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Impact of climate change on river hydrology and ecology: case study for interdisciplinary policy oriented research

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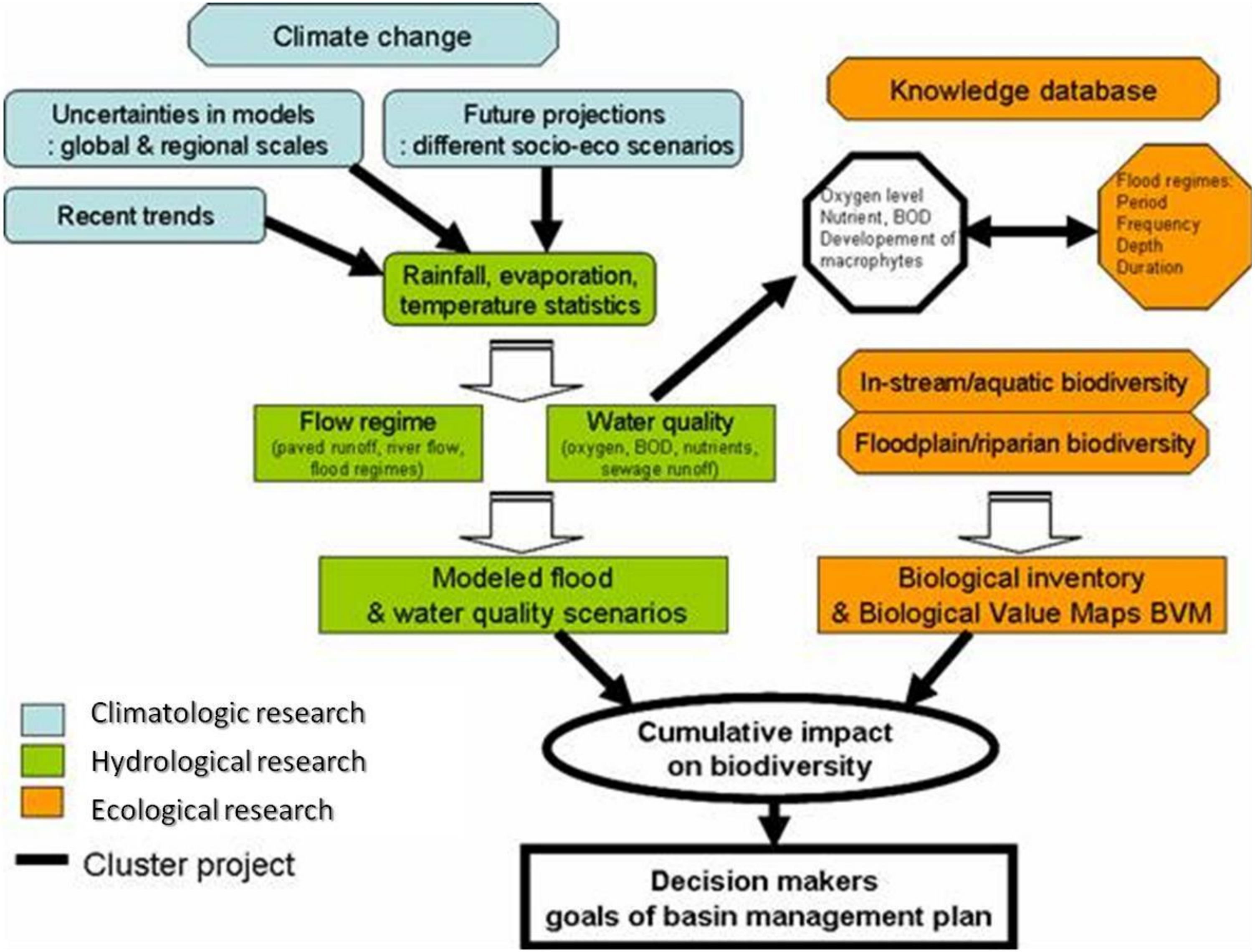
Universiteit Antwerpen

Overall framework



Climate change

Uncertainties in models : global & regional scales

Future projections : different socio-eco scenarios

Recent trends

Rainfall, evaporation, temperature statistics

Flow regime (paved runoff, river flow, flood regimes)

Water quality (oxygen, BOD, nutrients, sewage runoff)

Modeled flood & water quality scenarios

Knowledge database

Oxygen level
Nutrient, BOD
Developement of macrophytes

Flood regimes:
Period
Frequency
Depth
Duration

In-stream/aquatic biodiversity

Floodplain/riparian biodiversity

Biological inventory & Biological Value Maps BVM

Cumulative impact on biodiversity

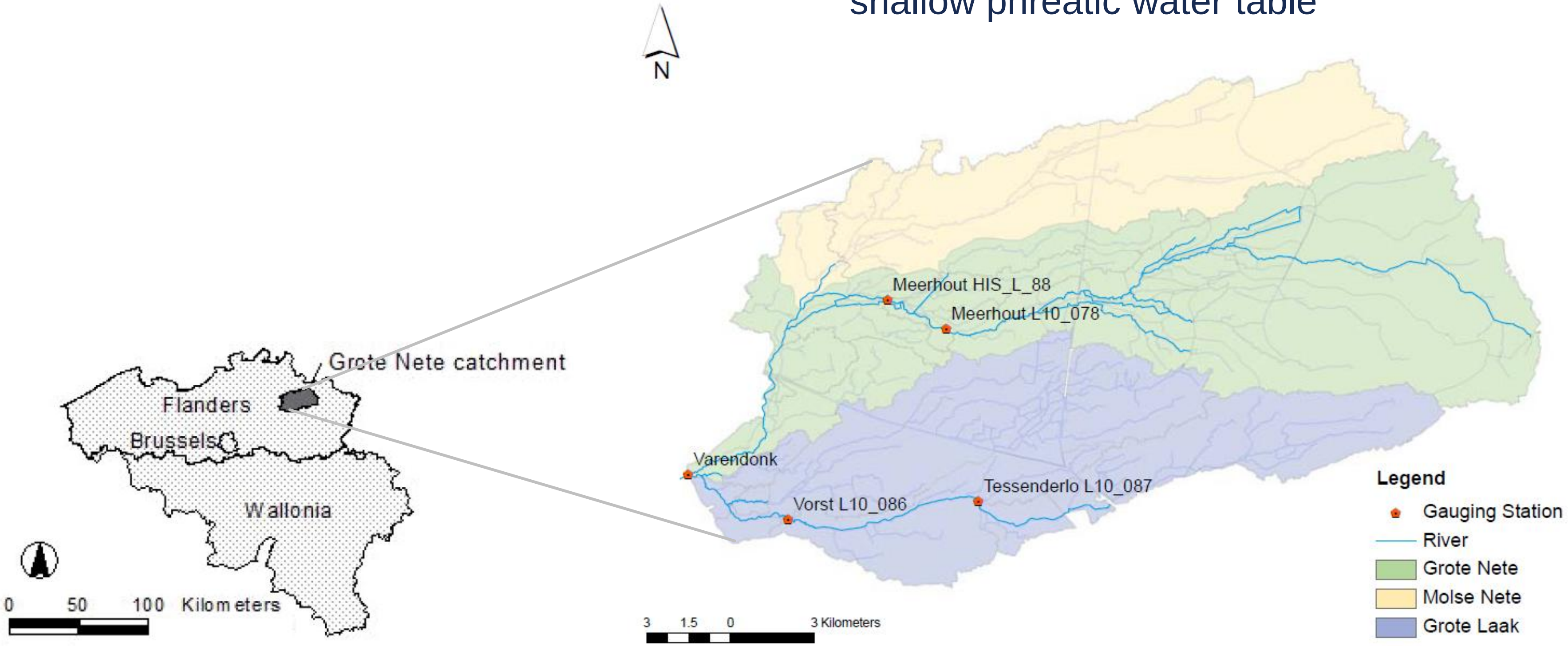
Decision makers goals of basin management plan

🟦 Climatologic research
🟩 Hydrological research
🟧 Ecological research
▬ Cluster project

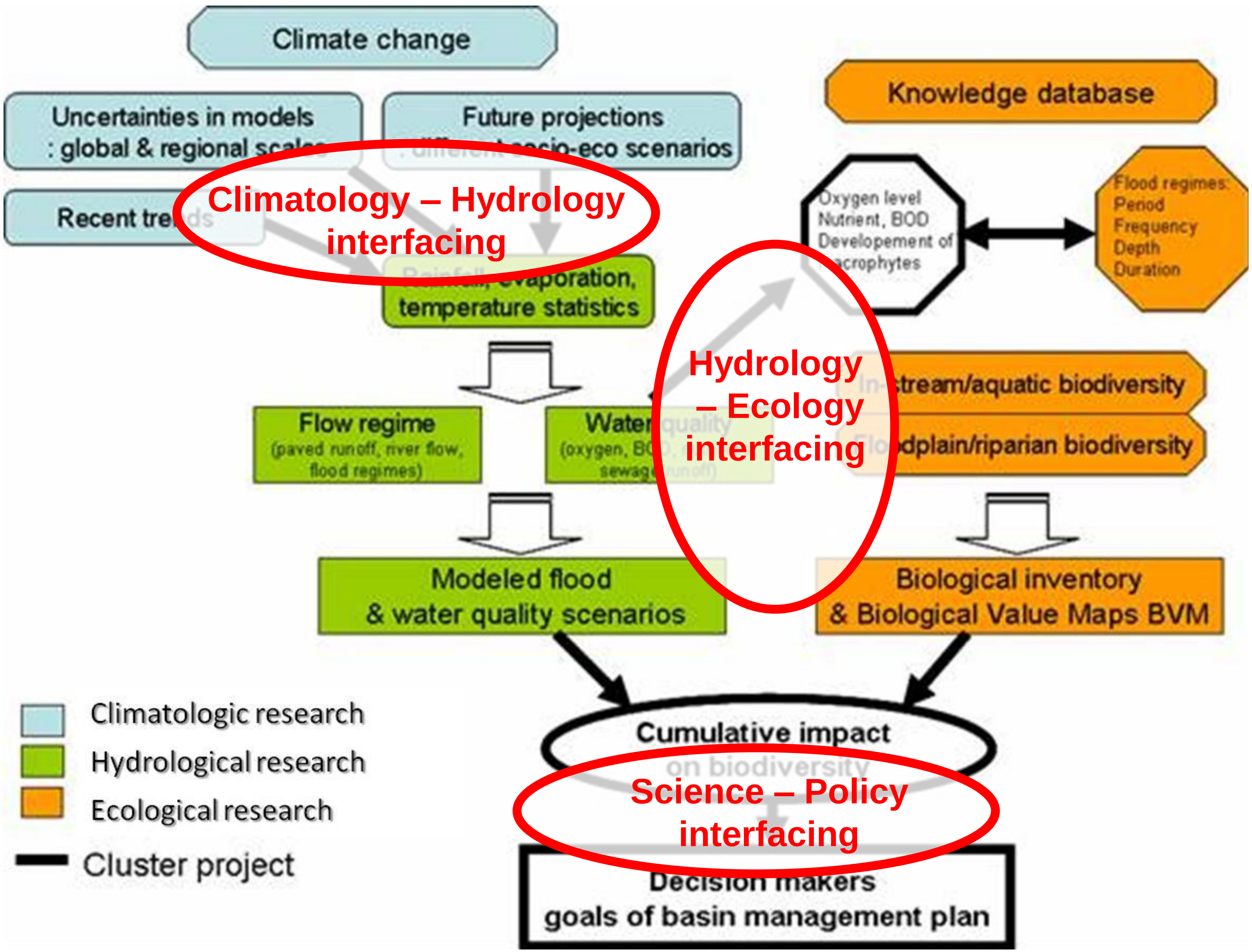
Case study

Grote Nete catchment (Scheldt basin)

385 km^2
average precipitation of 743 – 800 mm/year
flat topography (0.3% average slope)
sandy permeable soils, sandy loam and silt
shallow phreatic water table



Uncertainties and interfacing problems



Climatology – Hydrology interfacing

Hydrology – Ecology interfacing

Science – Policy interfacing

Climatology – Hydrology interfacing

Problems

- Climatologists:
  - Are not always well aware of the needs (time and space scales, accuracy, statistical indicators incl. extremes) for hydrological impact analysis
- Hydrologists:
  - Expect good/perfect predictions by climate models
  - Not always well aware of the climate model limitations (accuracy, time and space resolutions, unresolved processes: clouds, convection, land surface processes)
  - Not always used to deal with "ensemble" runs or with scenario uncertainty: tend to use 1 model and 1 run per type of impact
  - Do not always realize the need to preserve "physical consistency" between climate variables when using climate scenarios (e.g. seasonally depending correlation between precipitation change & temperature/PET change)
  - Apply bias correction and statistical downscaling methods without thorough understanding of climate model physics (limited ability to judge on downscaling assumptions made)

Climatology – Hydrology interfacing

Recommendations

Recommendations on climate change impact method:

- Ensemble approach: use several GCMs, RCMs, GHG emission scenarios, GCM/RCM intilialisations
- Evaluate the GCM/RCM runs, and potentially reject some runs
- Apply bias correction
- Apply statistical downscaling (in space and time): can be combined with bias correction
- Test the statistical downscaling method before use (assumptions involved, compare results from different methods/assumptions, apply ensemble approach on downscaling methods?)

Climatology – Hydrology interfacing

Statistical downscaling methods

Motivation:

- from large scale to small scale: local climate strongly determined by local topography and land surface heterogeneity
- GHG emission forcing mainly plays at larger (GCM) scales

→ Climate changes are less scale dependent than the climate itself

Related comment: dynamic downscaling not necessarily more accurate than statistical downscaling

Climatology – Hydrology interfacing

Statistical downscaling methods

Types of statistical downscaling methods + assumptions involved:

Empirical transfer function methods

Empirical fitting of relationships between predictors and predictants

Predictants do not need to be precipitation

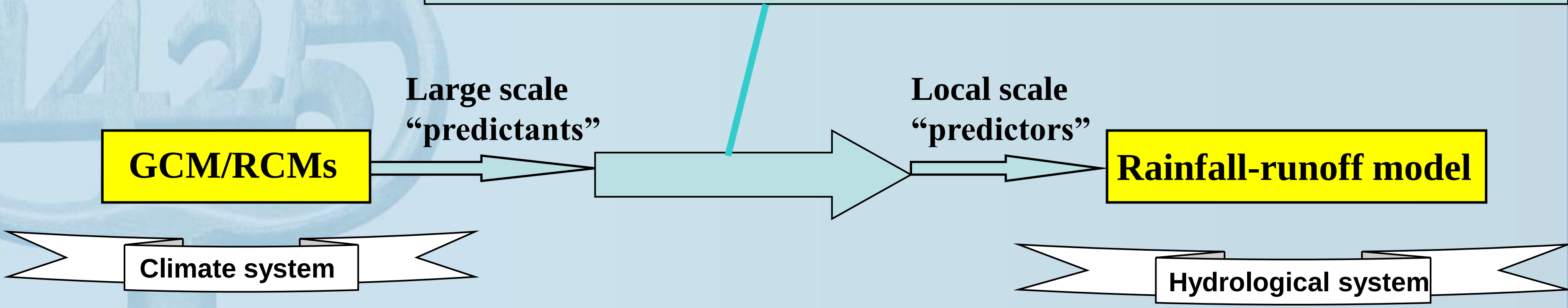
Resampling or weather typing based methods

Predictors based on analog days in the past or for different region (based on synoptic similarity)

Does not make direct use of the precipitation results of GCM/RCMs !

