment load over runoff hydrogram

- Linear: SC = SL/R
- Provisional, but satisfactory results



2. Sediment Export Model

Long term version model (<= 1 year)

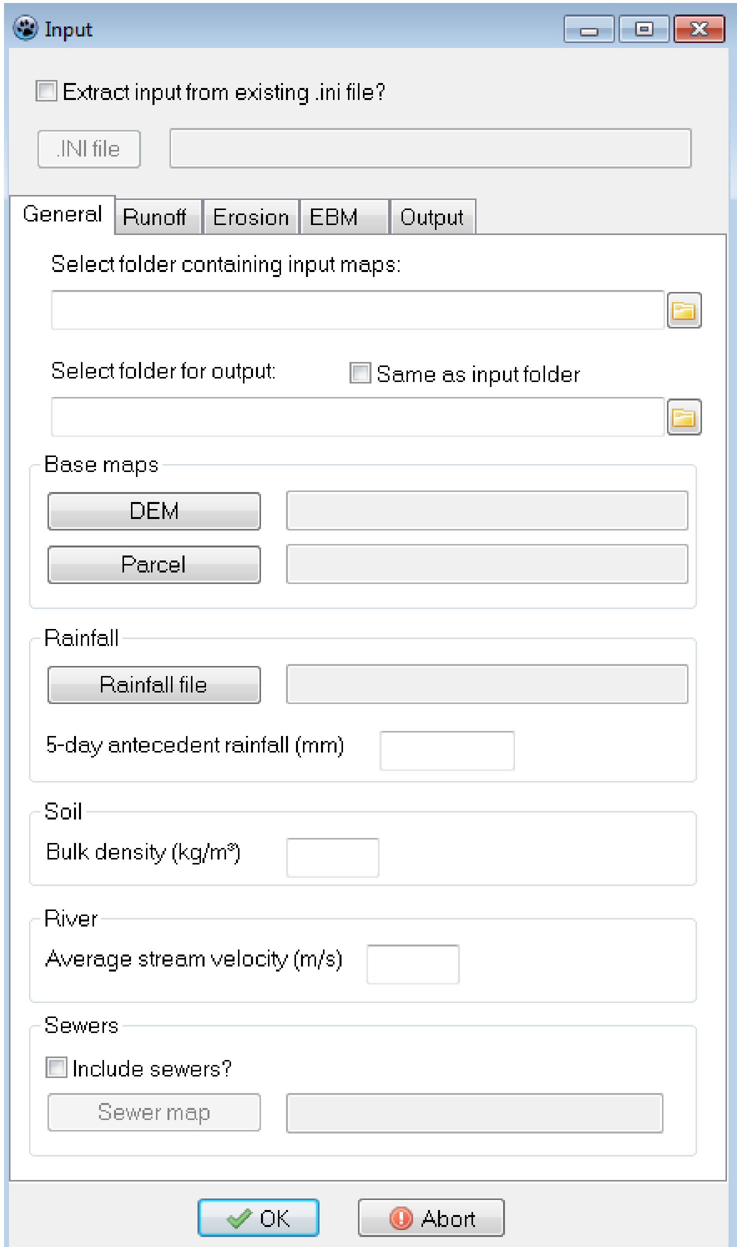
- Identification rainfall events
  - 6h criterium
  - rainfall > 1.27 mm
- CN_WS model is simulated per event and outputs are aggregated

- Temporal variance of CN and C-factor is taken into account:
  input map per hydrological season (4)
- Average river flow velocity variable per month

2. Sediment Export Model

Inputs (QGIS/IDRISI):

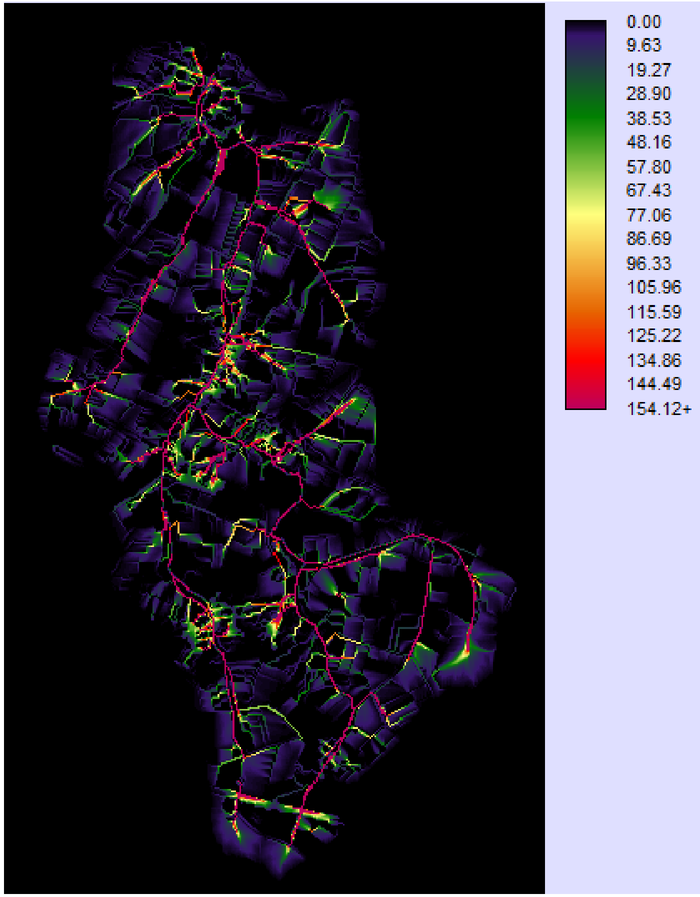
- DTM
- Parcel map and connectivity efficiency
- Rainfall
- CN map
- Soil bulk density
- Average stream velocity
- Tillage direction
- Calibration parameters α and β
- Sewer locations
- K, C, P, kTc, ktil maps
- VHA map and outflow locations
- Deviation dams and ditches (dir, CN, C)
- Buffers and dams map



2. Sediment Export Model

Outputs:

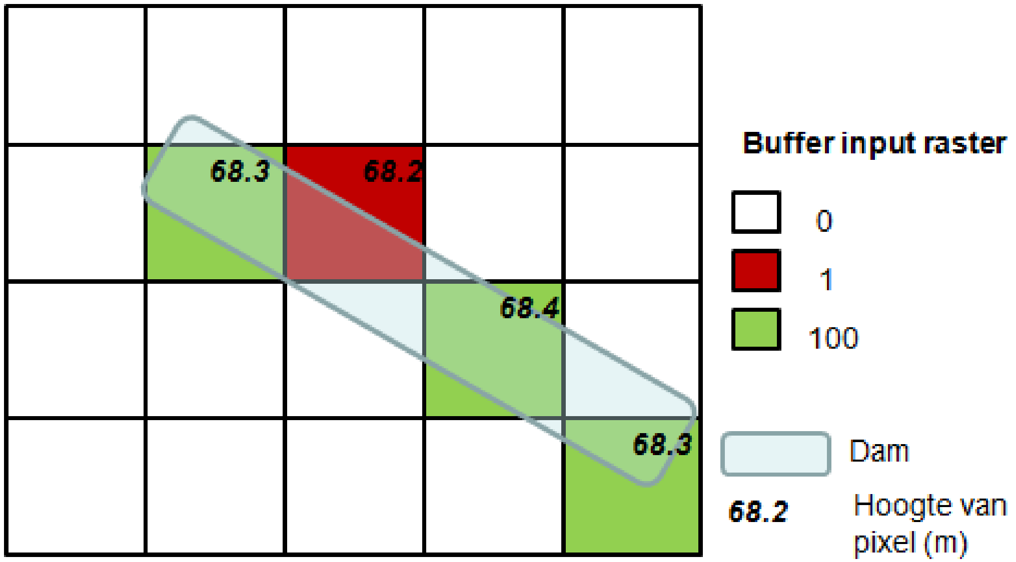
- Maps: rainfall excess, water erosion, tillage erosion, runoff, slope, etc.
- Sediment load
- Buffer outflow
- Total runoff
- Hydrogram -> input STM
- Sedigram -> input STM



2. Sediment Export Model

Implementation of Erosion Control Measures (ECM)

1. Buffers and dams
   - Dam height
   - Outlet dimensions
   - Buffer volume
   - Overflow width
   - Sediment trapping efficiency



2. Sediment Export Moc

- Low CN value (71)
- Adjustment runoff pattern:
  buffer and neighboring cells flow towards outlet
- Delayed runoff mechanism (Meert & Willems, 2013):
  - Volume < dead volume: no outflow

$$V_{dood} = \left(\frac{H_{opening}}{H_{dam}}\right) * V_{bekken}$$

  - Volume > dead volume and volume < total volume: outflow via outlet

$$R(t) = \left(Q_{max} * \sqrt{\frac{V(t)}{V_{bekken} - V_{dood}}}\right) * \Delta t \qquad Q_{max} = C_d * A_0 * \sqrt{2 * g * (H_{dam} - H_{opening})}$$

  - Volume > total volume: outflow via outlet + overflow

$$R_{opening} = Q_{max} * \Delta t \qquad R_{overloop}(t) = C_d * B_{dam} * \sqrt{g} * h(t)^{3/2} * \Delta t$$

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2. Sediment Export Model

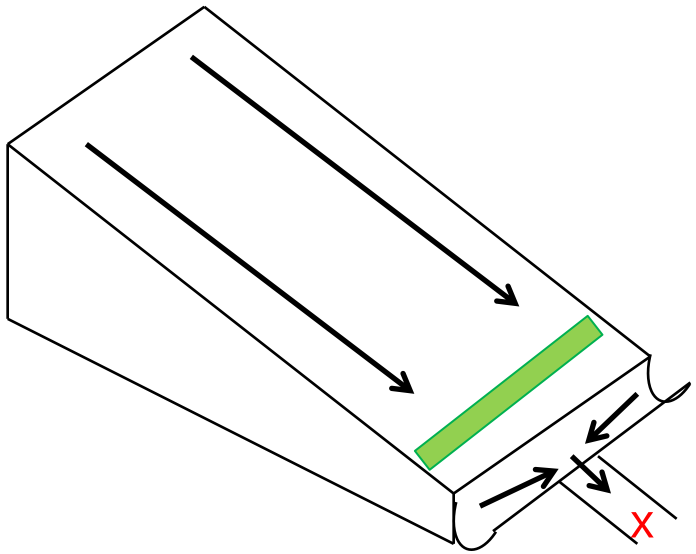
2. Grass buffer strips
   - Drawn on parcel map
   - Low CN value (74), C factor (0.01) and kTc
3. Deviation dams
   - Adjustment runoff pattern
   - Low CN value (71) and C factor (0.01)
4. Ditches (permanently filled)
   - Adjustment runoff pattern
   - High CN value (98) and low C factor (0)
5. Conservation tillage
   - Adjusted C factor (0.8) and low CN value

8	1	2
7	X	3
6	5	4

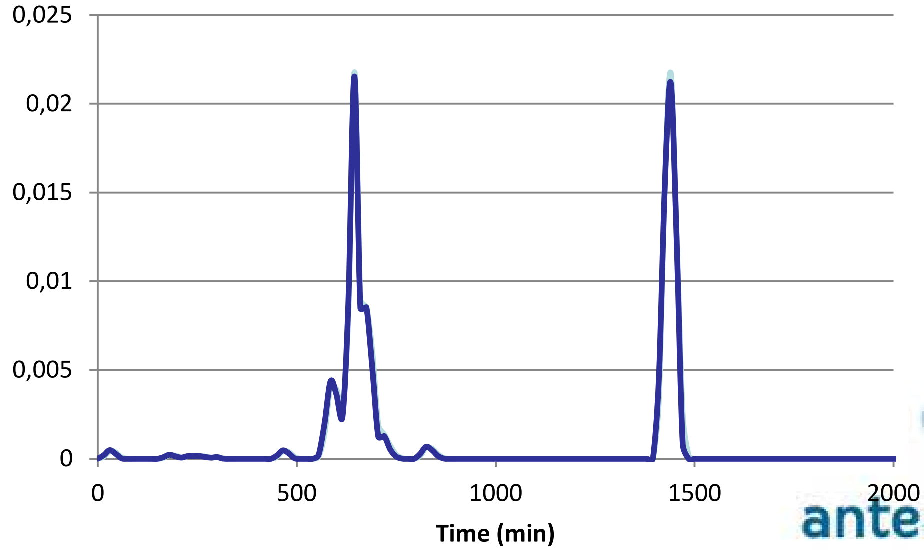
2. Sediment Export Model

Test case:

- Beet field
- 300 x 120 m
- Uniform slope
- Ditch below
- Characteristic rainfall event



Runoff:



Sediment load = 980 kg

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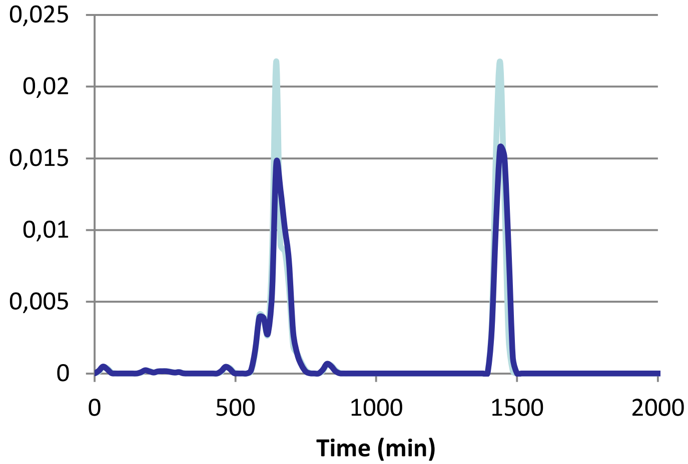
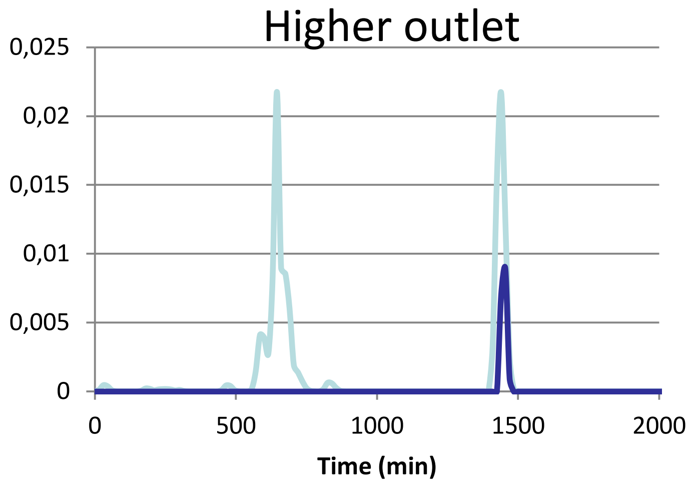
2. Sediment Export Model

1. Buffer with dam

- Significant runoff reduction



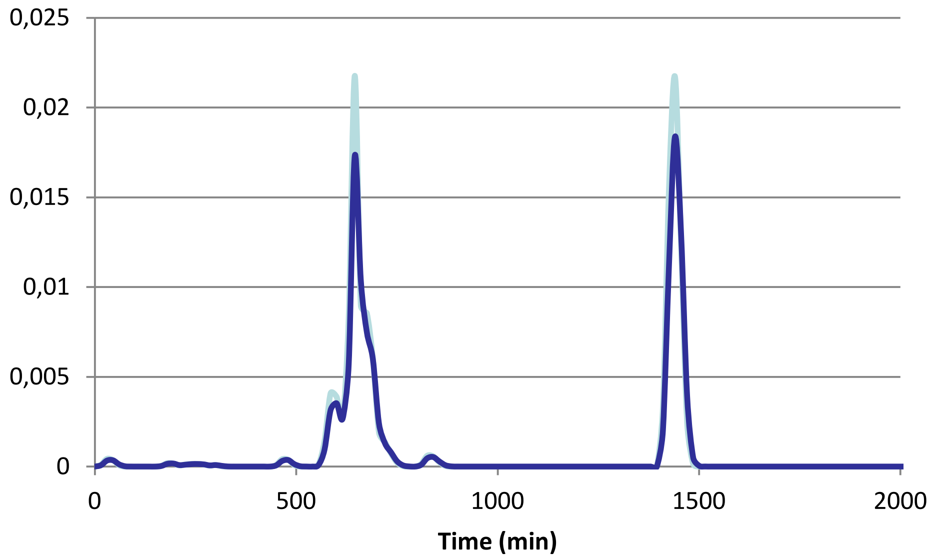


- Reduction sediment load: 445 kg (55%)

2. Sediment Export Model

2. Grass strip 20m

- Limited runoff reduction

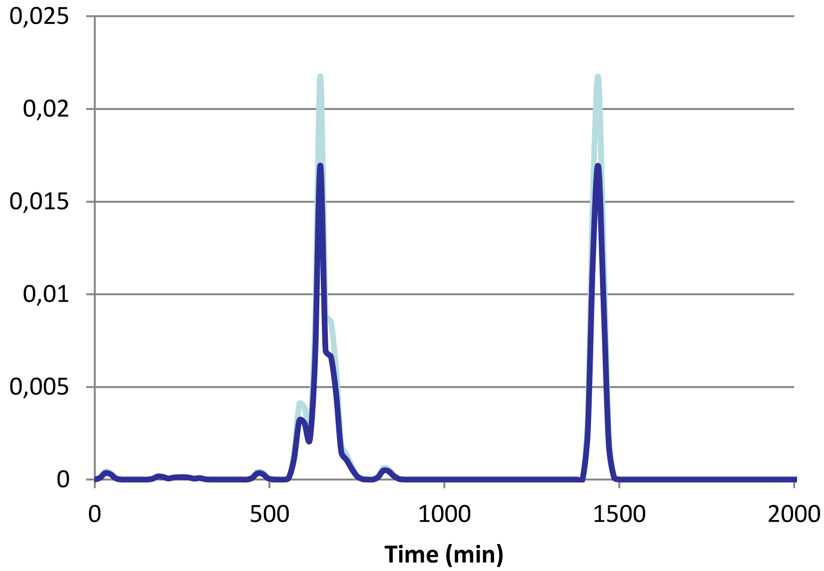


- Large reduction sediment load: 21 kg (98%)

2. Sediment Export Model

3. Conservation tillage

- Limited runoff reduction

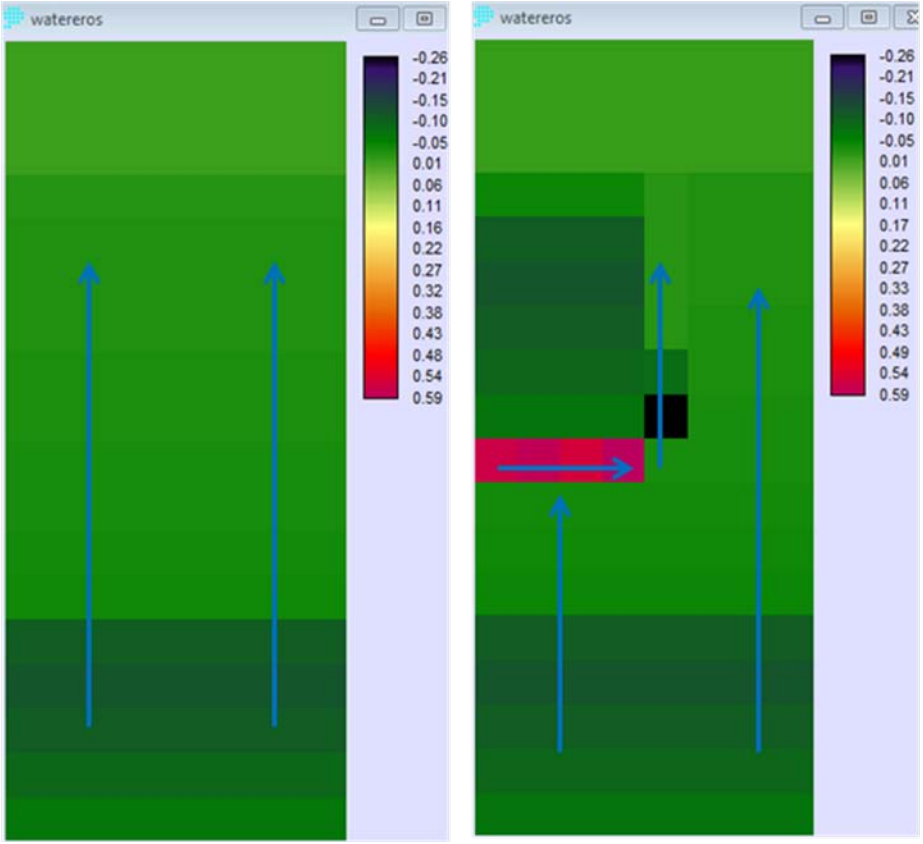


- Reduction sediment load: 195 kg (80%)

2. Sediment Export Model

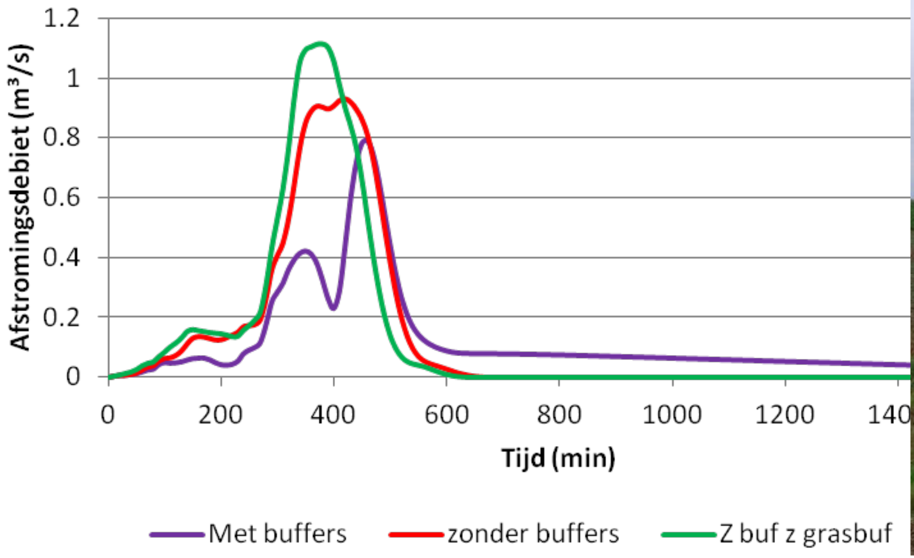
4. Deviation dam

- Effect on runoff pattern
- Effect on erosion pattern
- SL = 874 kg (11%)
- Clear water effect



2. Sediment Export Model

5. Simulation of existing bufferdams and grass strips:
Heulengracht (210 ha)



Sediment load:

Without ECM = 392 kg

With grass strips = 98 kg

With grass strips and bufferdam = 98 kg

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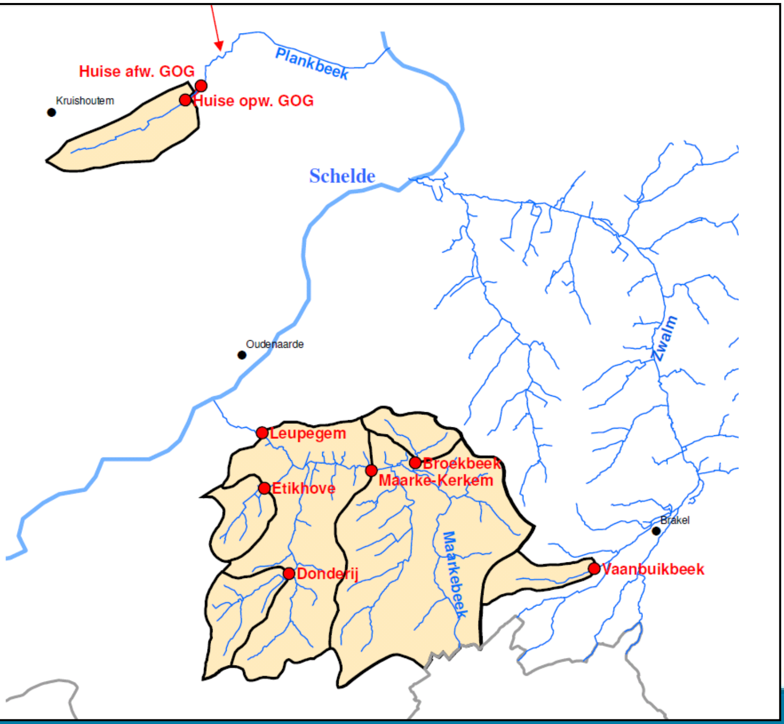
2. Sediment Export Model