Stochastic rainfall models

Extension of stochastic hydrology (e.g. stochastic rainfall generators)



Large scale “predictants”

Local scale “predictors”

GCM/RCMs

Rainfall-runoff model

Climate system

Hydrological system

Case study application

Databases on climate model runs

- **PRUDENCE (EU FP5)** 31 runs (12 RCMs, 3 GCMs)
  A2 (mainly) and B2
- **ENSEMBLES (EU FP6)** 26 RCM runs
  only A1B
- **AR4 (IPCC)** 27 runs with 20 GCMs
  also A1, B1 and B2

More info: http://www.kuleuven.be/hydr/CCI-HYDR

Case study application

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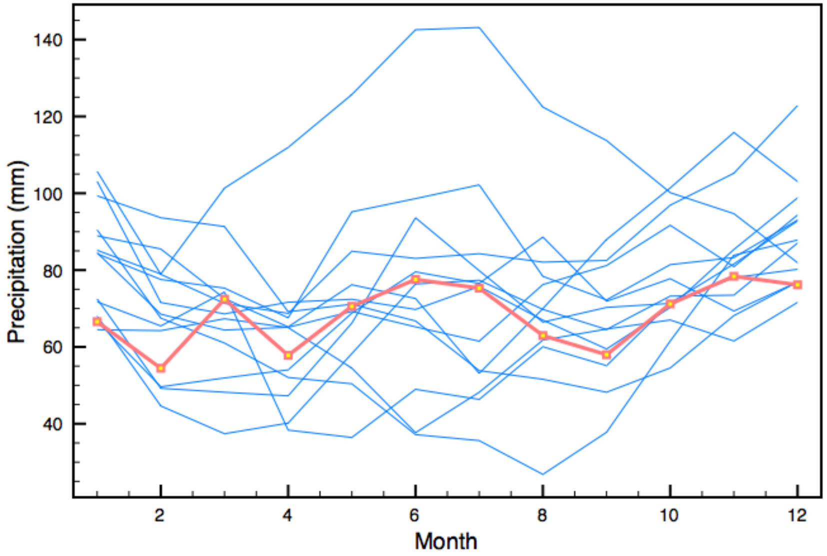
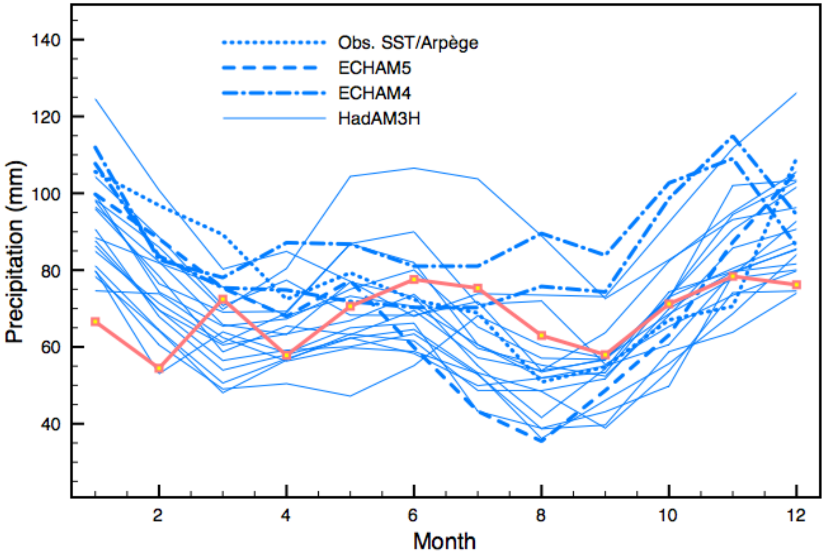
Climate model runs' validation (1961-1990):

GCMs 1961-1990 :



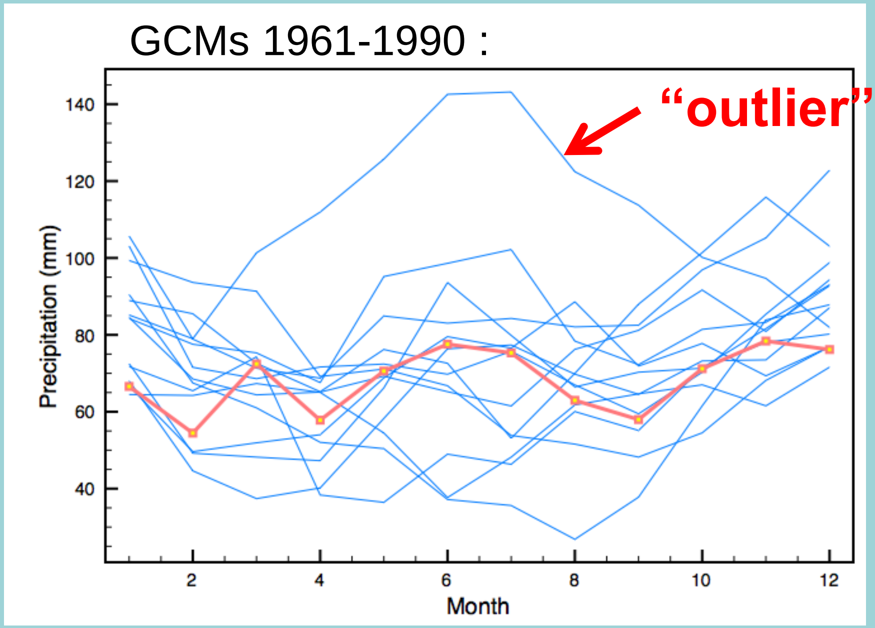
RCMs 1961-1990 :



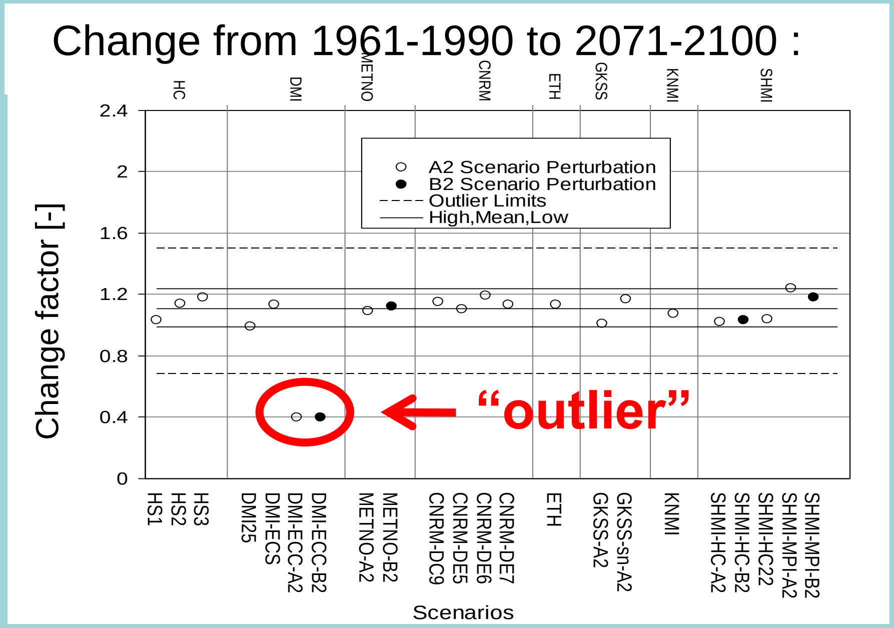
More info: Baguis, P., Roulin, E., Willems, P., Ntegeka, V. (2010). Climate change scenarios for precipitation and potential evapotranspiration over central Belgium. Theoretical and Applied Climatology 99(3-4), 273-286

Case study application

Climate model runs’ comparison and rejection of outliers:


GCMs 1961-1990 :

“outlier”


Change from 1961-1990 to 2071-2100 :

“outlier”

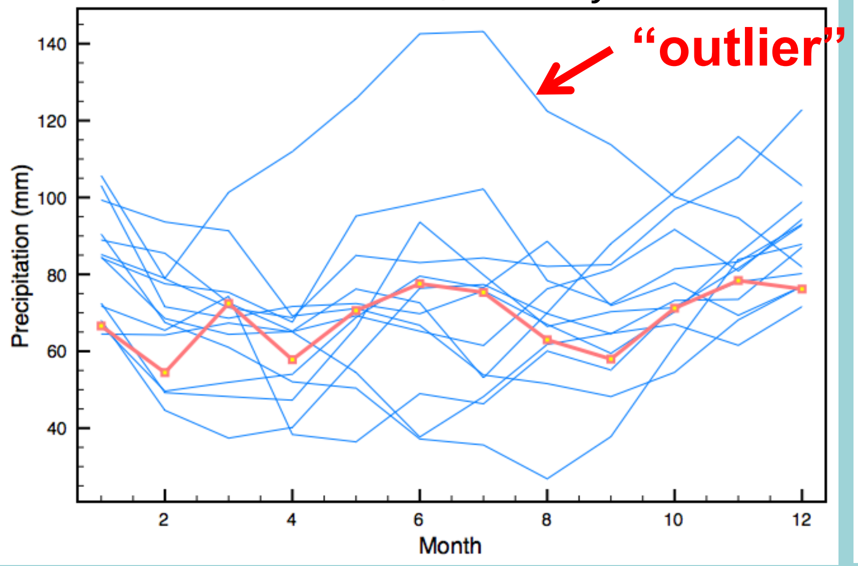
Questions remain: *Which physical climatology factors explain the statistical inconsistencies?*
Do we need to reject or accept statistically outlying climate model results?

More info: Baguis, P., Roulin, E., Willems, P., Ntegeka, V. (2010). Climate change scenarios for precipitation and potential evapotranspiration over central Belgium. Theoretical and Applied Climatology 99(3-4), 273-286

Case study application

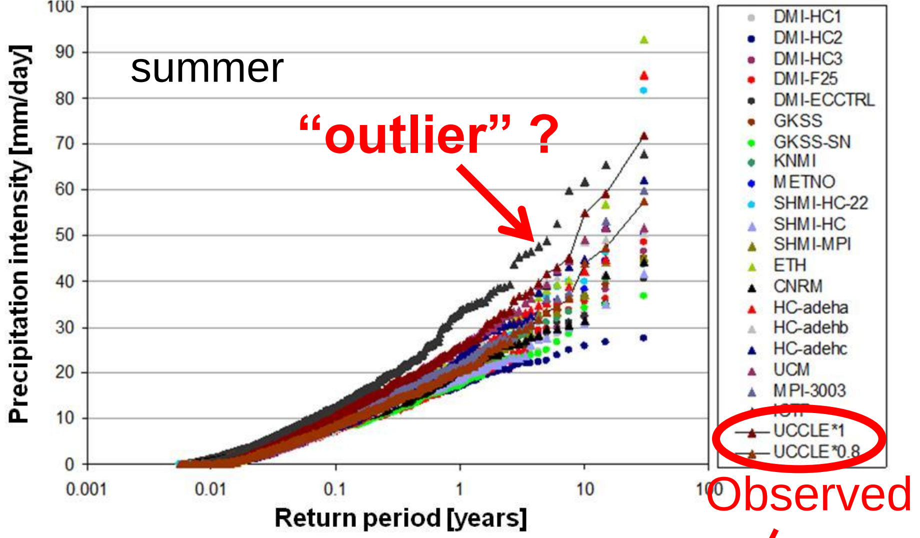
Climate model runs’ comparison and rejection of outliers:

GCMs 1961-1990, monthly :



“outlier”

RCMs 1961-1990, daily extremes :



“outlier” ?

Observed

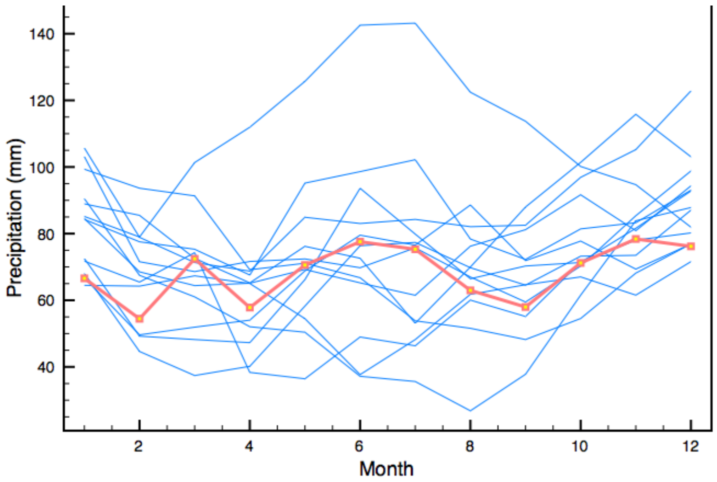
, but use of the “areal reduction factor” to account for the difference between areal and point rainfall

More info: Baguis, P., Roulin, E., Willems, P., Ntegeka, V. (2010). Climate change scenarios for precipitation and potential evapotranspiration over central Belgium. Theoretical and Applied Climatology 99(3-4), 273-286

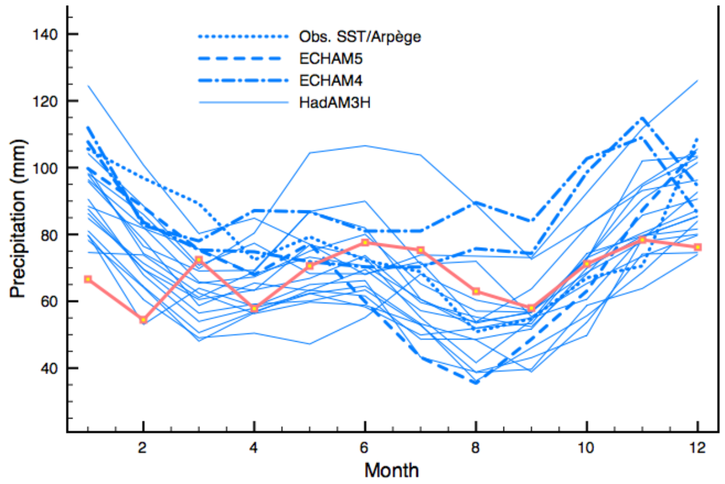
Case study application

Climate change: monthly precipitation cumulatives:

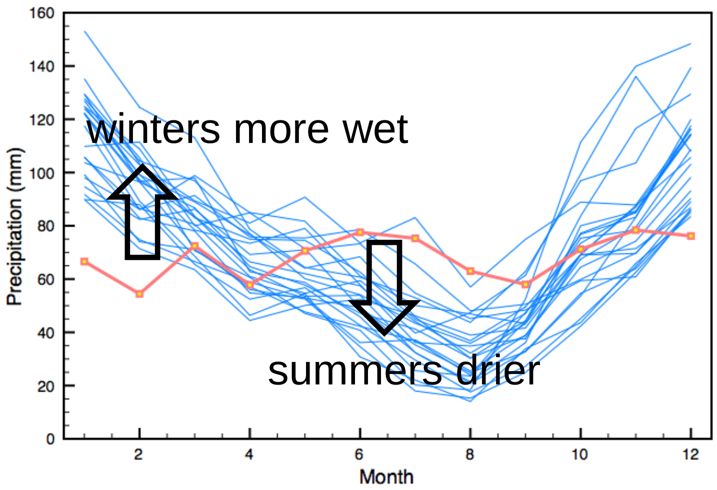
GCMs 1961-1990 :



RCMs 1961-1990 :



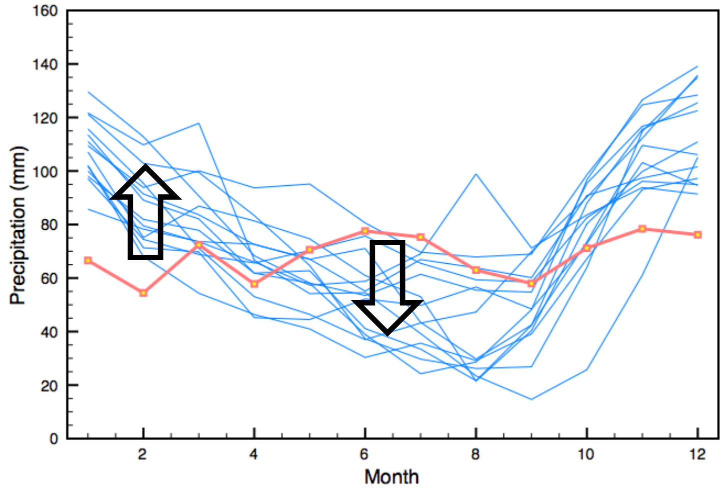
GCMs 2071-2100 :



winters more wet

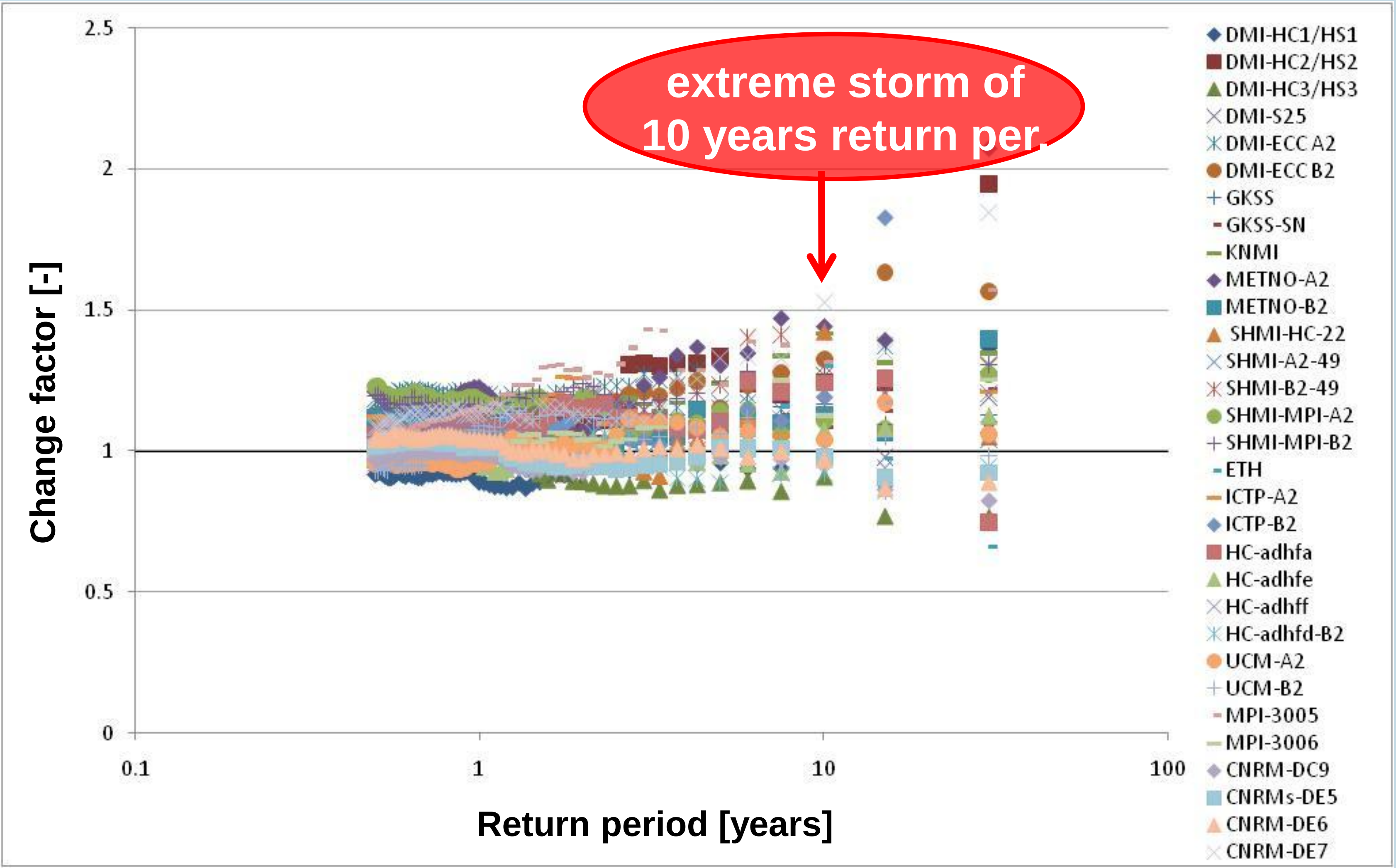
summers drier

RCMs 2071-2100 :



Case study application

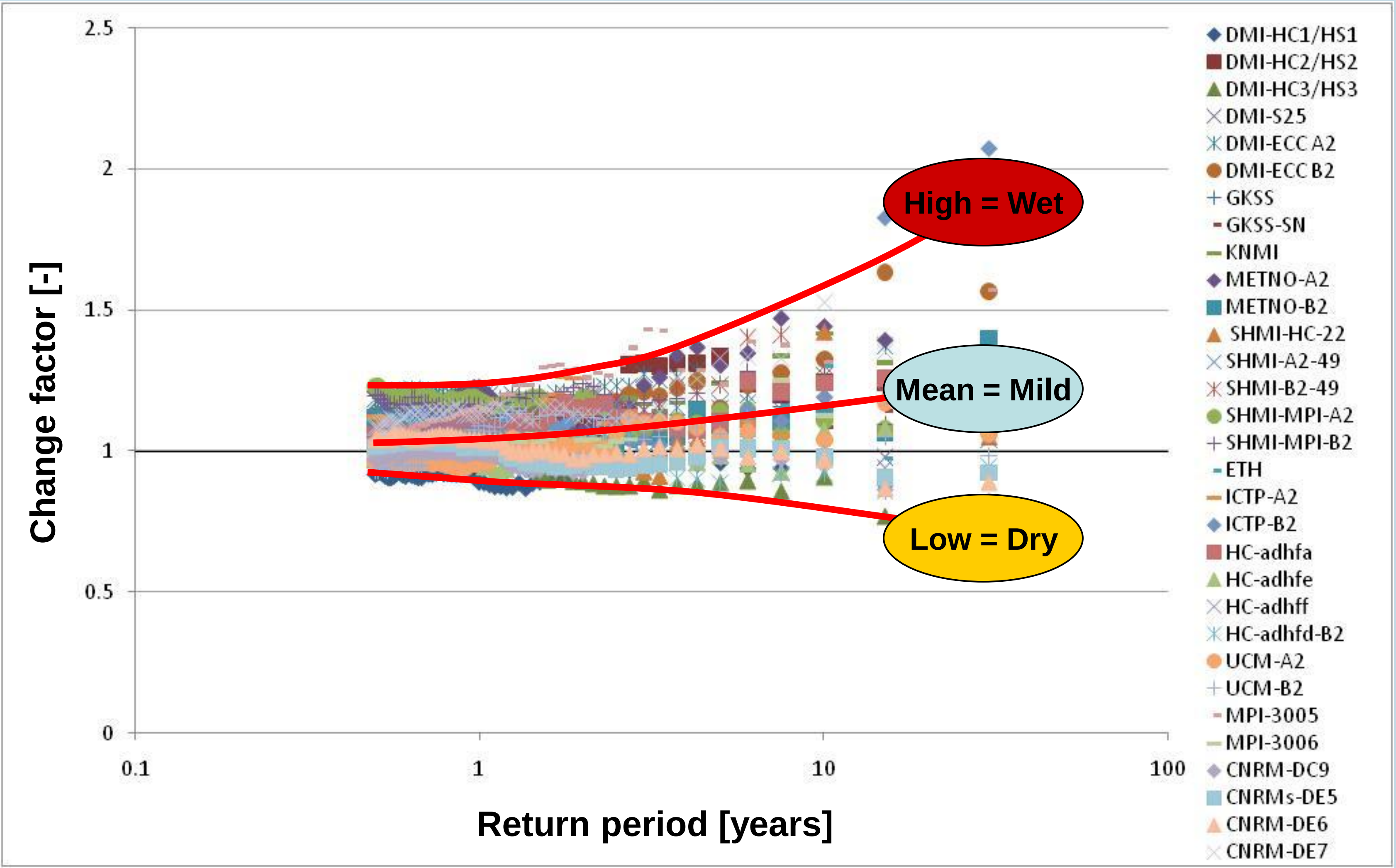
Climate change: daily summer extremes:



extreme storm of 10 years return per.

Climate change scenarios

Factor change from control to scenario period:



High = Wet

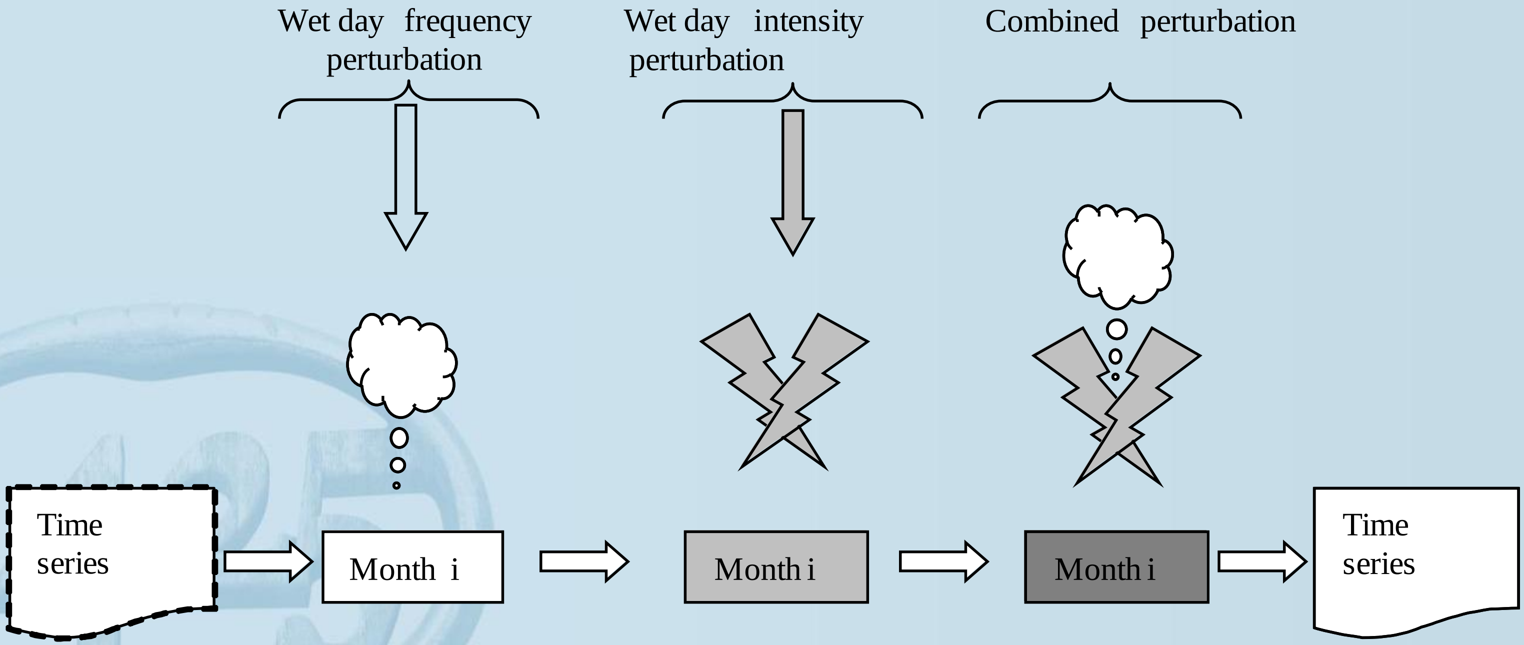
Mean = Mild

Low = Dry

Perturbation tool

Time series perturbations in:

- Wet day frequency (stochastic)
- Wet day intensities (return period dependent)



High = Wet

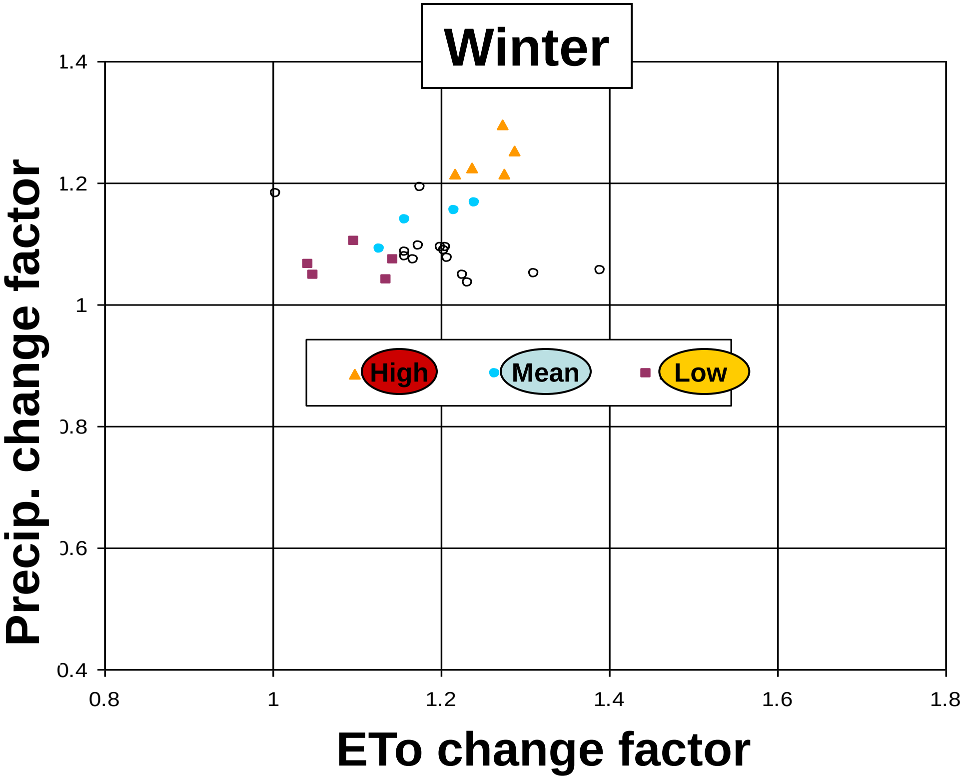
Mean = Mild

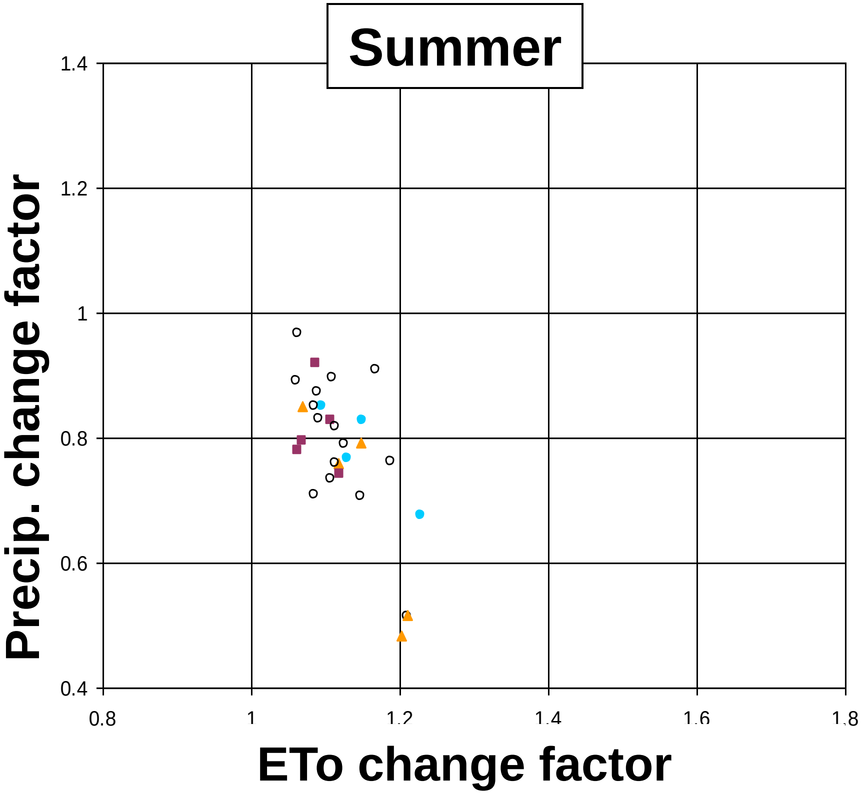
Low = Dry

+ statistical downscaling: daily -> hourly, 10min

Perturbation tool

Preserves physical consistency (dependency) between seasons and variables (precipitation, temperature and ETo)





Hydrological impact modelling

Rainfall, ETo

↓

Rainfall-runoff

NAM: lumped conceptual
MIKE-SHE: spatially distributed, detailed physically-based

↓

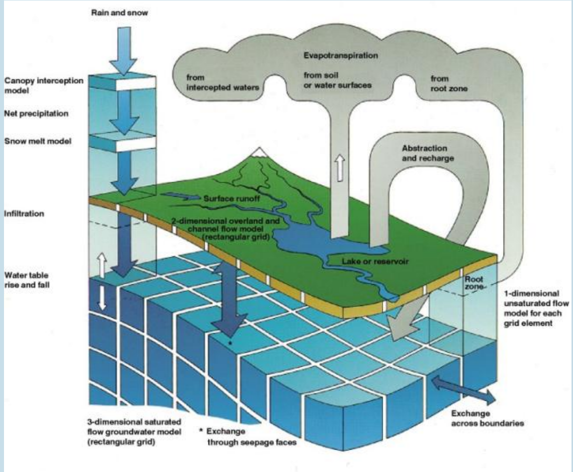
Hydrodynamics

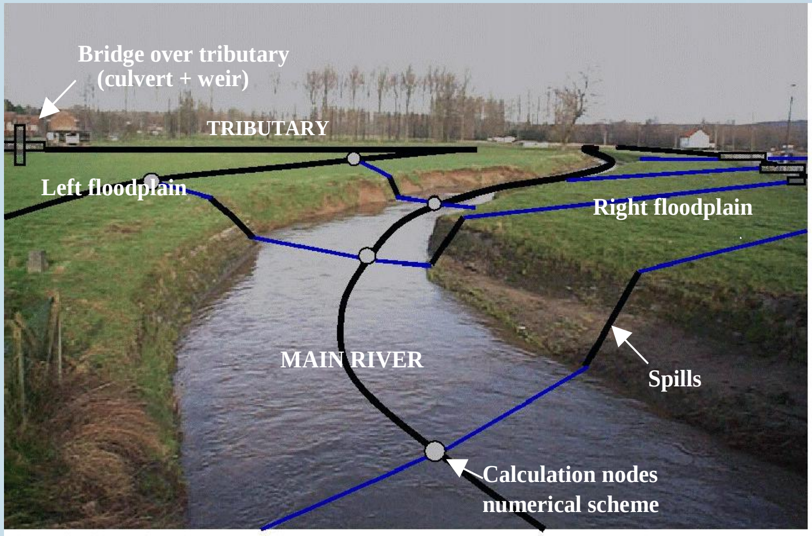
MIKE11 + quasi 2D floodplains
Conceptual model

↓

Physico-chemical water quality

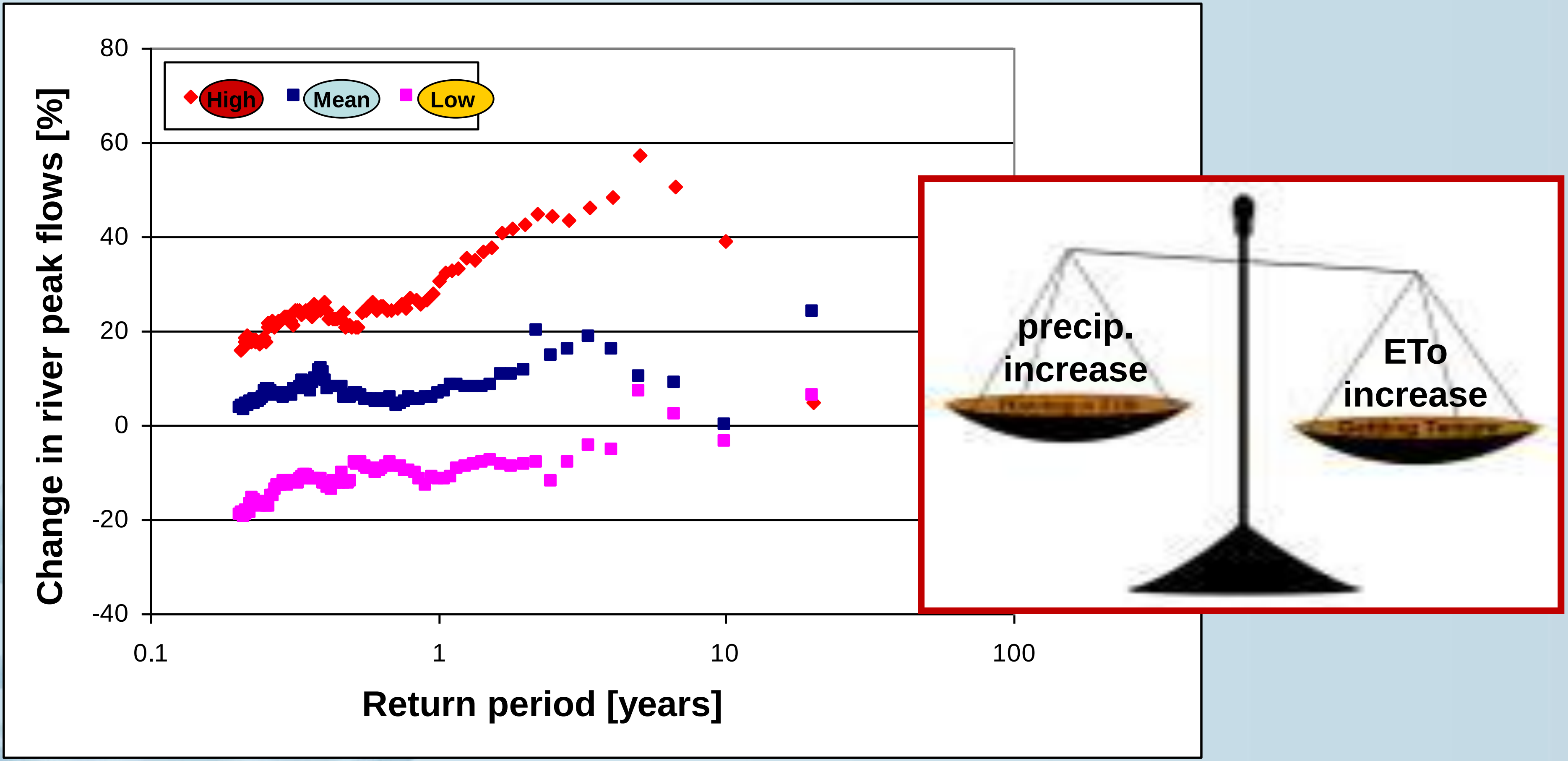
MIKE11/EcoLab





Hydrological impact

Impact of climate scenarios on hourly runoff peaks:

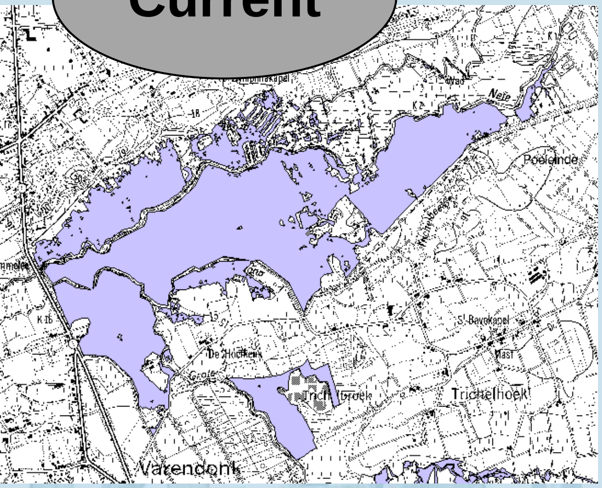


Hydrological impact

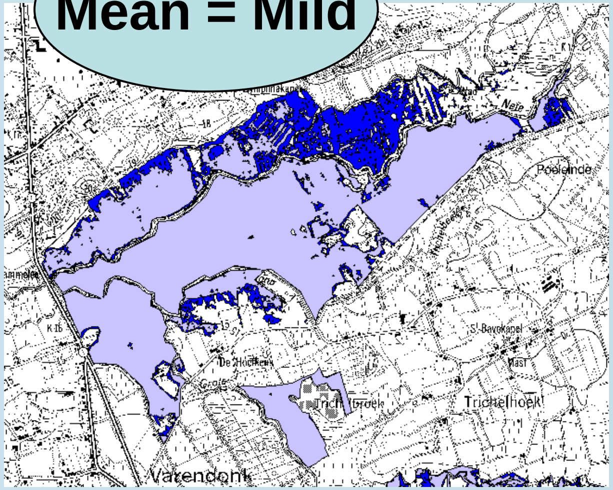
Impact of climate scenarios on floodplain inundations:

Flood hazard map for 10 years return period:

Current



Mean = Mild



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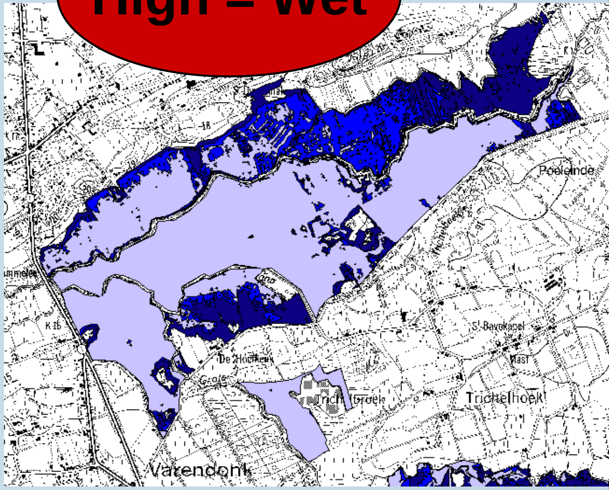
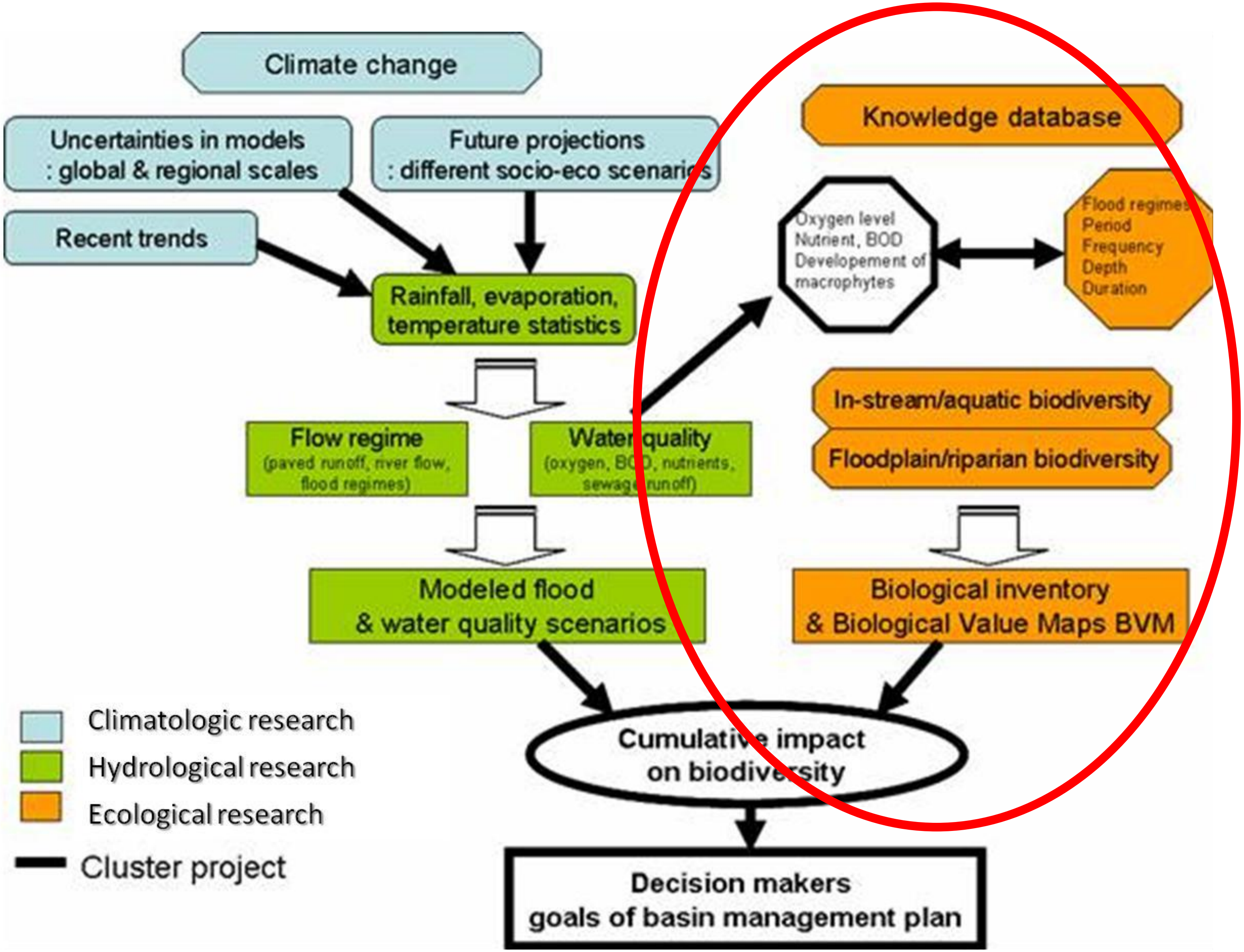


Hydrology – Ecology interfacing

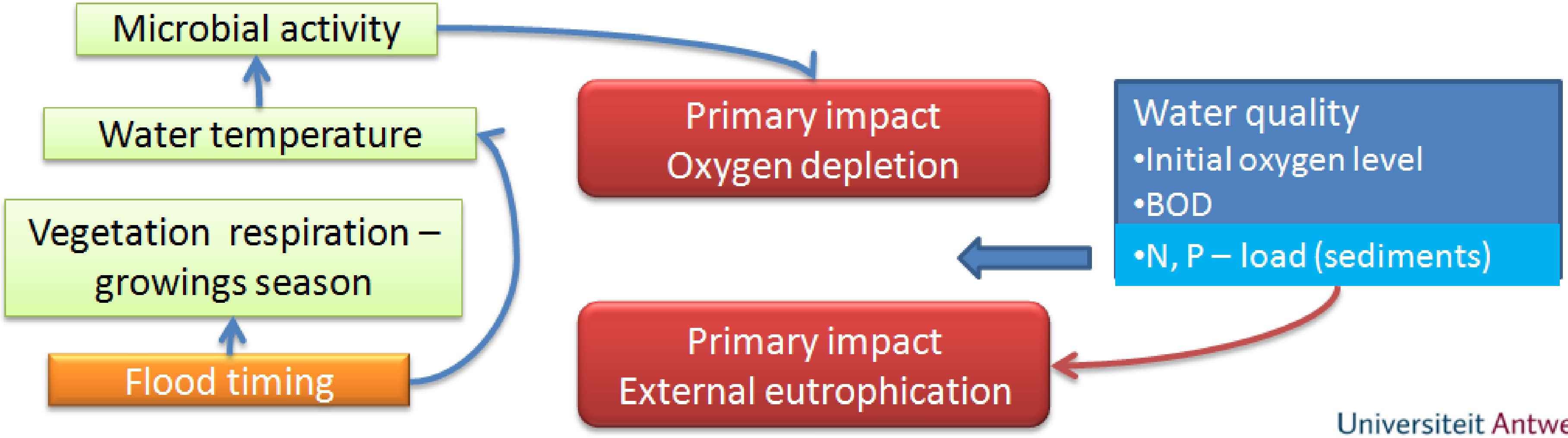


Flooding and ecology = Complexity

Primary impact
Oxygen depletion

Primary impact
External eutrophication

Flooding and ecology = Complexity



Microbial activity

Water temperature

Vegetation respiration – growings season

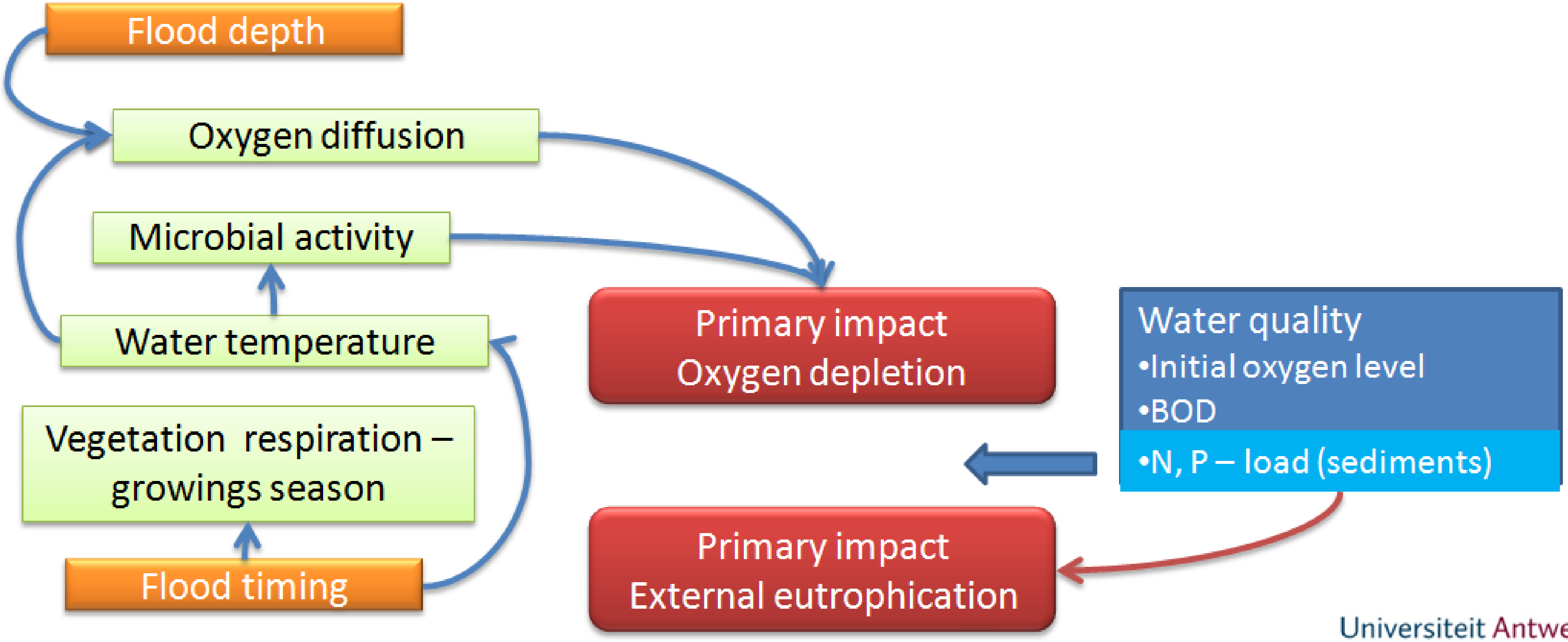
Flood timing

Primary impact
Oxygen depletion

Primary impact
External eutrophication

Water quality
- Initial oxygen level
- BOD
- N, P – load (sediments)

Flooding and ecology = Complexity



Flood depth

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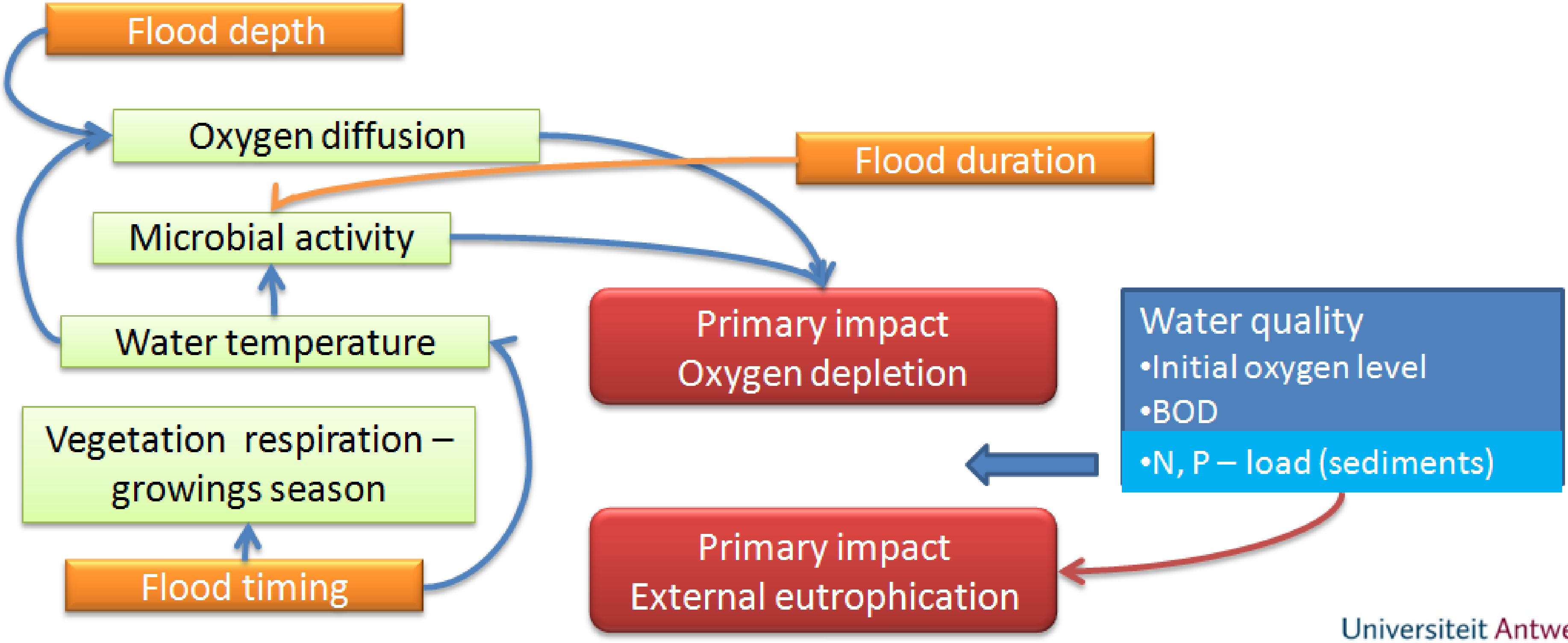

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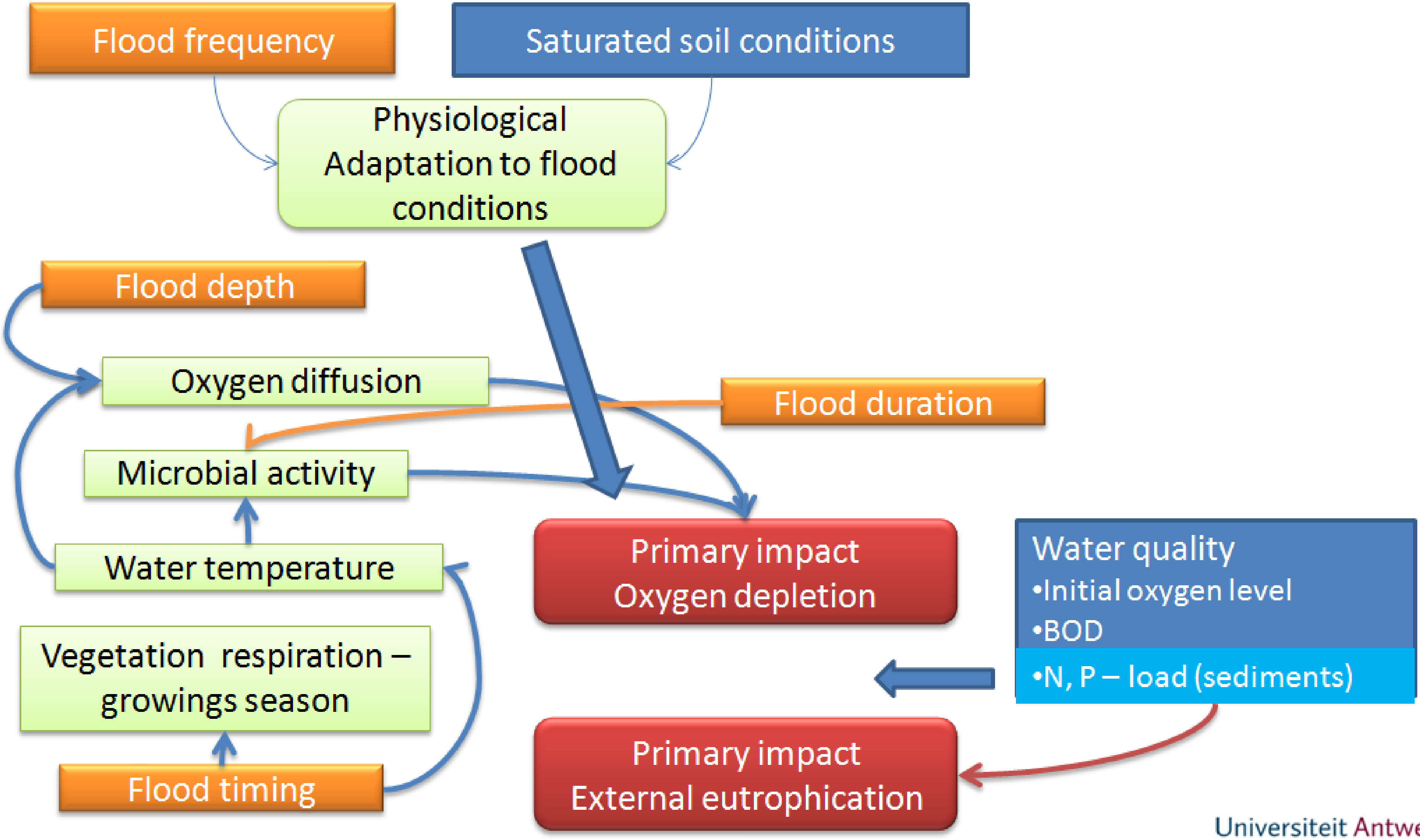