Evaluation of model performance

- 16 river catchments (1.7 – 107 km²) – incl. ECM
- 2 summer and 2 winter rainfall events
- Comparison of CN_WS results with Q and SSC measurements by Flemish Sediment Monitoring Network



2. Sediment Export Model

Evaluation of model performance

Catchment	Watercourse	River basin	Catchment area (ha)	Average baseflow ($m^3 s^{-1}$) - WETSPRO
Velm	Molenbeek	Demer	3049	0,072
Wellen	Herk	Demer	10717	0,263
Borlo	Molenbeek	Demer	336	0,000
Kerniel	St.-Annabeek	Demer	171	0,005
Muizen	Cicindria	Demer	1599	0,024
Mielen-boven-Aalst	Melsterbeek	Demer	859	0,011
Neerwinden	Waarbeek	Demer	257	0,000
Heks	Herkebeek	Demer	1115	0,038
Piringen	Fonteinbeek	Demer	773	0,035
Leupegem	Maarkebeek	Bovenschelde	5032	0,168
Etikhove	Marie Borrebeek	Bovenschelde	271	0,019
Donderij	Molenbeek	Bovenschelde	389	0,028
Broekbeek	Broekbeek	Bovenschelde	209	0,018
Maarke-kerkem	Maarkebeek	Bovenschelde	2803	0,090
Vaanbuikbeek	Vaanbuikbeek	Bovenschelde	220	0,021
Huise	Wallebeek	Bovenschelde	486	0,034

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2. Sediment Export Model

Stroomgebied	Seizoen	Model / meting (afstroming)	Model / meting (sediment)
Velm	Winter	2,15	1,63
Velm	Winter	3,04	3,81
Velm	Zomer	8,11	0,77
Velm	Zomer	6,09	1,71
Gemiddelde		**5,91**	**1,34**
Wellen	Winter	0,68	0,44
Wellen	Winter	0,90	1,74
Wellen	Zomer	2,26	0,47
Wellen	Zomer	3,78	3,57
Gemiddelde		**2,30**	**1,30**
Borlo	Winter	0,32	0,99
Borlo	Winter	0,17	1,90
Borlo	Zomer	0,16	0,67
Borlo	Zomer	0,33	1,24
Gemiddelde		**0,21**	**1,04**
Kerniel	Winter	0,24	0,08
Kerniel	Winter	0,36	0,51
Kerniel	Zomer	1,05	0,08
Kerniel	Zomer	1,34	0,22
Gemiddelde		**0,97**	**0,15**
Muizen	Winter	1,45	0,46
Muizen	Winter	1,95	0,59
Muizen	Zomer	9,33	1,34
Muizen	Zomer	10,12	-
Gemiddelde		**6,38**	**0,93**
Mielen	Winter	0,96	0,10
Mielen	Winter	1,13	0,16
Mielen	Zomer	5,02	0,19
Mielen	Zomer	11,21	5,75
Gemiddelde		**4,37**	**0,45**
Neerwinden	Winter	3,88	8,99
Neerwinden	Winter	3,53	4,01
Neerwinden	Zomer	11,62	0,77
Neerwinden	Zomer	71,69	150,15
Gemiddelde		**14,58**	**2,72**
Heks	Winter	0,48	-
Heks	Winter	0,48	-
Heks	Zomer	10,91	0,41
Heks	Zomer	5,12	0,27
Gemiddelde		**3,93**	**0,29**
Piringen	Winter	0,23	0,05
Piringen	Winter	0,30	0,44
Piringen	Zomer	2,16	9,64
Piringen	Zomer	2,59	0,31
Gemiddelde		**1,42**	**0,35**

Stroomgebied	Seizoen	Model / meting (afstroming)	Model / meting (sediment)
Leupegem	Winter	0,52	0,52
Leupegem	Winter	0,40	0,08
Leupegem	Zomer	4,77	8,95
Leupegem	Zomer	2,46	1,08
Gemiddelde		**0,84**	**0,46**
Etikhove	Winter	0,49	0,12
Etikhove	Winter	0,46	0,07
Etikhove	Zomer	3,44	14,93
Etikhove	Zomer	4,01	5,17
Gemiddelde		**0,98**	**0,23**
Donderij	Winter	0,36	0,17
Donderij	Winter	0,36	0,10
Donderij	Zomer	2,63	1,14
Donderij	Zomer	1,08	0,62
Gemiddelde		**0,59**	**0,26**
Broekbeek	Winter	0,76	1,14
Broekbeek	Winter	0,63	0,34
Broekbeek	Zomer	3,22	5,14
Broekbeek	Zomer	1,83	2,05
Gemiddelde		**1,11**	**1,26**
Maarke-kerkem	Winter	0,90	0,37
Maarke-kerkem	Winter	0,63	-
Maarke-kerkem	Zomer	4,37	4,81
Maarke-kerkem	Zomer	4,26	1,59
Gemiddelde		**1,66**	**2,27**
Vaanbuikbeek	Winter	0,50	0,97
Vaanbuikbeek	Winter	0,27	0,71
Vaanbuikbeek	Zomer	1,94	0,44
Vaanbuikbeek	Zomer	1,67	-
Gemiddelde		**0,77**	**0,45**
Huise	Winter	0,50	0,32
Huise	Winter	0,21	0,07
Huise	Zomer	1,61	0,29
Huise	Zomer	5,15	8,08
Gemiddelde		**0,69**	**0,27**
Totaal gemiddelde		**1,60**	**0,77**

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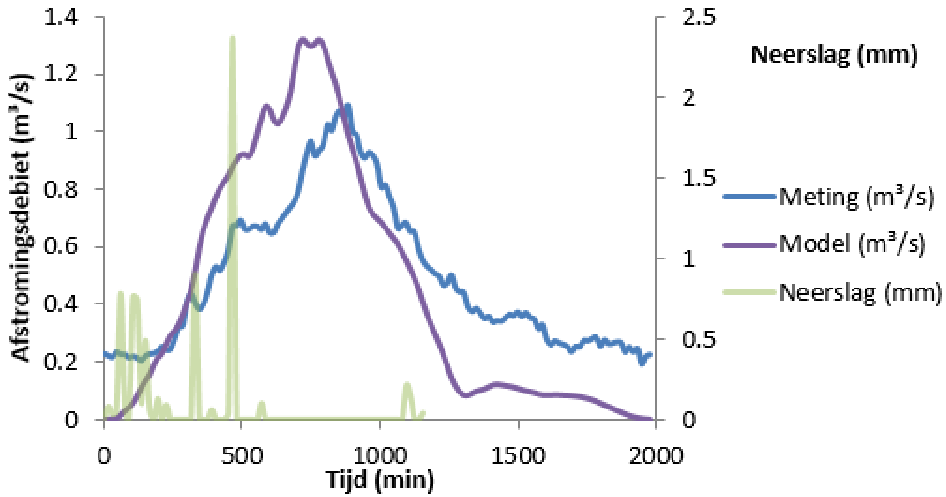
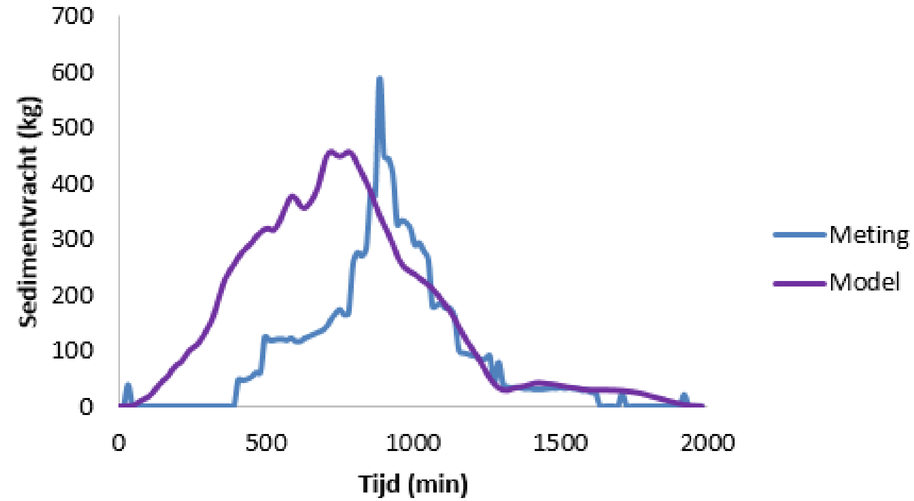
2. Sediment Export Model

Evaluation of model performance

- Hydrogram and Sedigram, e.g. Wellen february 2008





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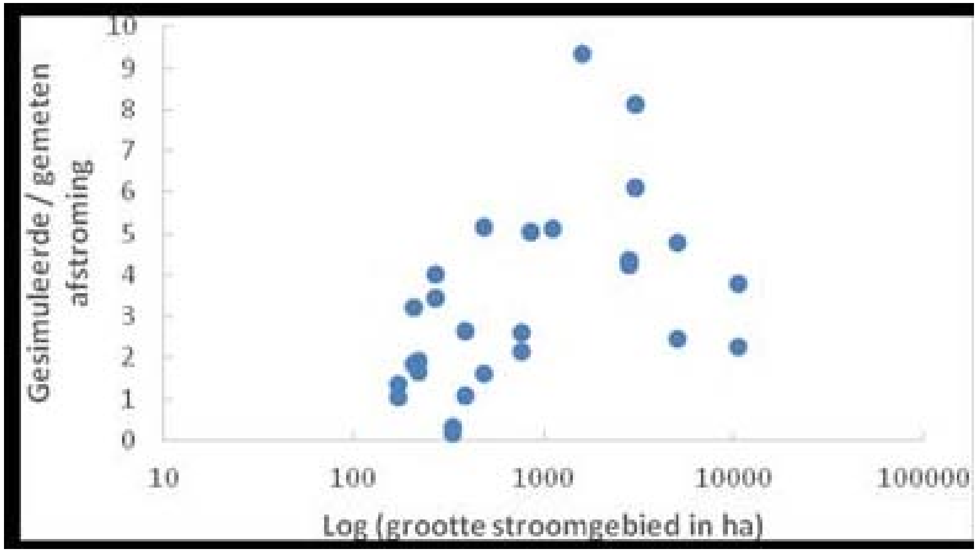
2. Sediment Export Model

- Overestimation of runoff:
  - Overestimation of CN values (in summer) -> SA
  - Quality of rainfall data in test (single station)
  - No sewers implemented
  - Scale effect: catchment ≠ ∑(individual fields)

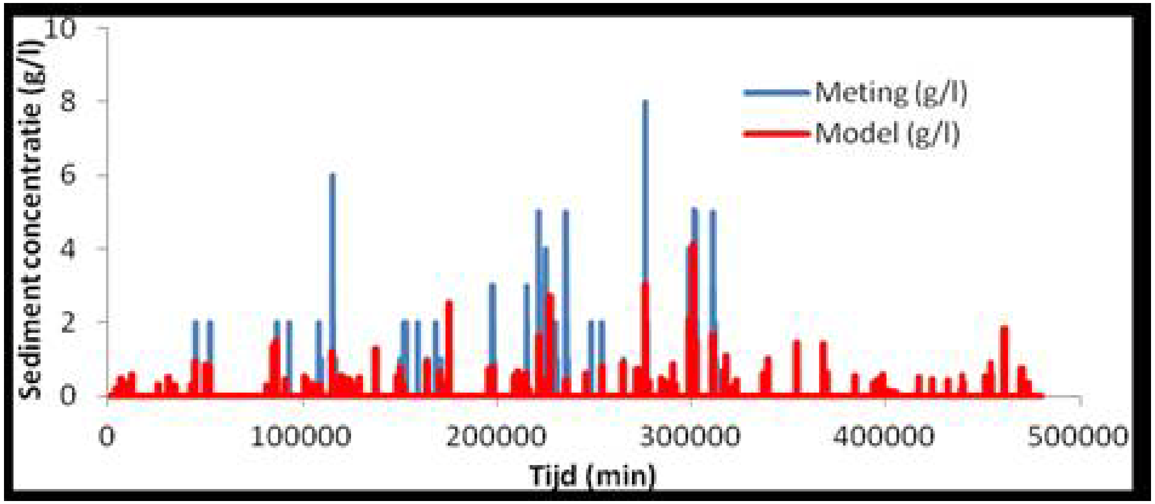


  - Errors in model structure, assumptions, input data, etc.?