Flood frequency

Saturated soil conditions

Physiological Adaptation to flood conditions

Flood depth

Oxygen diffusion

Flood duration

Microbial activity

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Vegetation respiration – growings season

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Primary impact
External eutrophication

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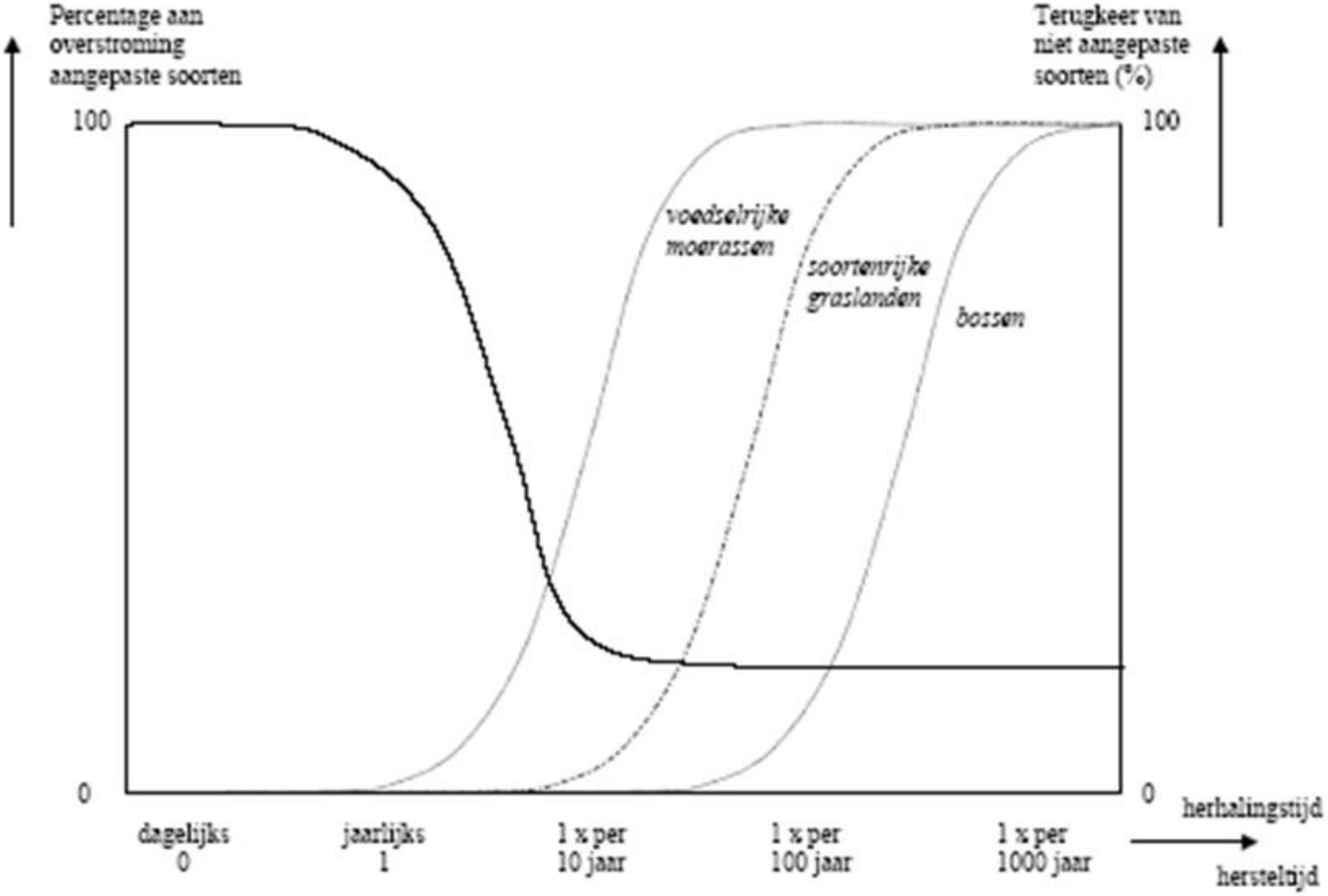
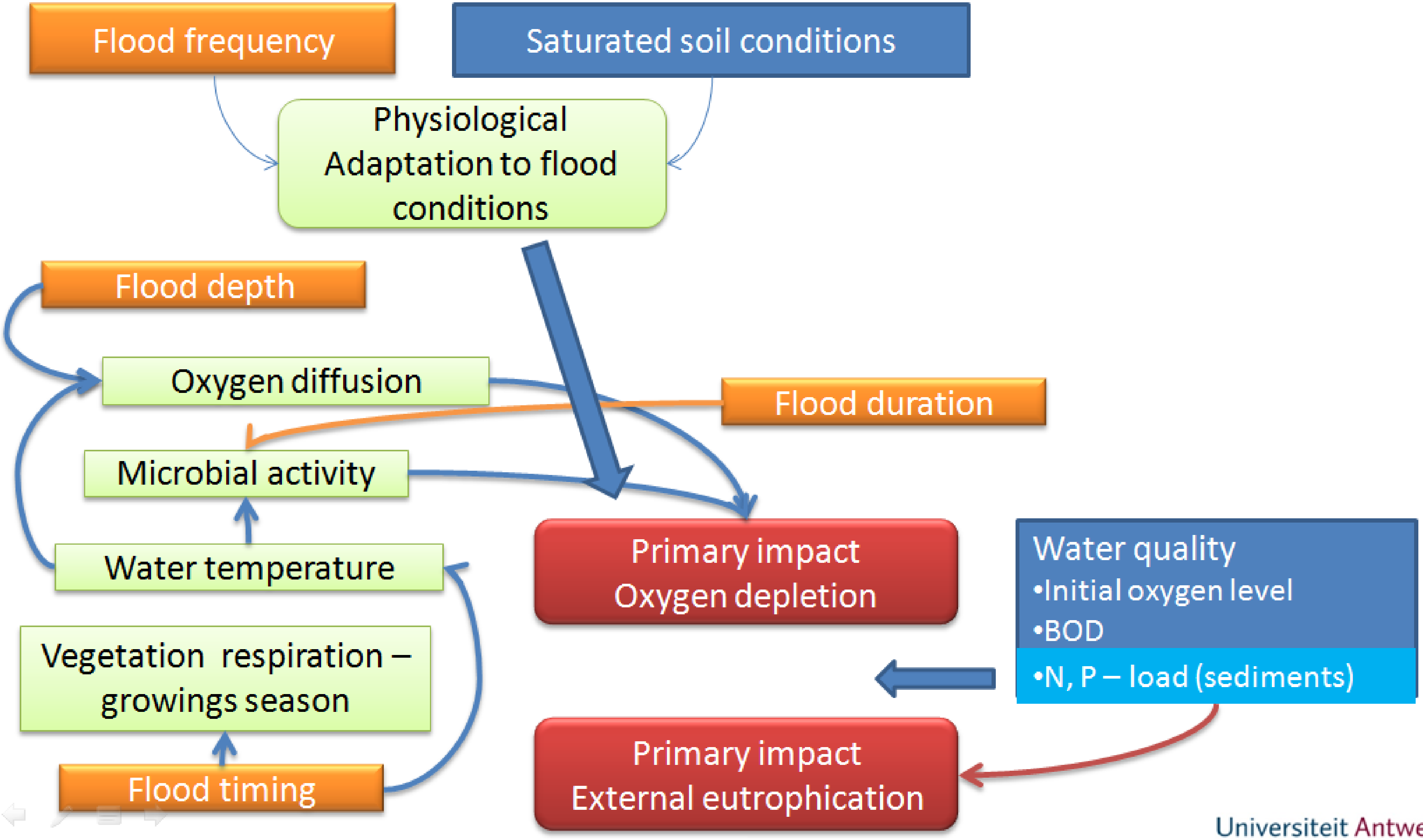
Why flood frequency/regularity is important



Effect of return period on % of adapted species

Flooding and ecology = Complexity



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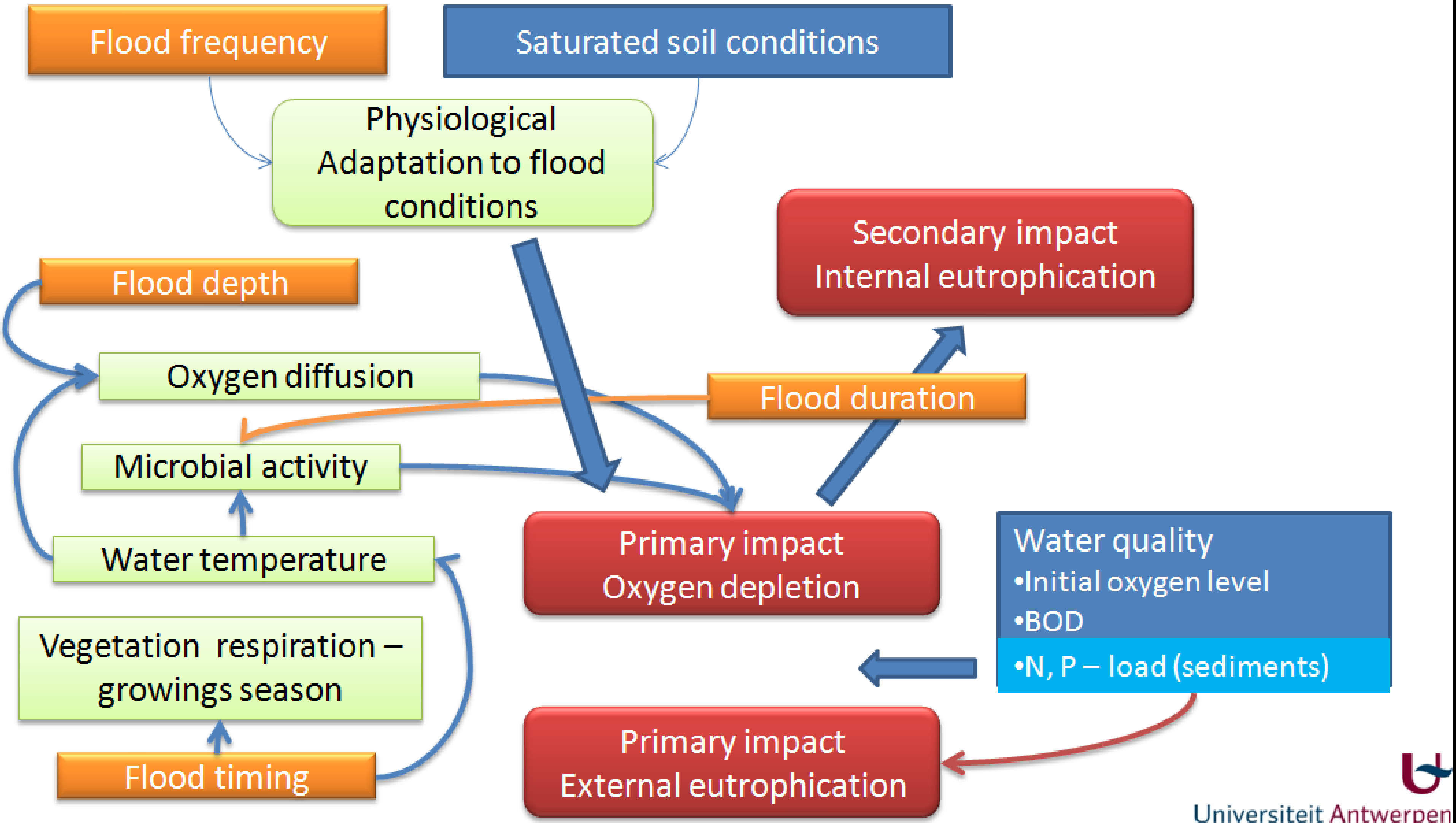
Primary impact
External eutrophication

Flooding and ecology = Complexity



Flood frequency

Saturated soil conditions

Physiological Adaptation to flood conditions

Secondary impact
Internal eutrophication

Flood depth

Oxygen diffusion

Flood duration

Microbial activity

Water temperature

Primary impact
Oxygen depletion

Water quality
- Initial oxygen level
- BOD
- N, P – load (sediments)

Vegetation respiration – growings season

Flood timing

Primary impact
External eutrophication

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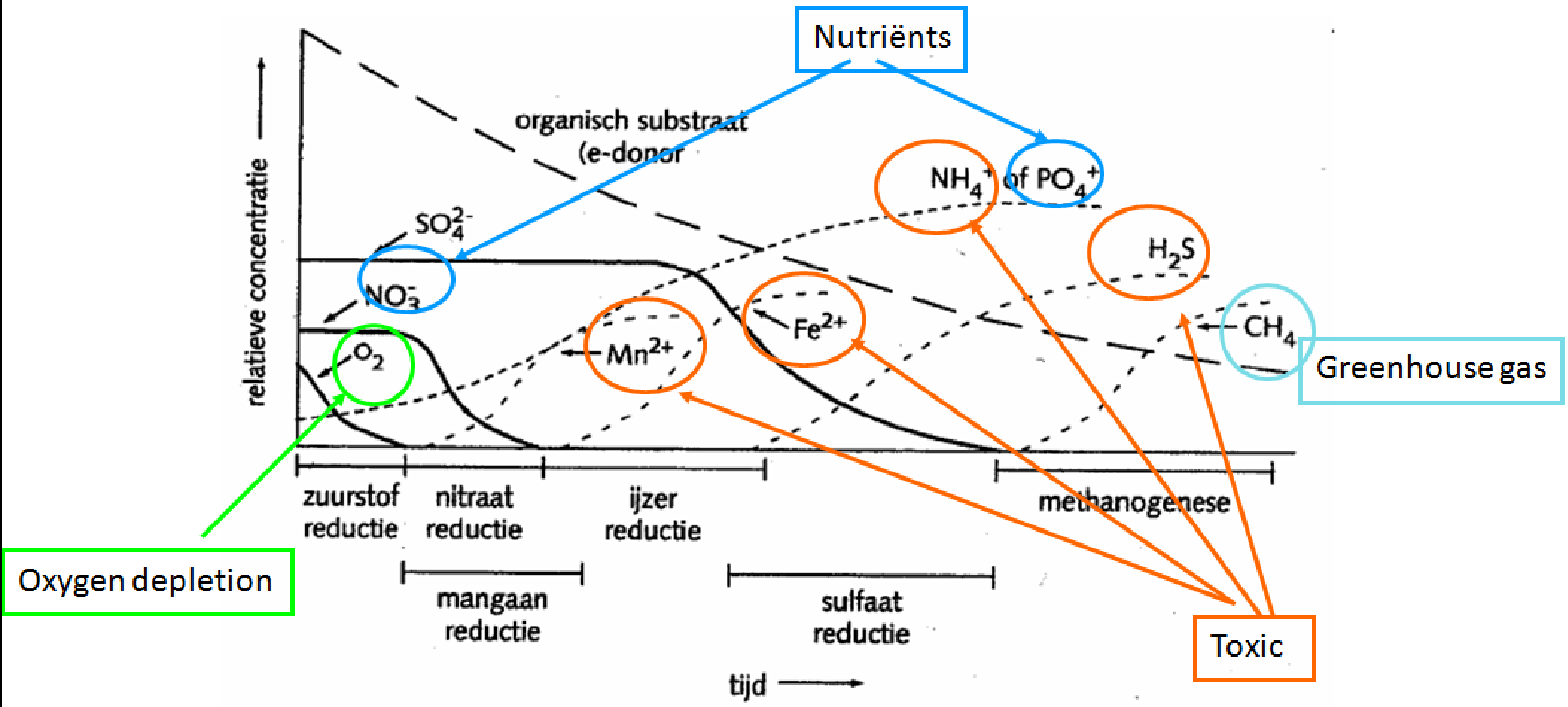
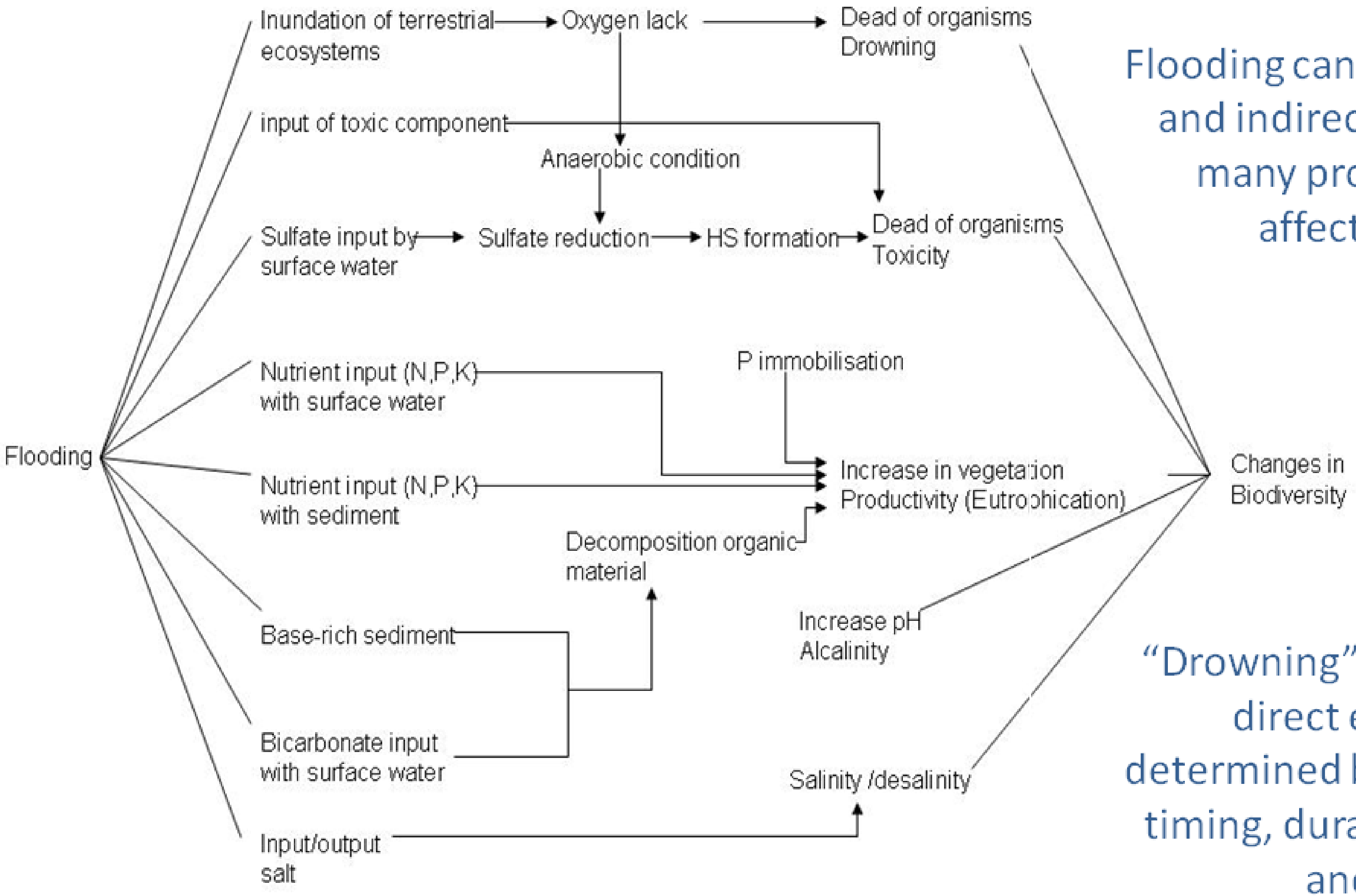
Why timing and duration of the inundation is crucial !!!



Consecutive reduction processes in function of flood duration (Mitsch& Gosselink, 1993).

Determination of ecological impact of changes in flood characteristics



Flooding

Inundation of terrestrial ecosystems

Oxygen lack

Dead of organisms
Drowning

input of toxic component

Anaerobic condition

Sulfate input by surface water

Sulfate reduction

HS formation

Dead of organisms
Toxicity

Nutrient input (N,P,K) with surface water

P immobilisation

Nutrient input (N,P,K) with sediment

Increase in vegetation
Productivity (Eutrophication)

Decomposition organic material

Base-rich sediment

Increase pH
Alcalinity

Bicarbonate input with surface water

Salinity /desalinity

Input/output salt

Changes in Biodiversity

Flooding can have direct and indirect impact on many processes that affect vegetation

“Drowning” is the most direct effect and is determined by the flood timing, duration, depth and frequency

Processes dealing with the effect of flooding on the biodiversity of an ecosystem

Hydrology – Ecology interfacing

Needs/Problems in flood context

- Most important flood parameters for ecology are:

  Flood timing > flood duration > flood regularity > flood depth

- Flood risk assessments usually focus on:

  Extreme events (flood depth at max. extent)

- Often no information on:
  - Changes in timing and frequency of regular floods (annual, bi-annual)
  - Flood duration is often not modelled, and is spatially variable during flood events

- Some advances in flood risk modelling actually reduce the information content for other applications

  Trade-offs between calculation time and information content

Hydrology – Ecology interfacing

Recommendations

- Statistical methods that assess changes in frequency and regularity of combinations of timing, duration and depth:
  - Traditional flood hazard estimation method to be extended with long term simulations and statistical post-processing of results
  - To limit calculation time: Simplified river and floodplain model calibrated to full hydrodynamic model + GIS spatial mapping of results
- A reference time series to be compared with a future scenario:
  - Reference will determine current flood resistence (adaptation or recovery status)
  - The impact occurs through changes in both regular as extreme events

Case study application

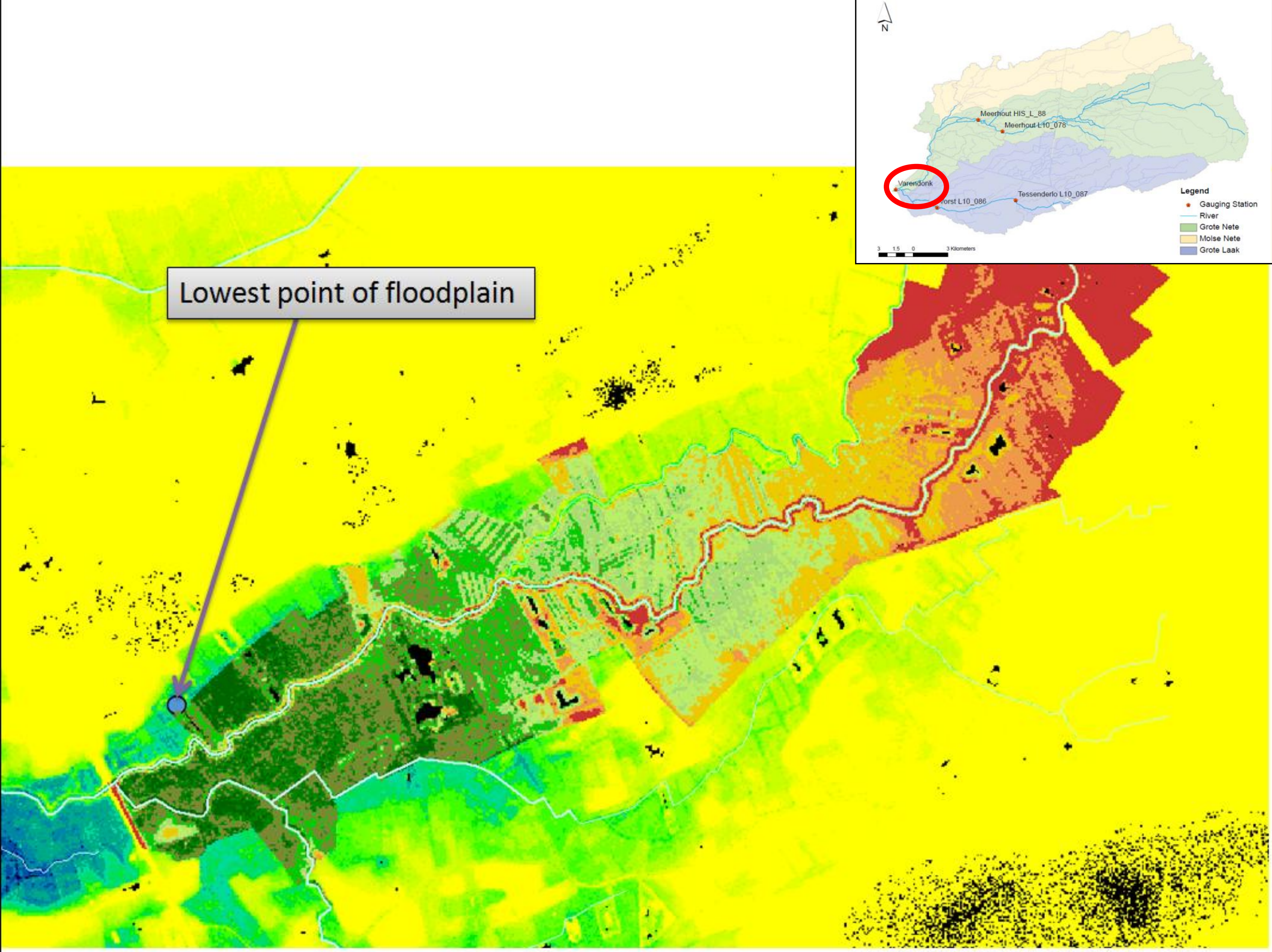
Steps

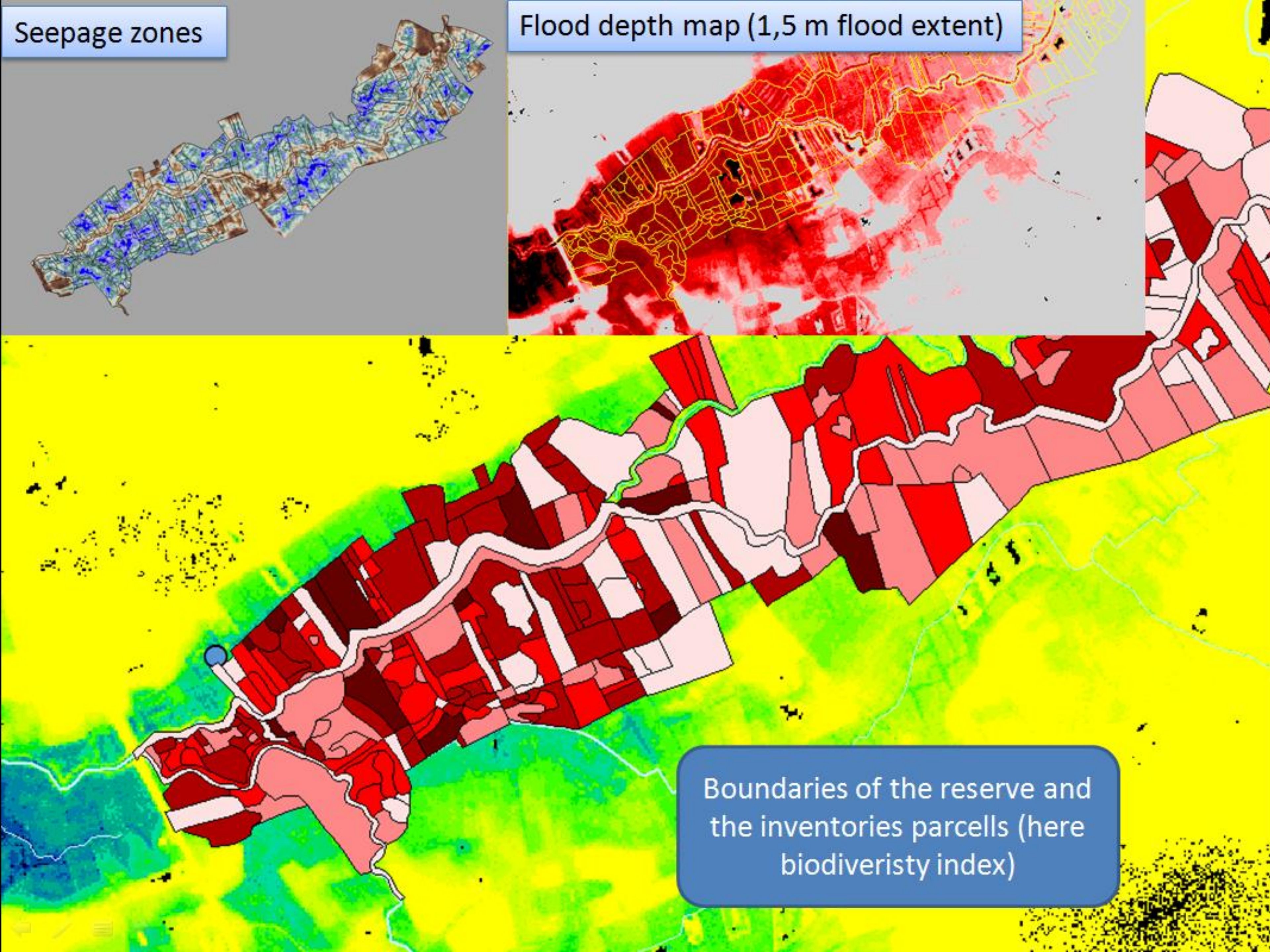
- Floodplain wetland considered with high ecological values
- Current climate results were compared with the high climate scenario for 15 year time window (1986-2002)
- Changes were studied in occurence of 12 floodtypes at elevation intervals of 10 cm within the floodplain

winter	< 14 d	< 20
winter	< 14 d	20-40
winter	< 14 d	> 40
winter	< 14 d	< 20
winter	< 14 d	20-40
winter	< 14 d	> 40
summer	> 14 d	< 20
summer	> 14 d	20-40
summer	> 14 d	> 40
summer	> 14 d	< 20
summer	> 14 d	20-40
summer	> 14 d	> 40

<u>Differentiation in flood regularity</u>

- Frequent (annual)
- Regular (bi-annual)
- Irregular (once in 2-5 years)
- Seldom (once in 5-25 years)





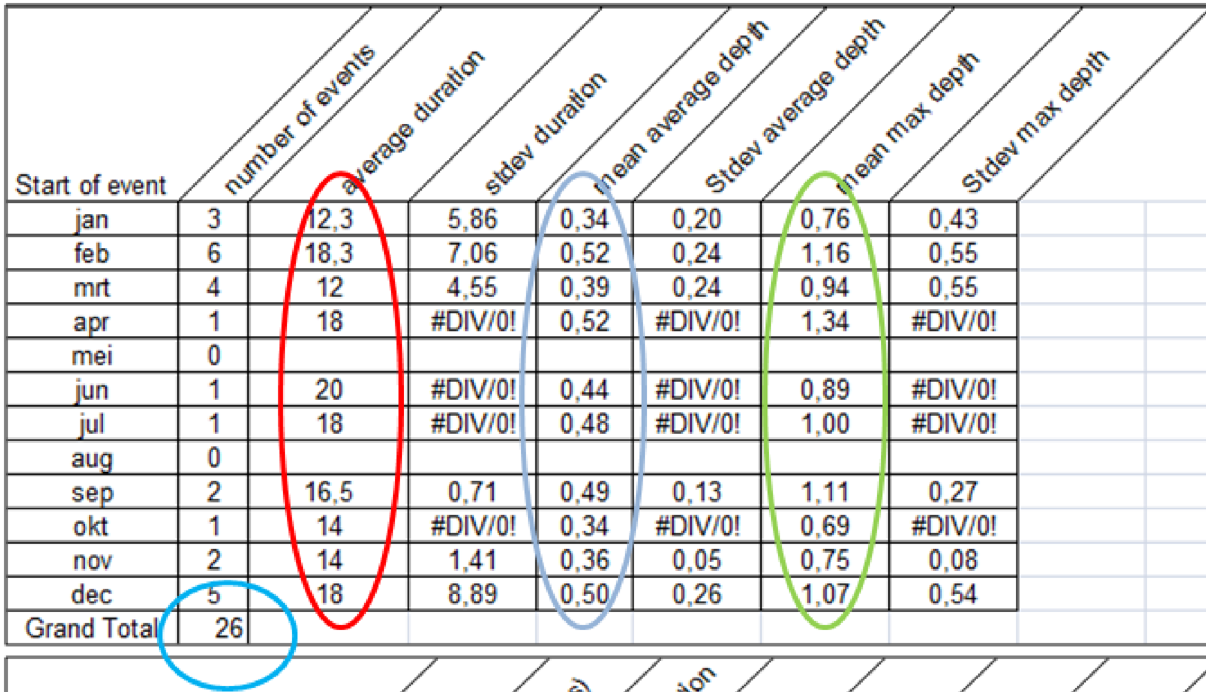
Seepage zones

Flood depth map (1,5 m flood extent)

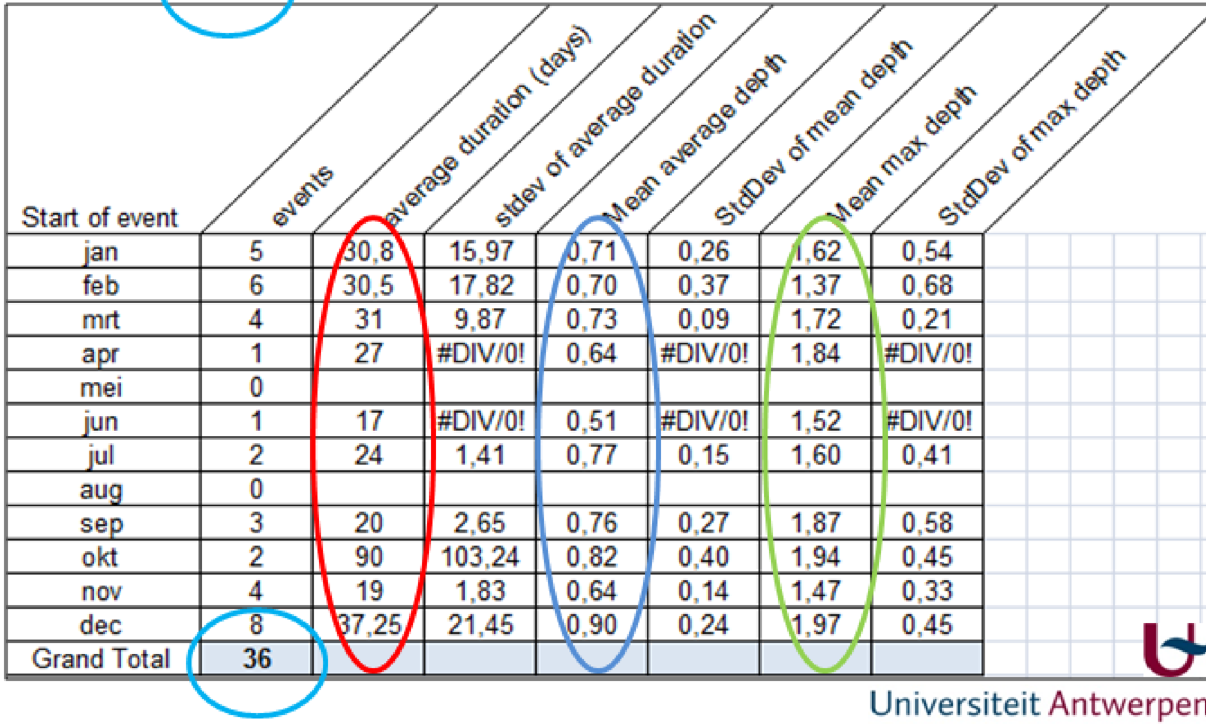
Boundaries of the reserve and the inventories parcells (here biodiveristy index)