2. Sediment Export Model

Evaluation of model performance

- Simulation for 1 year



Stroomgebied	Model / meting (afstroming)	Model / meting (sediment)
Velm	2,80	2,09
Wellen	1,46	1,35
Borlo	0,15	0,78
Kerniel	0,55	0,07
Muizen	3,68	0,73
Mielen	2,53	0,40
Neerwinden	14,72	12,53
Heks	1,40	0,07
Piringen	0,68	0,18
Leupegem	1,09	1,01
Etikhove	0,93	0,54
Donderij	0,82	0,62
Broekbeek	1,02	2,50
Maarke-kerkem	1,04	0,68
Vaanbuikbeek	0,56	0,62
Huise	0,60	0,24
Gemiddelde	1.28	0,79

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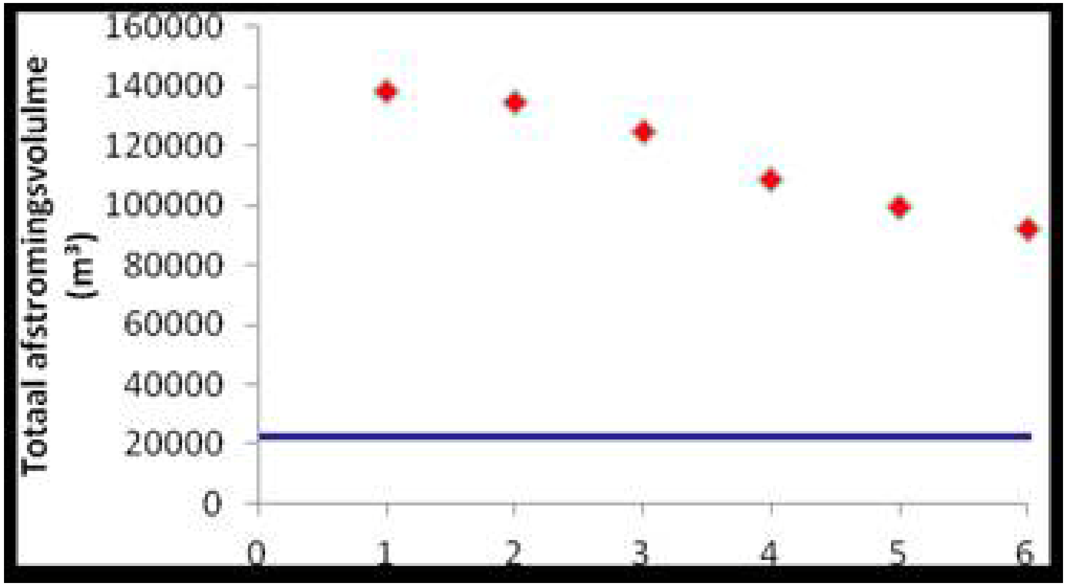
2. Sediment Export Model

Evaluation of model performance

- Sensitivity analysis
  - CN value: Velm

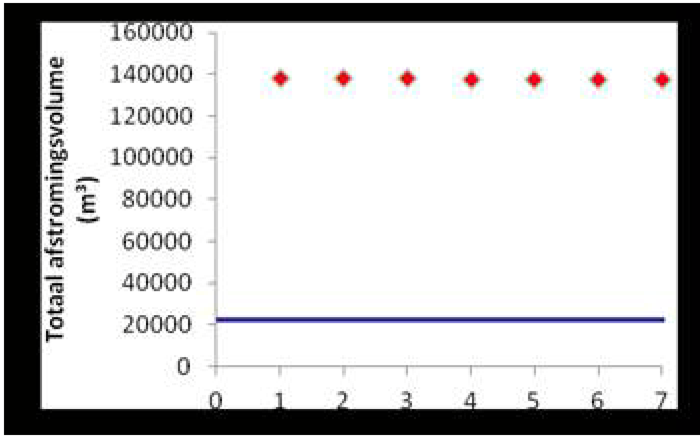


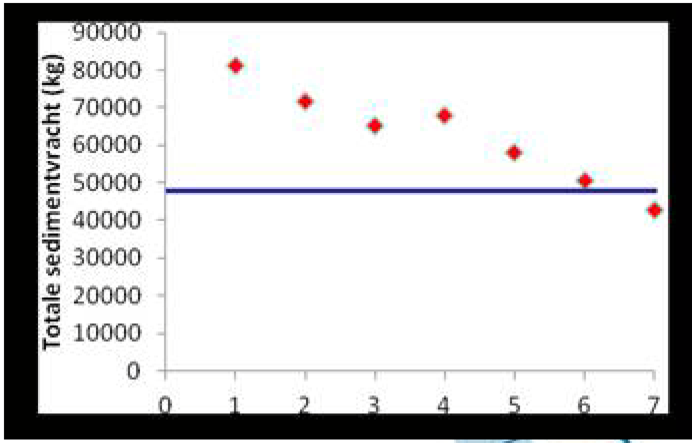
  - High sensitivity for CN -> proper calibration factor
  - Can be justified in terms of soil type and seasonality

2. Sediment Export Model

Evaluation of model performance

- Sensitivity analysis
  - Parcel connectivity: Velm
  - Low sensitivity for runoff:
    Generated throughout catchment
    Mostly from parcels close to outlet
  - High sensitivity for sediment:
    Generated on uphill parcels
    Mostly from parcels far from outlet





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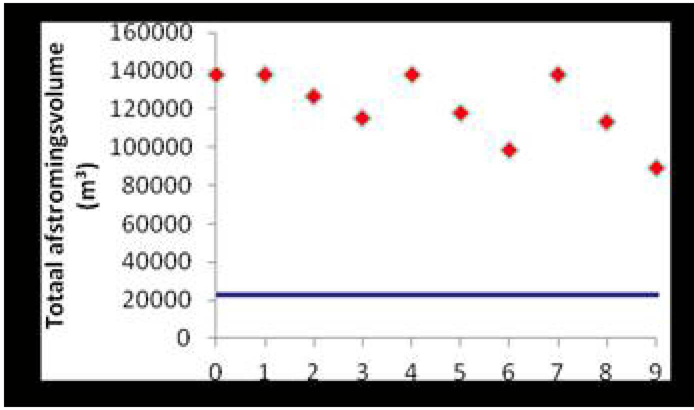
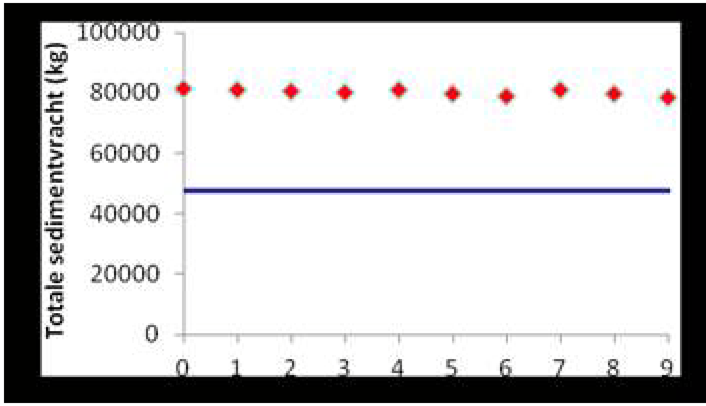
2. Sediment Export Model

Evaluation of model performance

- Sensitivity analysis
  - Sewers: Velm
  - High sensitivity for runoff: Generated throughout catchment
  - Low sensitivity for sediment: Generated in non-urban zones





2. Sediment Export Model

Future research?

- Monitoring campaigns for further model calibration
- Monitoring campaigns for ECM calibration
- Implementation of a crop growth model
- Seasonality K factor
- Distribution of SL over hydrogram
- Temporally distributed erosion model (dynamic link with runoff)
- Automatisation of i.a. input generation

General conclusion: SEM is capable of generating hydrograms and sedigrams for catchments of variable size both on event and annual base. Output maps give a clear view on the dynamics of runoff and erosion. The effect of ECMs can easily be simulated.

3. Sediment Transport Model

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3. Sediment Transport Model

- SEM: runoff + sediment

  ➔ add baseflow and transport throughout river system
- Simulate sedimentation and bed erosion

- Calibration data: Flemish Sediment Monitoring Network (Q, SSC) and actual deposition monitoring (Maarkebeek, Dijle)

- InfoWorks River Systems (IWRS) and Integrated Catchment Modelling (ICM) by Innovyze Ltd.
- 1D hydrodynamic model
- Full SWE in finite volume scheme

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3. Sediment Transport Model

IWRS

$$(1-\lambda)\, W \frac{\partial z}{\partial t} + \frac{\partial G}{\partial x} = 0 \qquad \textbf{(1)}$$

where:

λ = bed porosity
W = water surface width
z = bed elevation
t = time
G = sediment transport rate (m^3/s)
x = distance in flow direction

- Engelund-Hansen Model (1967)
- Ackers-White Model (1973)
- Ackers-White Model (1993)
- Westrich-Jurashek Model (1985)

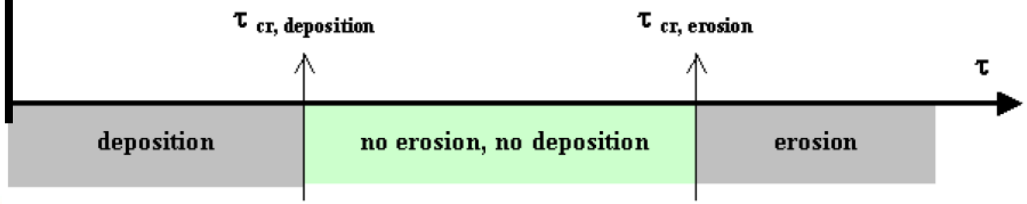
ICM

$$\frac{dc}{dt} + u\frac{dc}{dx} = 0$$

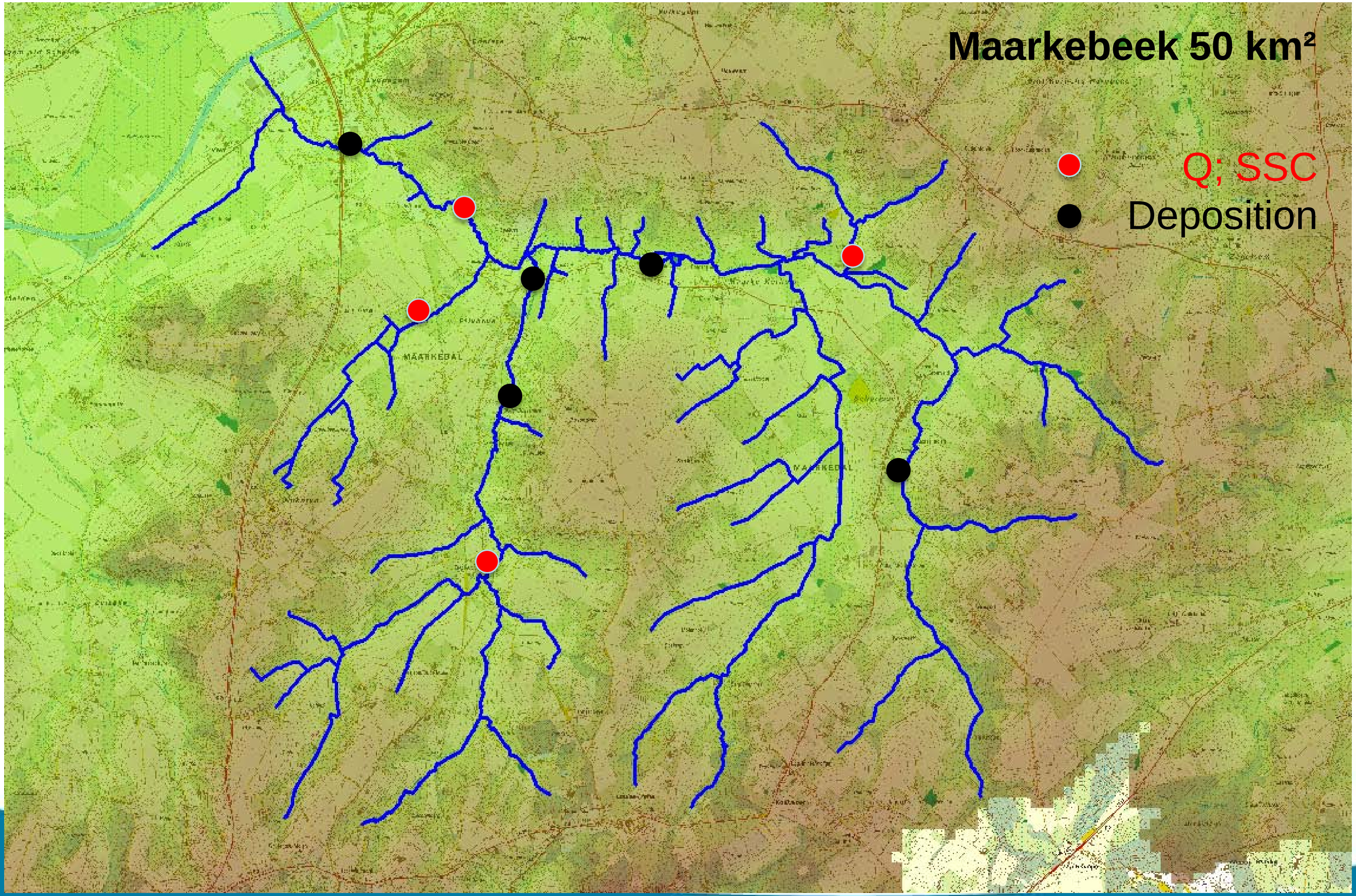
where

c is the concentration (kg/m^3)
u is the flow velocity (m/s) - obtained from the hydraulic simulation
t is time (s)
x is the spatial co-ordinate (m).