- Number of events increases, but mostly in winter
- Duration increases significantly (almost doubles)
- Mean depth doubles
- Max depth doubles

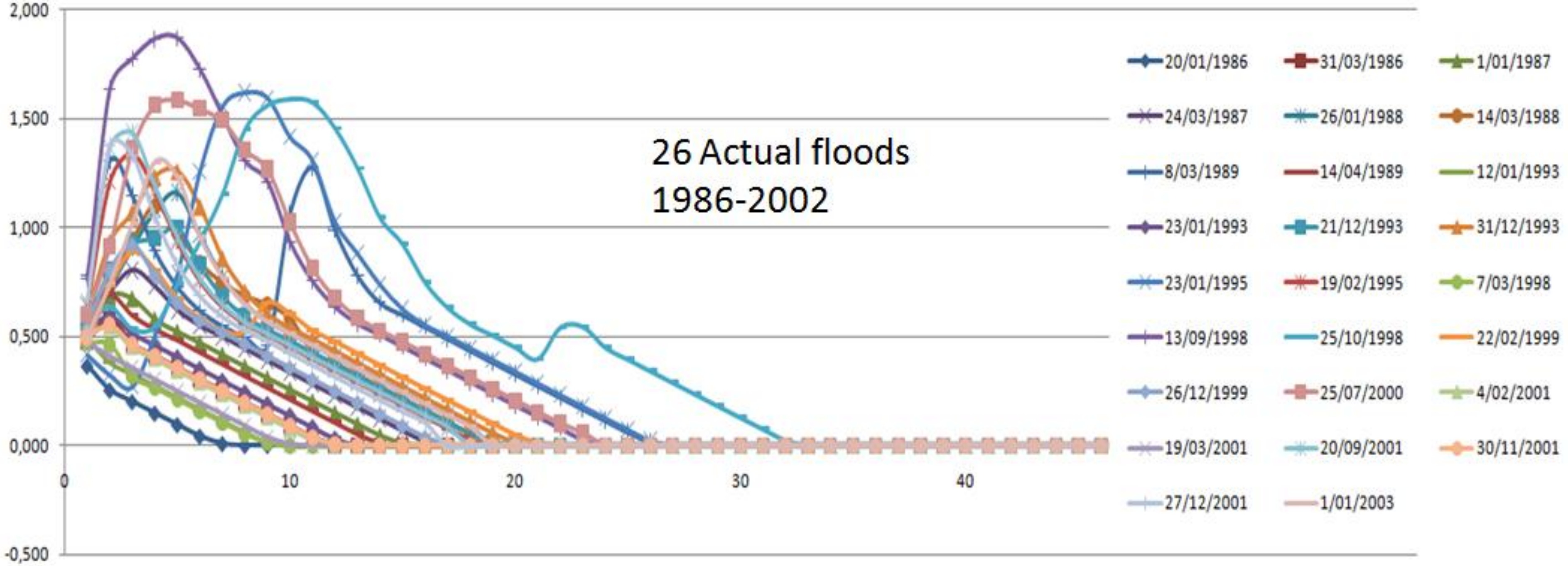
- The peak flow did not last long enough to fill the floodplain in the past
- But under the high scenario, peak flows last longer and occur more frequent
- Therefore events are significantly more extreme and single peak events merge into multiple peak events



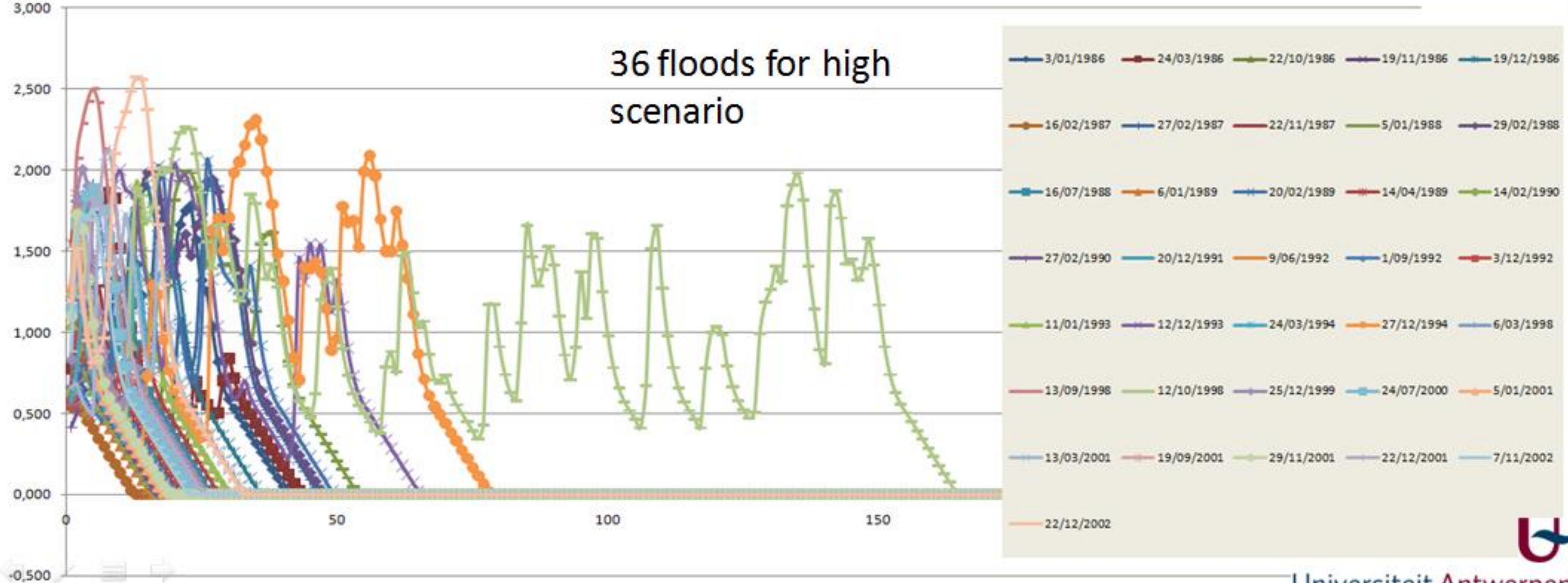
Start of event	number of events	average duration	stdev duration	mean average depth	Stdev average depth	mean max depth	Stdev max depth
jan	3	12,3	5,86	0,34	0,20	0,76	0,43
feb	6	18,3	7,06	0,52	0,24	1,16	0,55
mrt	4	12	4,55	0,39	0,24	0,94	0,55
apr	1	18	#DIV/0!	0,52	#DIV/0!	1,34	#DIV/0!
mei	0						
jun	1	20	#DIV/0!	0,44	#DIV/0!	0,89	#DIV/0!
jul	1	18	#DIV/0!	0,48	#DIV/0!	1,00	#DIV/0!
aug	0						
sep	2	16,5	0,71	0,49	0,13	1,11	0,27
okt	1	14	#DIV/0!	0,34	#DIV/0!	0,69	#DIV/0!
nov	2	14	1,41	0,36	0,05	0,75	0,08
dec	5	18	8,89	0,50	0,26	1,07	0,54
Grand Total	26						



Start of event	events	average duration (days)	stdev of average duration	Mean average depth	StdDev of mean depth	Mean max depth	StdDev of max depth
jan	5	30,8	15,97	0,71	0,26	1,62	0,54
feb	6	30,5	17,82	0,70	0,37	1,37	0,68
mrt	4	31	9,87	0,73	0,09	1,72	0,21
apr	1	27	#DIV/0!	0,64	#DIV/0!	1,84	#DIV/0!
mei	0						
jun	1	17	#DIV/0!	0,51	#DIV/0!	1,52	#DIV/0!
jul	2	24	1,41	0,77	0,15	1,60	0,41
aug	0						
sep	3	20	2,65	0,76	0,27	1,87	0,58
okt	2	90	103,24	0,82	0,40	1,94	0,45
nov	4	19	1,83	0,64	0,14	1,47	0,33
dec	8	37,25	21,45	0,90	0,24	1,97	0,45
Grand Total	36						



26 Actual floods 1986-2002



36 floods for high scenario

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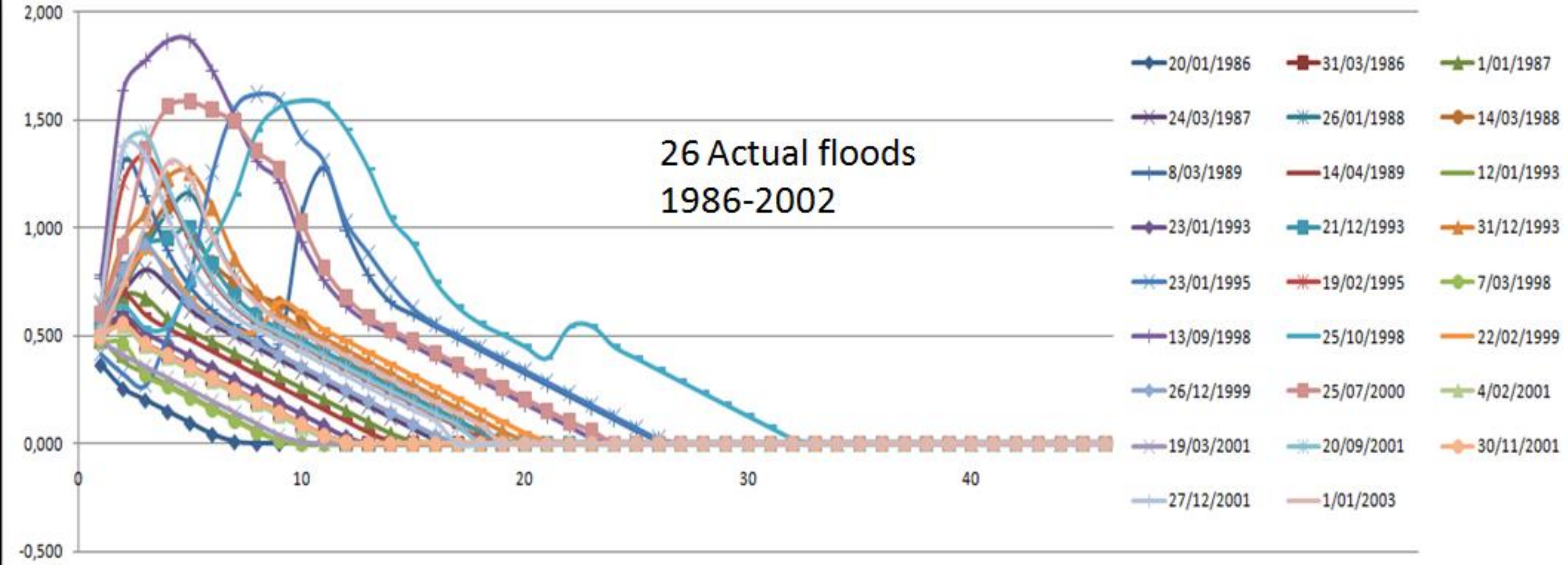
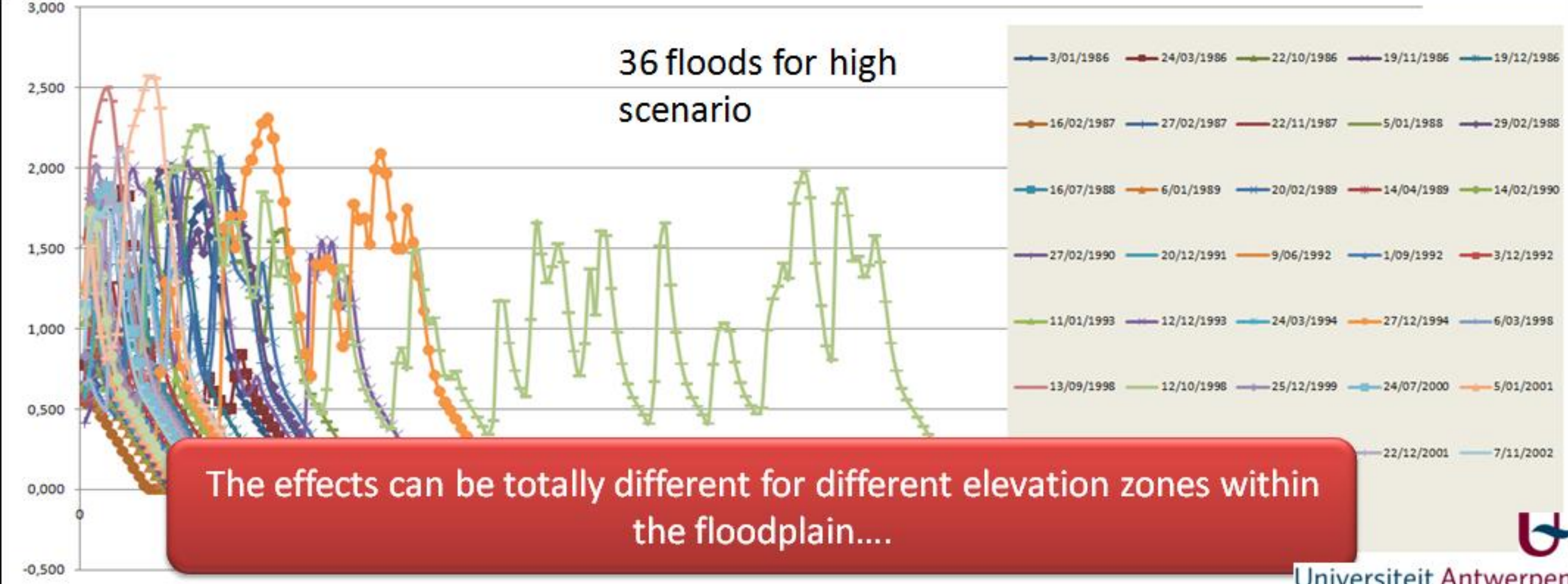
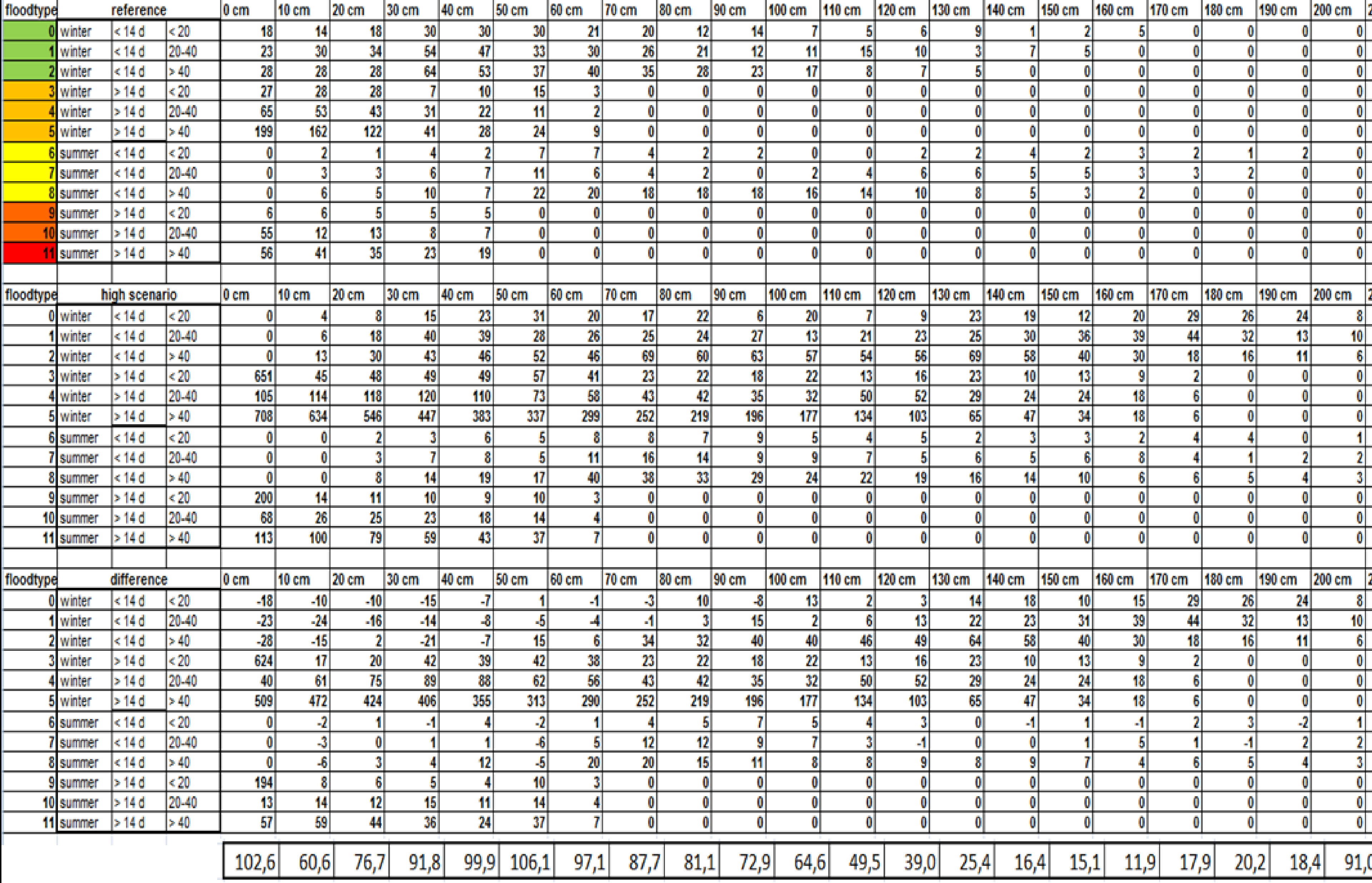


26 Actual floods 1986-2002



36 floods for high scenario

The effects can be totally different for different elevation zones within the floodplain....



floodtype	reference			0 cm	10 cm	20 cm	30 cm	40 cm	50 cm	60 cm	70 cm	80 cm	90 cm	100 cm	110 cm	120 cm	130 cm	140 cm	150 cm	160 cm	170 cm	180 cm	190 cm	200 cm
🟩 0	winter	< 14 d	< 20	18	14	18	30	30	30	21	20	12	14	7	5	6	9	1	2	5	0	0	0	0
🟩 1	winter	< 14 d	20-40	23	30	34	54	47	33	30	26	21	12	11	15	10	3	7	5	0	0	0	0	0
🟩 2	winter	< 14 d	> 40	28	28	28	64	53	37	40	35	28	23	17	8	7	5	0	0	0	0	0	0	0
🟧 3	winter	> 14 d	< 20	27	28	28	7	10	15	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
🟧 4	winter	> 14 d	20-40	65	53	43	31	22	11	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0
🟧 5	winter	> 14 d	> 40	199	162	122	41	28	24	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0
🟨 6	summer	< 14 d	< 20	0	2	1	4	2	7	7	4	2	2	0	0	2	2	4	2	3	2	1	2	0
🟨 7	summer	< 14 d	20-40	0	3	3	6	7	11	6	4	2	0	2	4	6	6	5	5	3	3	2	0	0
🟨 8	summer	< 14 d	> 40	0	6	5	10	7	22	20	18	18	18	16	14	10	8	5	3	2	0	0	0	0
🟧 9	summer	> 14 d	< 20	6	6	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
🟧 10	summer	> 14 d	20-40	55	12	13	8	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
🟥 11	summer	> 14 d	> 40	56	41	35	23	19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

floodtype	high scenario			0 cm	10 cm	20 cm	30 cm	40 cm	50 cm	60 cm	70 cm	80 cm	90 cm	100 cm	110 cm	120 cm	130 cm	140 cm	150 cm	160 cm	170 cm	180 cm	190 cm	200 cm
0	winter	< 14 d	< 20	0	4	8	15	23	31	20	17	22	6	20	7	9	23	19	12	20	29	26	24	8
1	winter	< 14 d	20-40	0	6	18	40	39	28	26	25	24	27	13	21	23	25	30	36	39	44	32	13	10
2	winter	< 14 d	> 40	0	13	30	43	46	52	46	69	60	63	57	54	56	69	58	40	30	18	16	11	6
3	winter	> 14 d	< 20	651	45	48	49	49	57	41	23	22	18	22	13	16	23	10	13	9	2	0	0	0
4	winter	> 14 d	20-40	105	114	118	120	110	73	58	43	42	35	32	50	52	29	24	24	18	6	0	0	0
5	winter	> 14 d	> 40	708	634	546	447	383	337	299	252	219	196	177	134	103	65	47	34	18	6	0	0	0
6	summer	< 14 d	< 20	0	0	2	3	6	5	8	8	7	9	5	4	5	2	3	3	2	4	4	0	1
7	summer	< 14 d	20-40	0	0	3	7	8	5	11	16	14	9	9	7	5	6	5	6	8	4	1	2	2
8	summer	< 14 d	> 40	0	0	8	14	19	17	40	38	33	29	24	22	19	16	14	10	6	6	5	4	3
9	summer	> 14 d	< 20	200	14	11	10	9	10	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	summer	> 14 d	20-40	68	26	25	23	18	14	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	summer	> 14 d	> 40	113	100	79	59	43	37	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0

floodtype	difference			0 cm	10 cm	20 cm	30 cm	40 cm	50 cm	60 cm	70 cm	80 cm	90 cm	100 cm	110 cm	120 cm	130 cm	140 cm	150 cm	160 cm	170 cm	180 cm	190 cm	200 cm
0	winter	< 14 d	< 20	-18	-10	-10	-15	-7	1	-1	-3	10	-8	13	2	3	14	18	10	15	29	26	24	8
1	winter	< 14 d	20-40	-23	-24	-16	-14	-8	-5	-4	-1	3	15	2	6	13	22	23	31	39	44	32	13	10
2	winter	< 14 d	> 40	-28	-15	2	-21	-7	15	6	34	32	40	40	46	49	64	58	40	30	18	16	11	6
3	winter	> 14 d	< 20	624	17	20	42	39	42	38	23	22	18	22	13	16	23	10	13	9	2	0	0	0
4	winter	> 14 d	20-40	40	61	75	89	88	62	56	43	42	35	32	50	52	29	24	24	18	6	0	0	0
5	winter	> 14 d	> 40	509	472	424	406	355	313	290	252	219	196	177	134	103	65	47	34	18	6	0	0	0
6	summer	< 14 d	< 20	0	-2	1	-1	4	-2	1	4	5	7	5	4	3	0	-1	1	-1	2	3	-2	1
7	summer	< 14 d	20-40	0	-3	0	1	1	-6	5	12	12	9	7	3	-1	0	0	1	5	1	-1	2	2
8	summer	< 14 d	> 40	0	-6	3	4	12	-5	20	20	15	11	8	8	9	8	9	7	4	6	5	4	3
9	summer	> 14 d	< 20	194	8	6	5	4	10	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	summer	> 14 d	20-40	13	14	12	15	11	14	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11	summer	> 14 d	> 40	57	59	44	36	24	37	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0
				102,6	60,6	76,7	91,8	99,9	106,1	97,1	87,7	81,1	72,9	64,6	49,5	39,0	25,4	16,4	15,1	11,9	17,9	20,2	18,4	91,

Changes in floodtype occurence are non-linear with the elevation classes (flood depth), since timing + duration are determining for floodtype

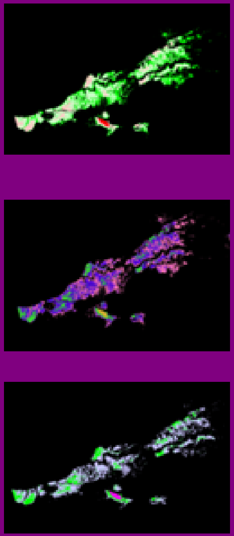
Vegetation vulnerability to changes in flood characteristics

Vegetation mapping

- Veg. Comm. 1
- Veg. Comm. 2
- Veg. Comm. 3
- Veg. Comm. …
- Veg. Comm. …
- Veg. Comm. 67
- Veg. Comm. 68

Flood Characteristics

- Season
- Regularity
- Duration
- Depth
- **Quality**



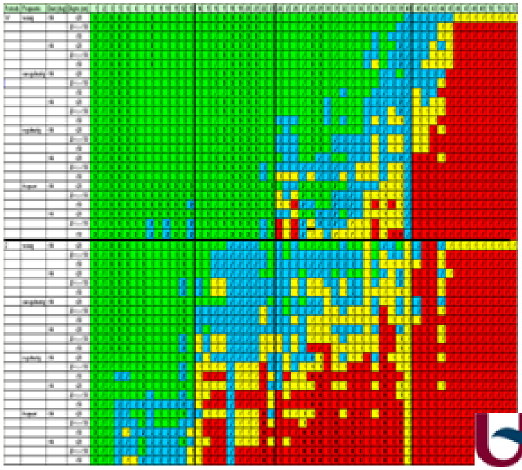
68 vegetation communities

48 Floodtypes

- Experts
- Literature
- Field data

Ecological vulnerability:

1 Very vulnerable
2 Vulnerable
3 Tolerant
4 Very Tolerant



Case study application

Next steps

- Next step – is to combine the floodtype changes with the vegetation vulnerability matrix and the vegetation maps
  - For each vegetation type, the vulnerability to each floodtype is determined (literature, experts)
  - The vegetation types have been mapped within the reserve
  - We know which floodtypes occur within each elevation zone for the reference situation and the high climate scenario
- The combination will spatially explicit map the flood impact of the changes in flood regimes due to climate change
- Finally, ecological risk is determined – not all vegetation types are equally valuable (rareness, uniqueness of the vegetation)

Relevance of this type of ecological impact analysis ?

- Climate change will impact biodiversity of floodplains through changes in flood regimes
- Many habitat directive areas are located along rivers
- Water management and nature development may need to recognize climate change in setting their goals and objectives for these floodplain ecosystems
  - Adapt long-term ecological objectives (choose different vegetation types as objective)
  - Control flood regimes (locally or upstream)
  - Investigate which zones allow the development of ecological values for future flood regimes (and incorporate these zones within the reserves)

More info

CCI-HYDR project on “Impact of climate change on hydrological extremes (peak and low flows) along rivers (Scheldt and Meuse basins) and urban drainage systems in Belgium” (funded by Belgian Federal Science Policy):

http://www.kuleuven.be/hydr/CCI-HYDR

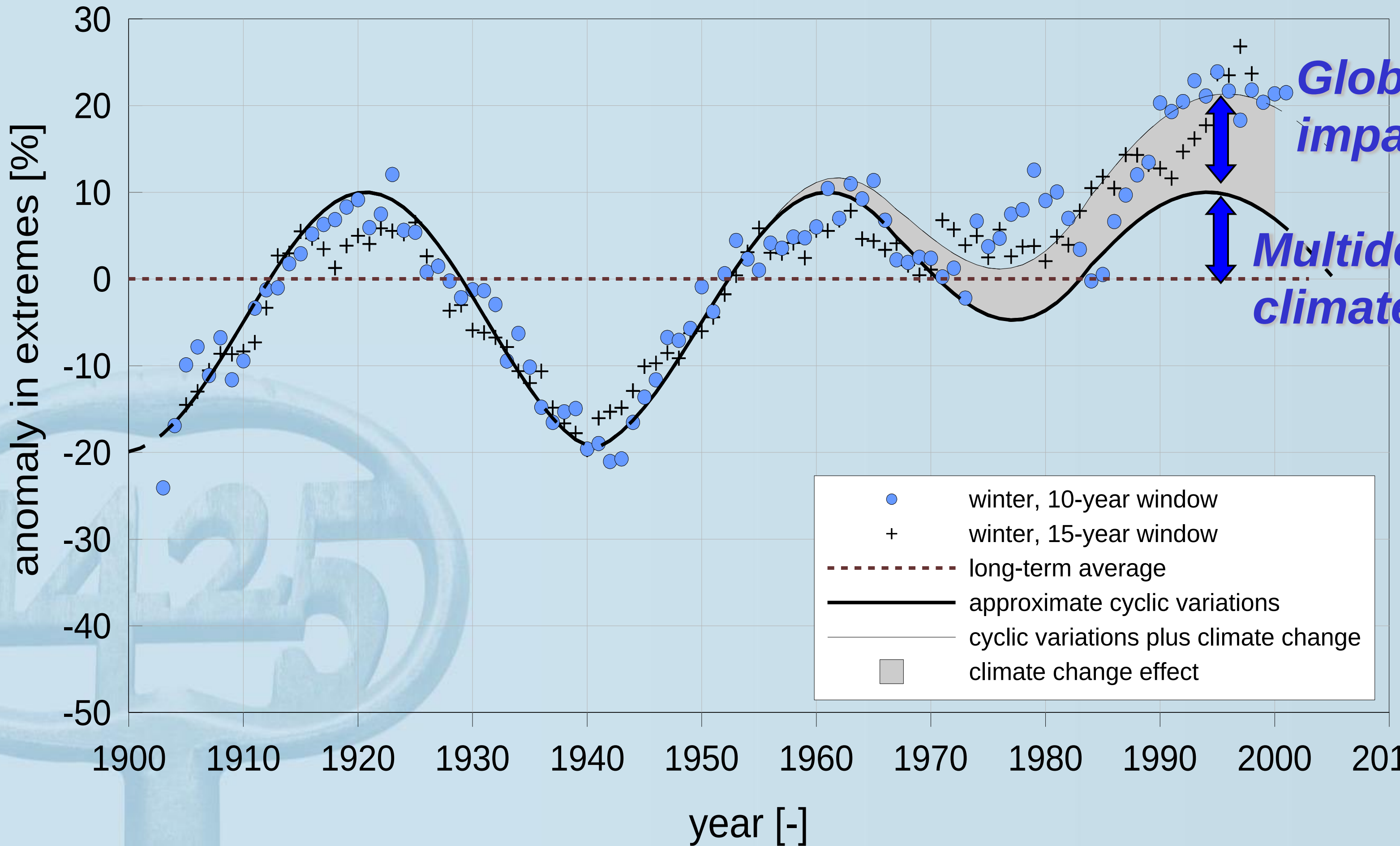
Patrick.Willems@bwk.kuleuven.be

SUDEM project on “climate change and ecological impact analysis”
(funded by Belgian Federal Science Policy): jan.staes@ua.ac.be

Climate change scenarios

Comparison of GCM/RCM results with historical trends

Winter precipitation extremes Brussels (10 min -> seasonal) 1898-2005:



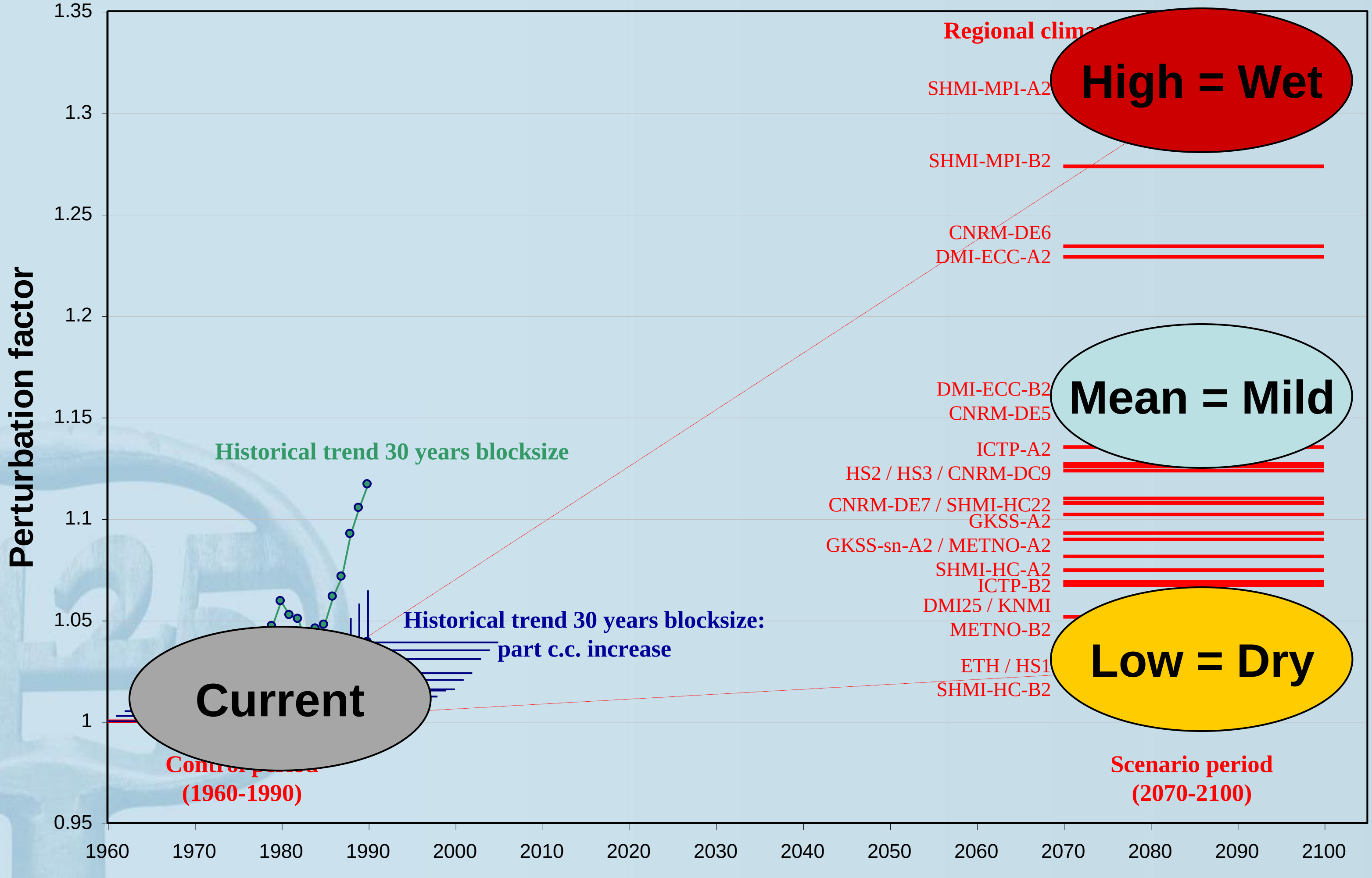
Global warming impact

Multidecadal climate oscillation

Climate change scenarios

Consistency check with historical trend analysis

Example: Winter daily precipitation extremes:



Science – Policy interfacing

- Classical science – policy interfacing problems …
- Use of uncertainties in climate change impact results on decision making (incl. climate adaptation needs): based on risk/precautionary concept
- Rapidly evolving climate science: regular update of the scenarios needed
  - From AOGCMs to Earth Modelling Systems
  - From IPCC SRES scenarios to new IPCC scenarios based on “Representative Concentration Pathways (RCPs)” (including the effect of mitigation)
- (Psychological) effect that communication on climate change and related uncertainties can have on social-political support (e.g. for adaptation plans)