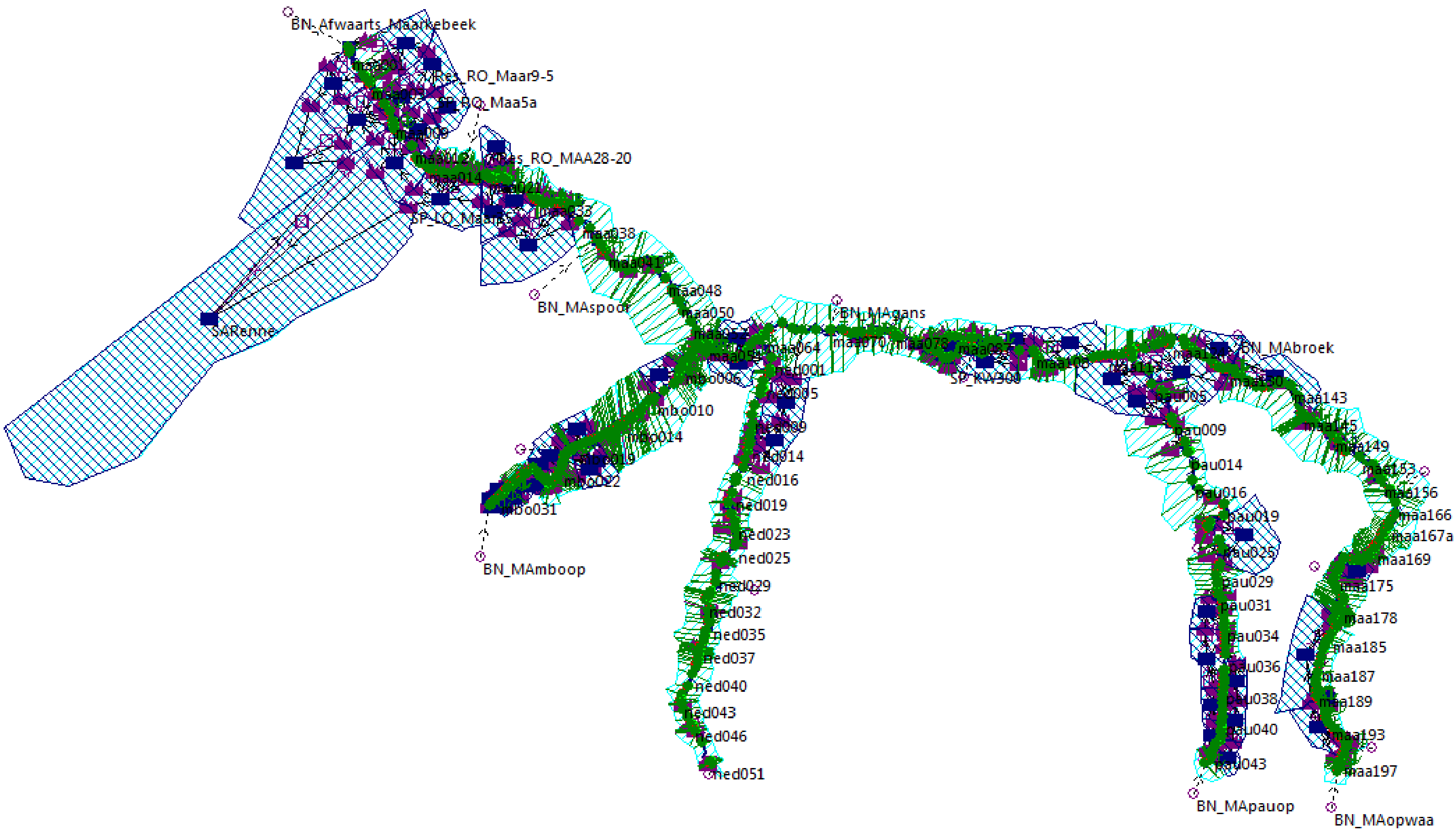
- Ackers-White Model (1991)
- Velikanov Model (1998)
- KUL Model (2002)



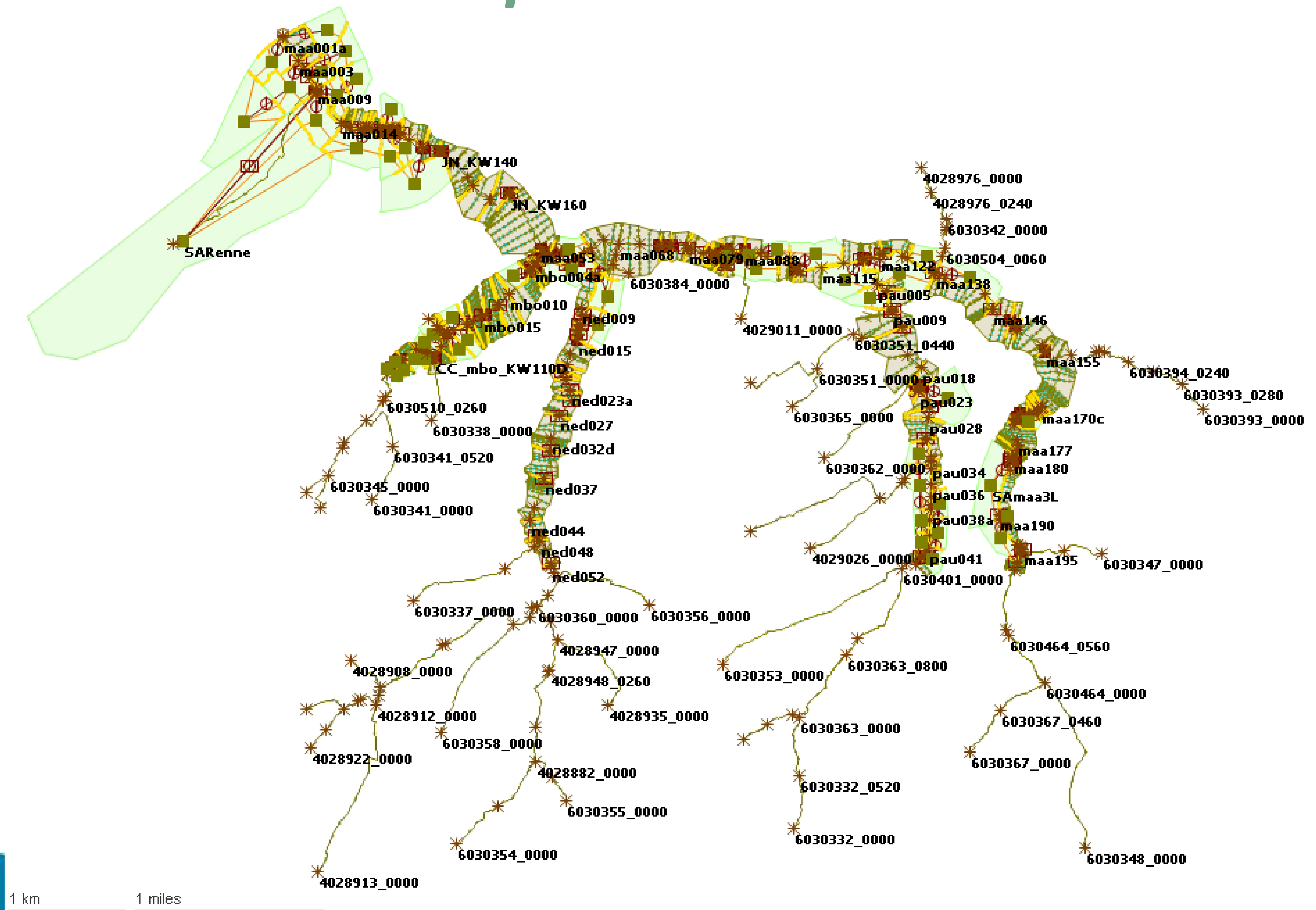
3. Sediment Transport Model



3. Sediment Transport Model



3. Sediment Transport Model



3. Sediment Transport Model

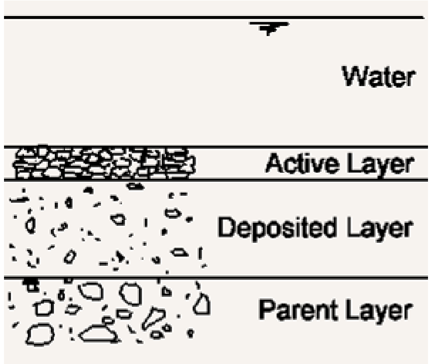
Evaluation and sensitivity analysis:

- IWRS:
  - model adjustments for compatibility and stability reasons
    -> inaccuracies
  - elaborate sediment transport modelling options (BUT)
  - final version (bugs)
- ICM
  - calculates faster and more stable
  - extensive 2D options
  - elaborate WQ module + coupling with sewer system

3. Sediment Transport Model

Development of ICM ST module for open water systems:

- Definition of an initial sediment depth, locally adjustable
- Inclusion of Active layer concept, locally adjustable thickness



- Inclusion of the sediment grading and sorting processes
- Locally adjustable erosion and deposition limits
- Detailed simulation output file (sediment budget)
- Implementation of other transport equations
- Improvement of hydraulic updating method
- Additional sediment fractions

3. Sediment Transport Model

Sediment parameters:

Active Layer Thickness (mm)	0.5
Bed Depth Calculation	
Bed d50 (mm)	0.1
Bed Specific Gravity	2.5
1D erosion/deposition model	
Erosion/deposition model	Ackers-White / Velicanov / KUL
Active layer depth method (1D)	Explicit
Sediment fraction 1 (and 2)	
d50 of sf1 (mm)	0.015
Specific gravity of sf1	2.5
Settling velocity of sf1	--
Velikanov: critical erosion efficiency for sf1	0.00225
Velikanov: critical deposition efficiency sf1	0.00275
KUL: alpha deposition for sf1	1
KUL: beta deposition for sf1	1
KUL: gamma deposition for sf1	1
KUL: alpha erosion for sf1	1
KUL: beta erosion for sf1	1
KUL: gamma erosion for sf1	1
Erosion limit	Unlimited
Deposition limit	Unlimited

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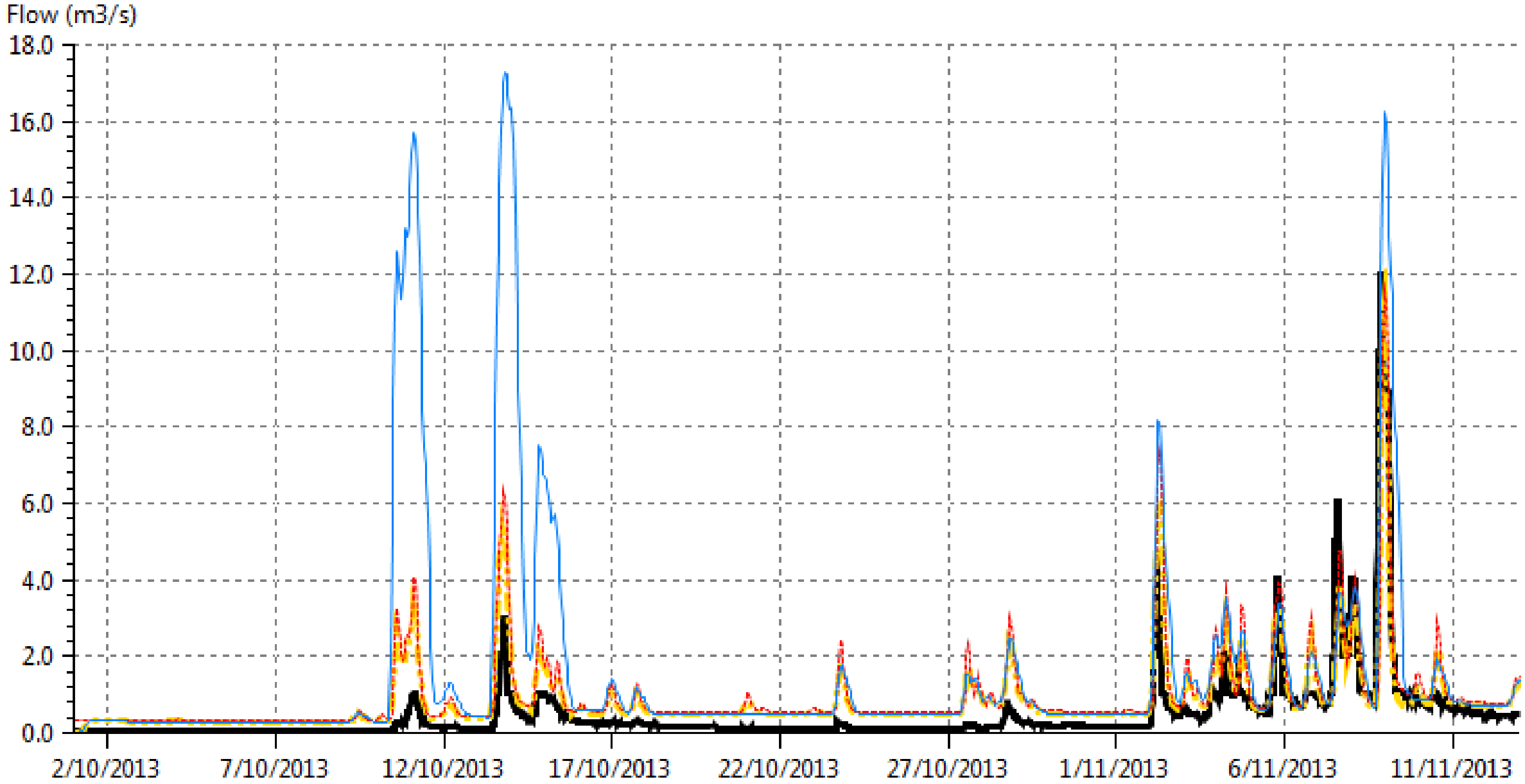
3. Sediment Transport Model

Comparison of flows - downstream:



Q Measured
Q PDM IWRS
Q PDM ICM
Q CNWS (+ PDM baseflow)

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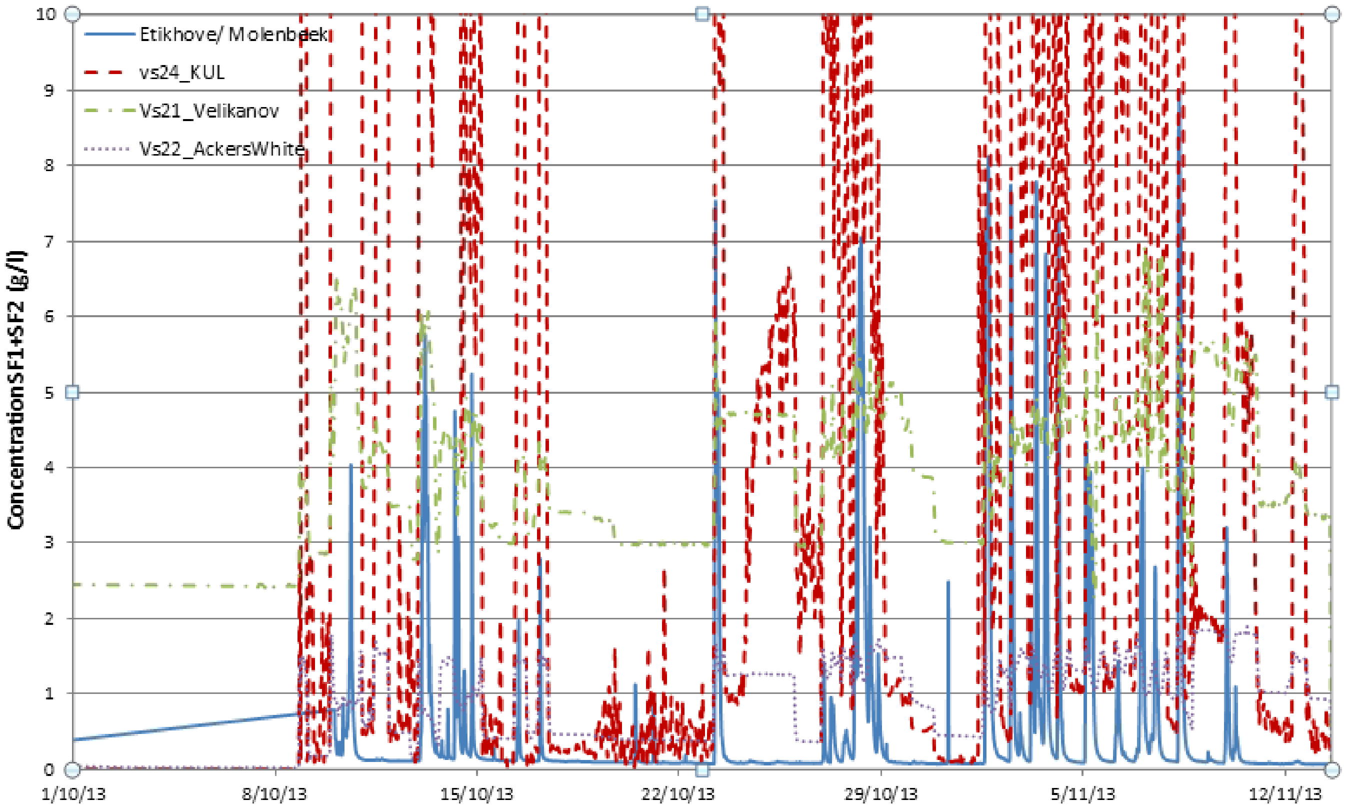
3. Sediment Transport Model

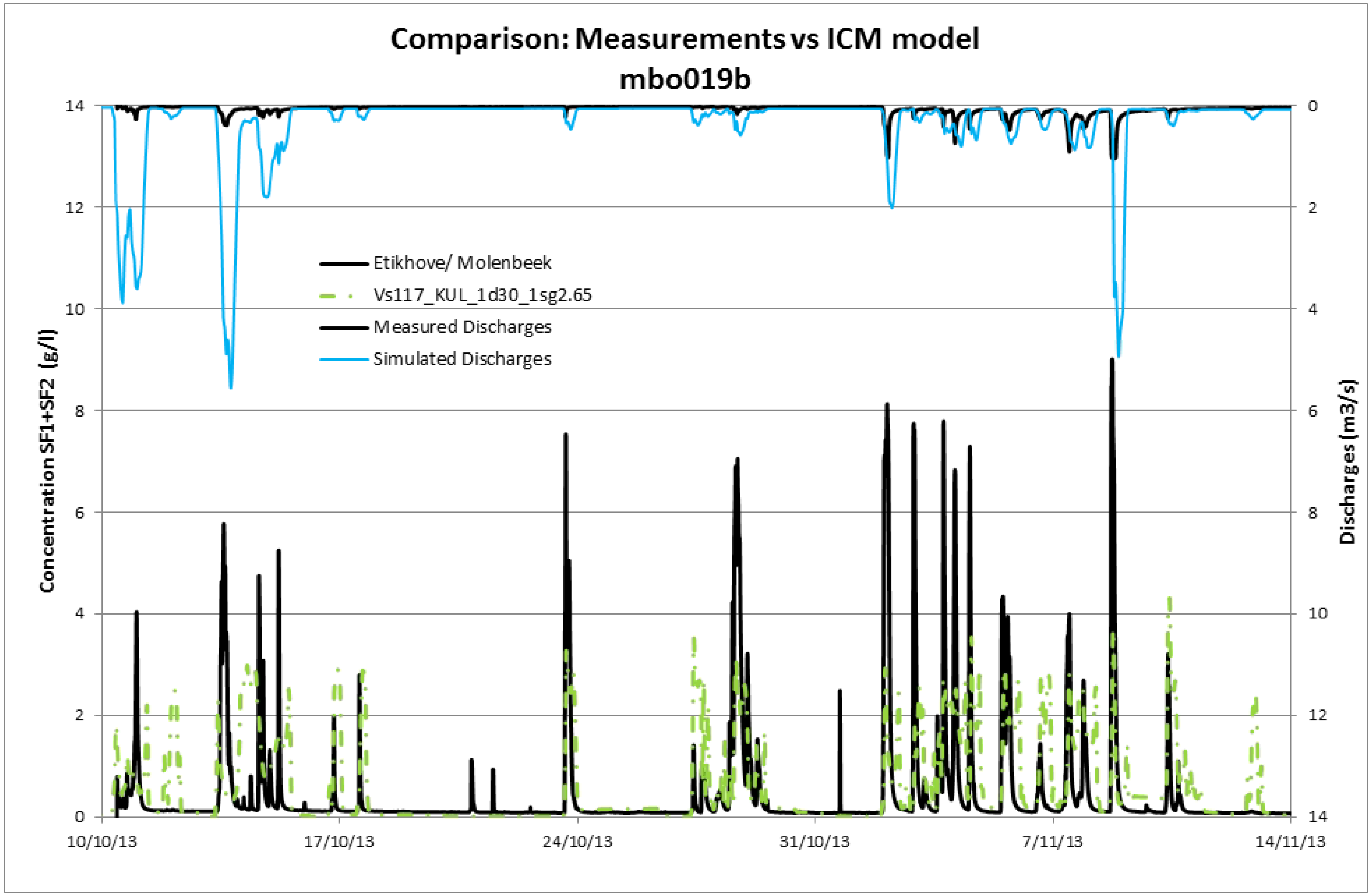
Initial model – default parameters:



SSC Measured
SSC Velikanov
SSC KUL
SSC Ackers-White

3. Sediment Transport Model

Calibration ongoing (v117) – upstream:



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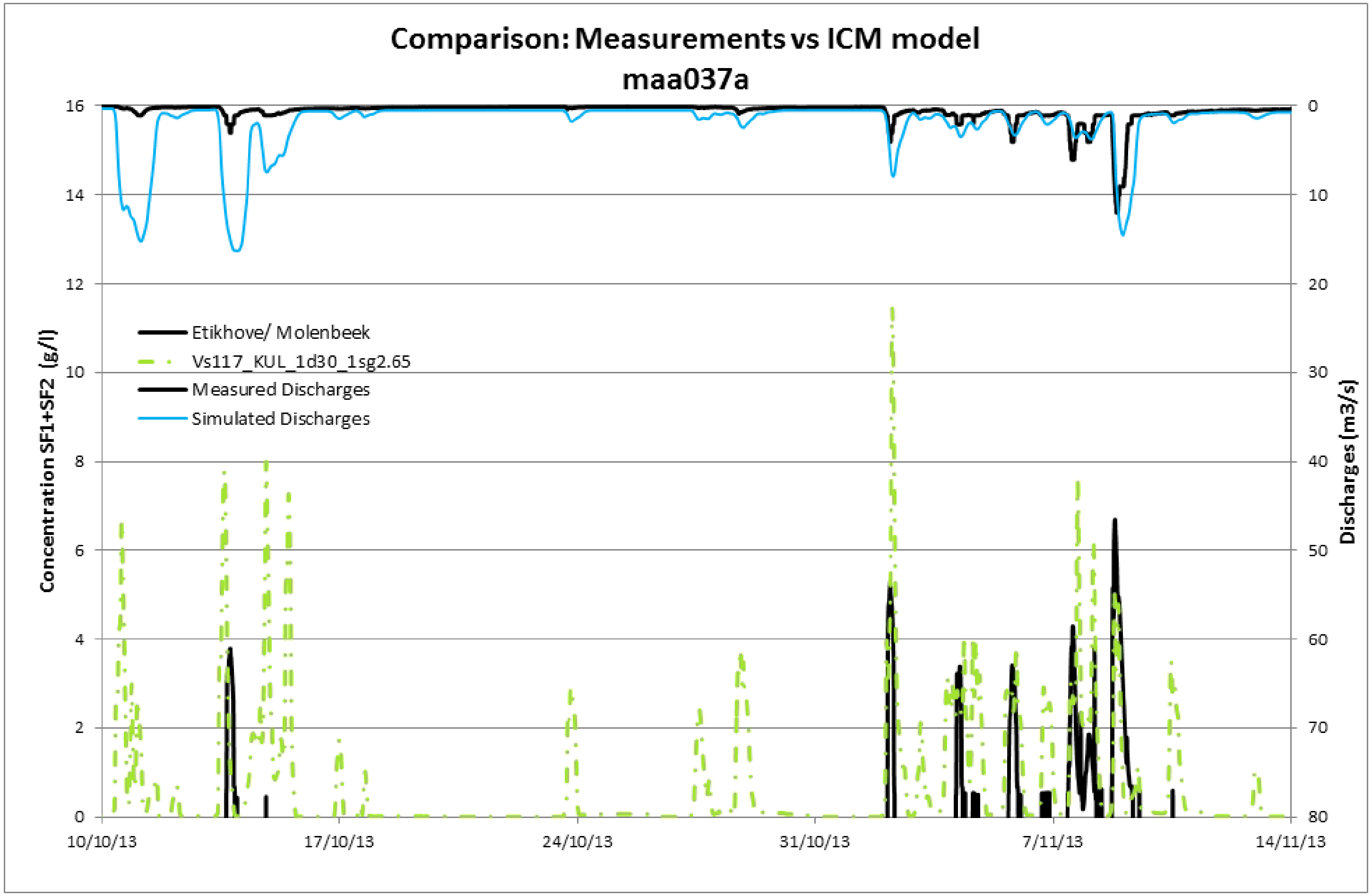
3. Sediment Transport Model

Calibration ongoing (v117) – downstream:



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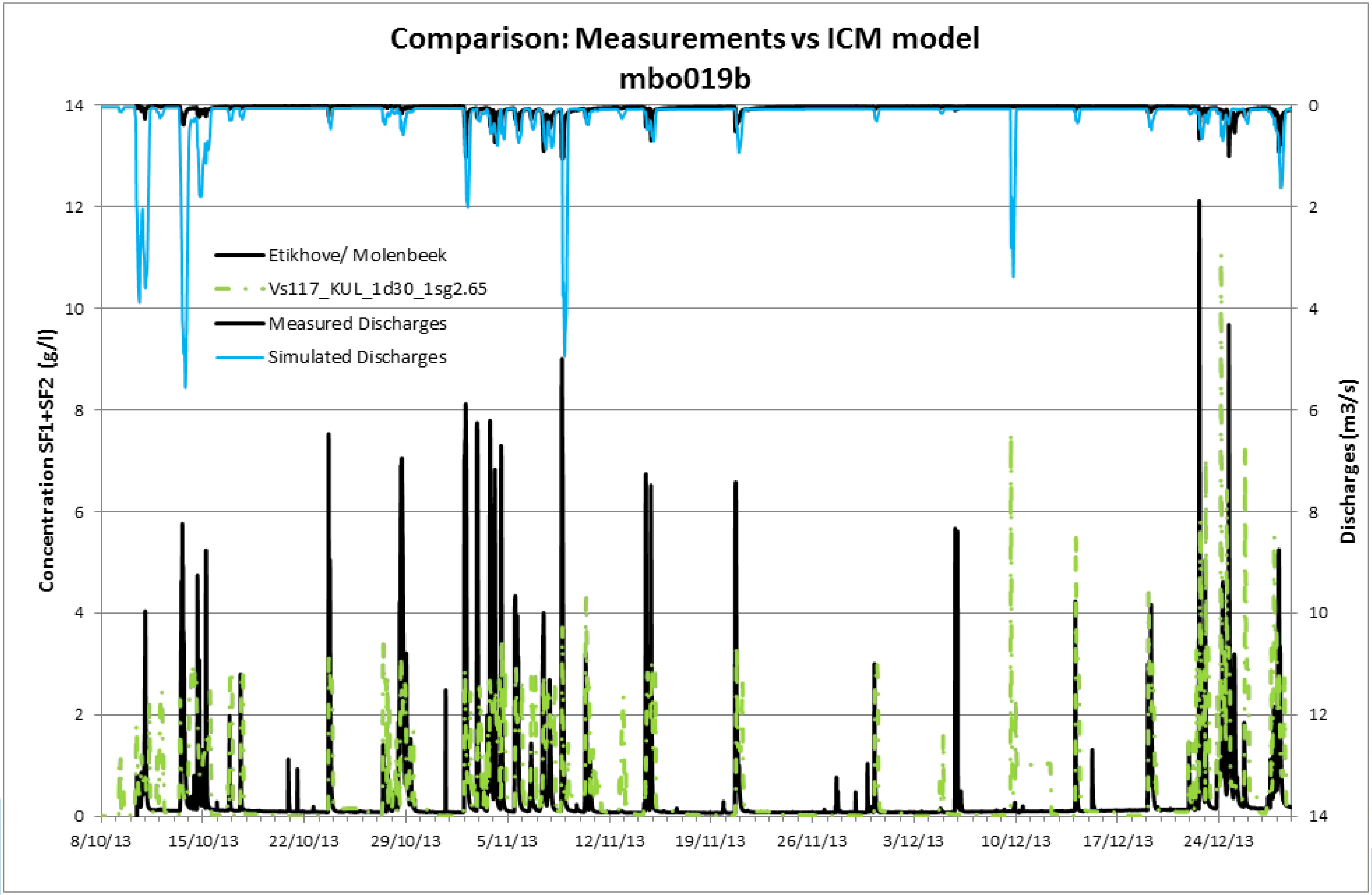
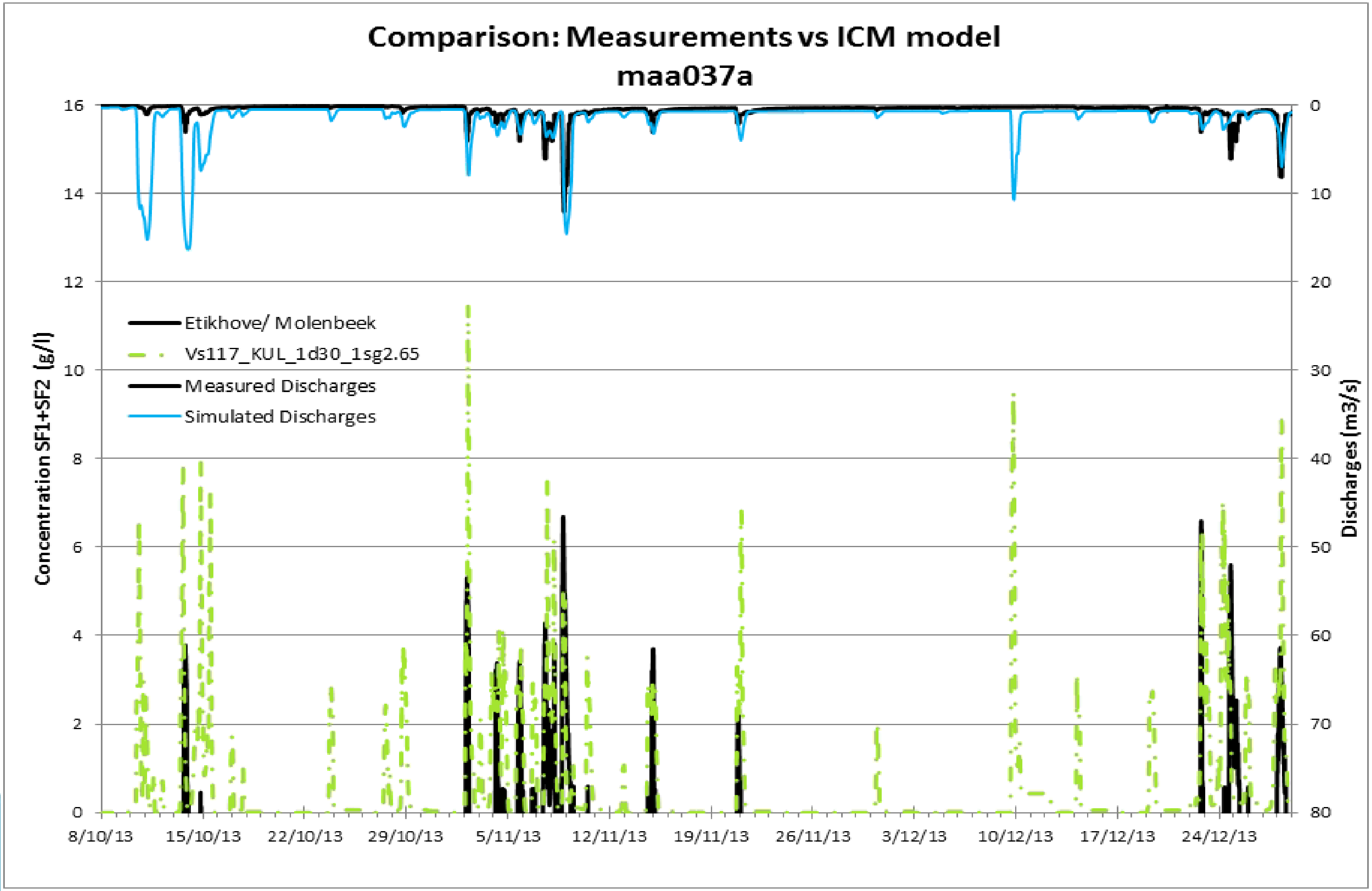
3. Sediment Transport Model

Validation (v117) – upstream:



3. Sediment Transport Model

Validation (v117) – downstream:

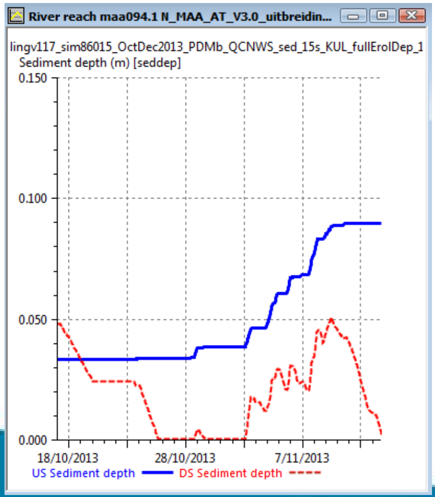


3. Sediment Transport Model

Calibration/Validation (v117) – deposition (cm):

Location	Event Nov'13		Event Dec'13		1 Year
	Meas.	Mod.	Meas.	Mod.	Mod.
Borgtmolen	5	5	5	3	67
Nonnemolen	-20	10	6	2	41
Gansbeekstraat	-20	-1	-	-	3
Kasteelmolen	-10	5	-	-	0

Borgtmolen: combination of erosion & deposition as observed



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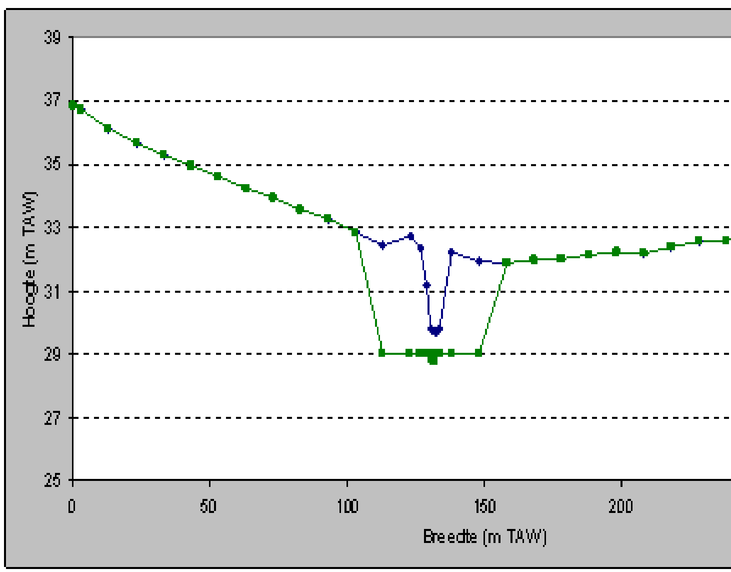
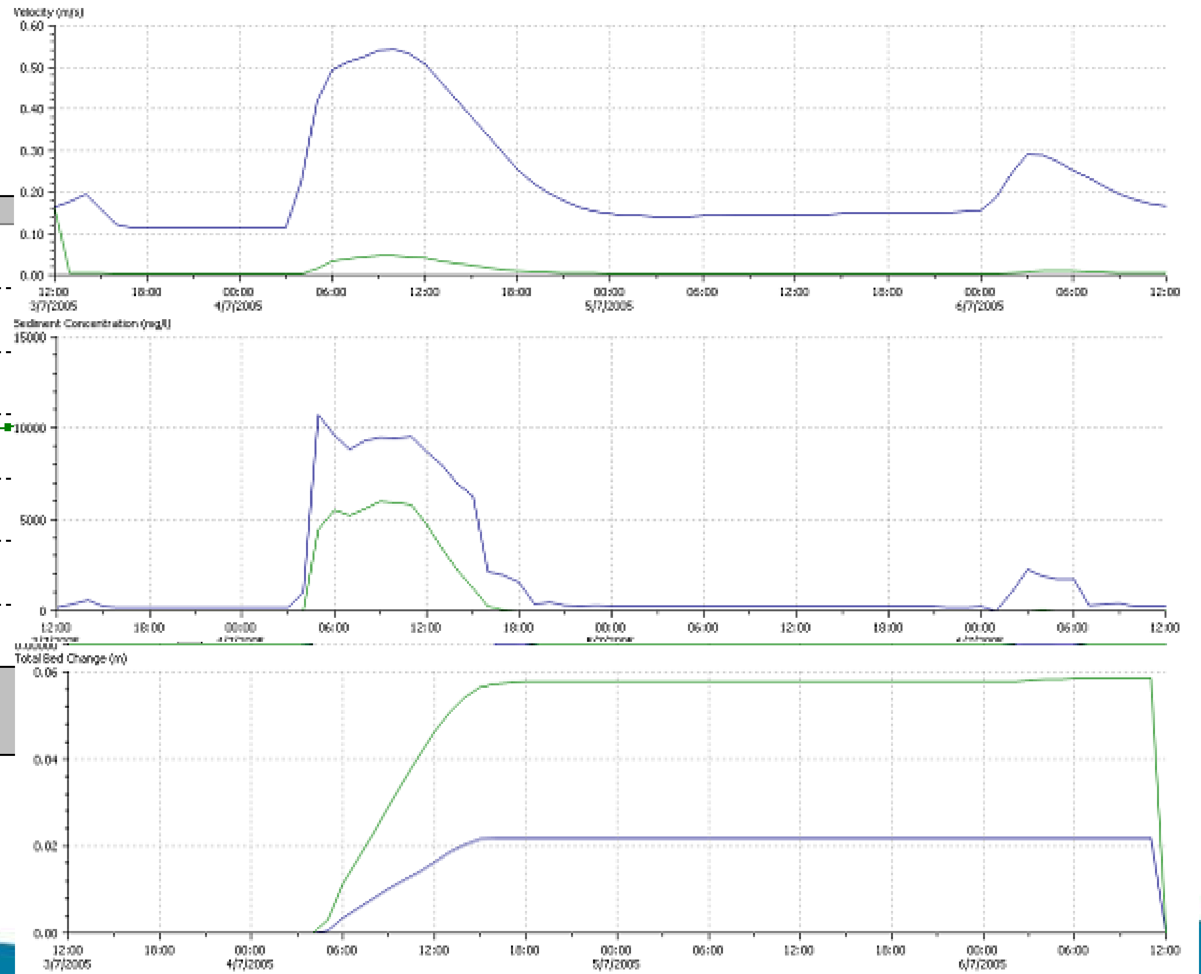
3. Sedment Transport Model

Modelling of river engineering measures:

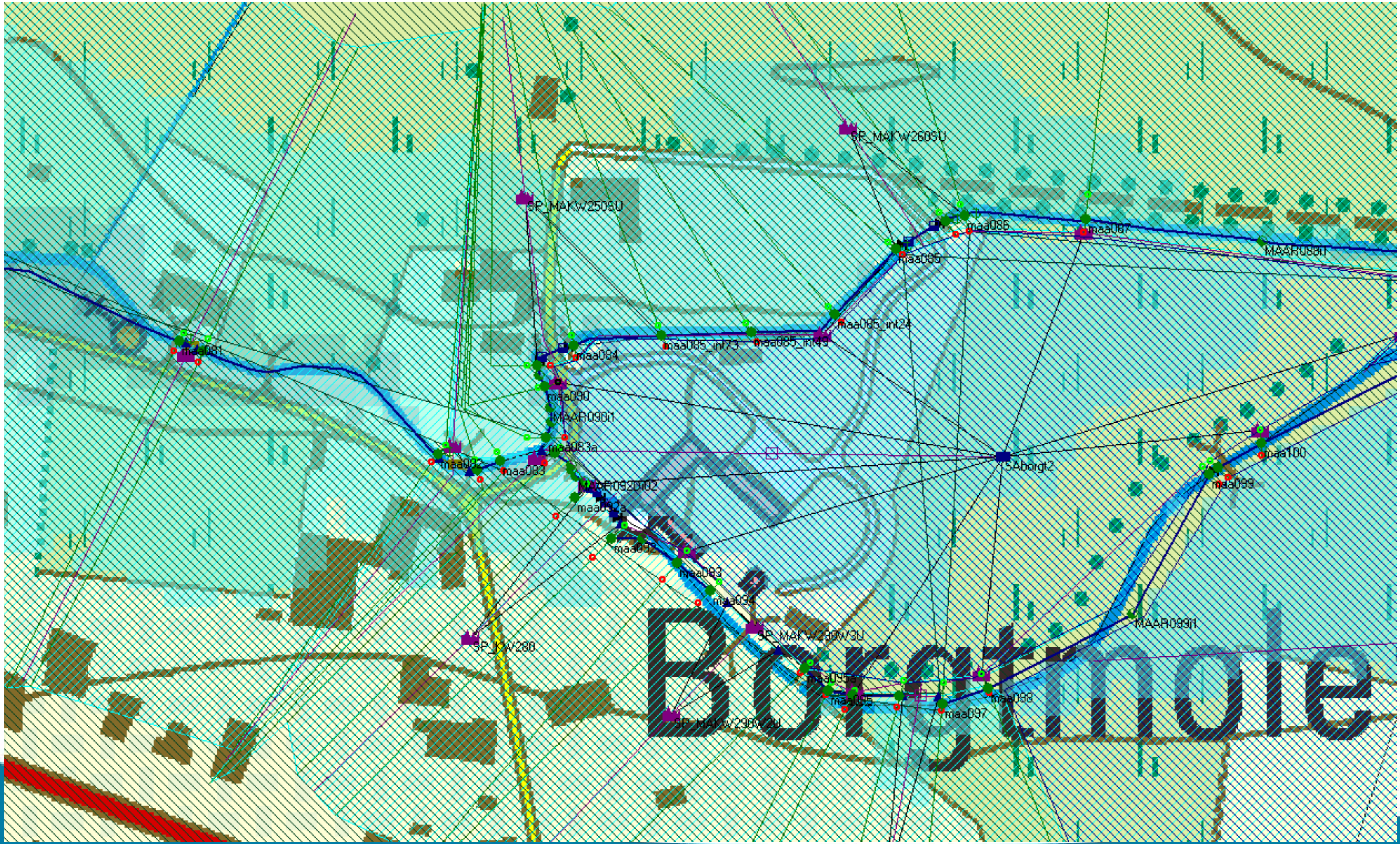
Sediment trap





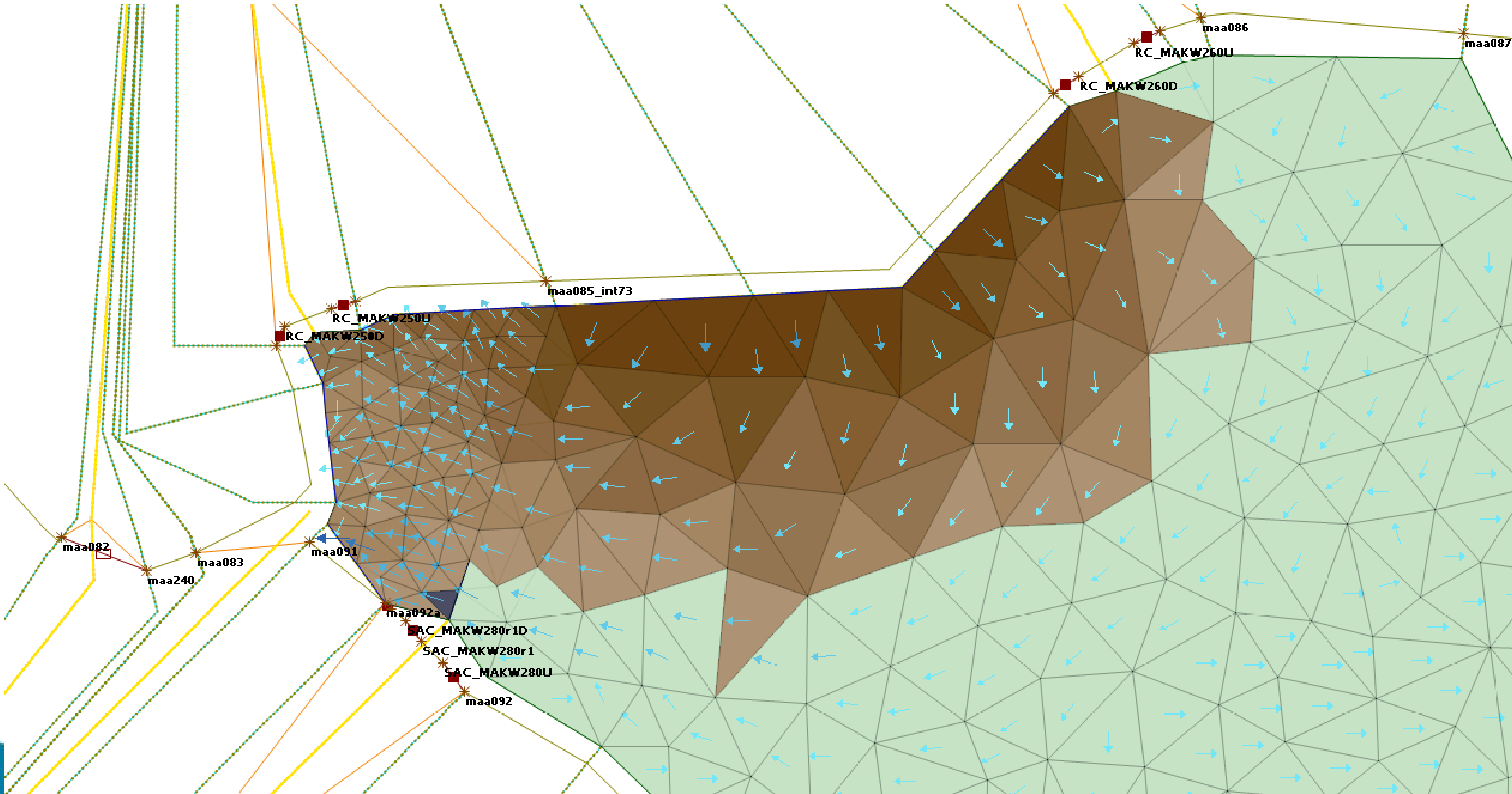
3. Sediment Transport Model

Simplified 2D approach for foodplains:



3. Sediment Transport Model

Simplified 2D approach for foodplains:



3. Sediment Transport Model

Conclusion

Limitations:

- Uncertainty on hydrodynamic input (SEM hydrogram)
- Uncertainty on sediment input (SEM sedigram)
- Uncertainty on calibration data (turbidity)
- Simplified model (1D, empirical ST equations, etc.)

STM is able to reproduce/predict the orders of magnitude and dynamics of sediment transport and deposition on a large temporal and spatial scale, and is capable of simulating the effect of river engineering measures

Future efforts:

- Improve Q and SSC inputs (SEM)
- Finetune calibration
- Development of ICM 1D ST module
- Quantification of uncertainty

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Thanks for your attention

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