GEUS

Groundwater abstraction, ecological flow and quantitative status assessment

WFD/RBMP2 and municipality groundwater abstraction licenses

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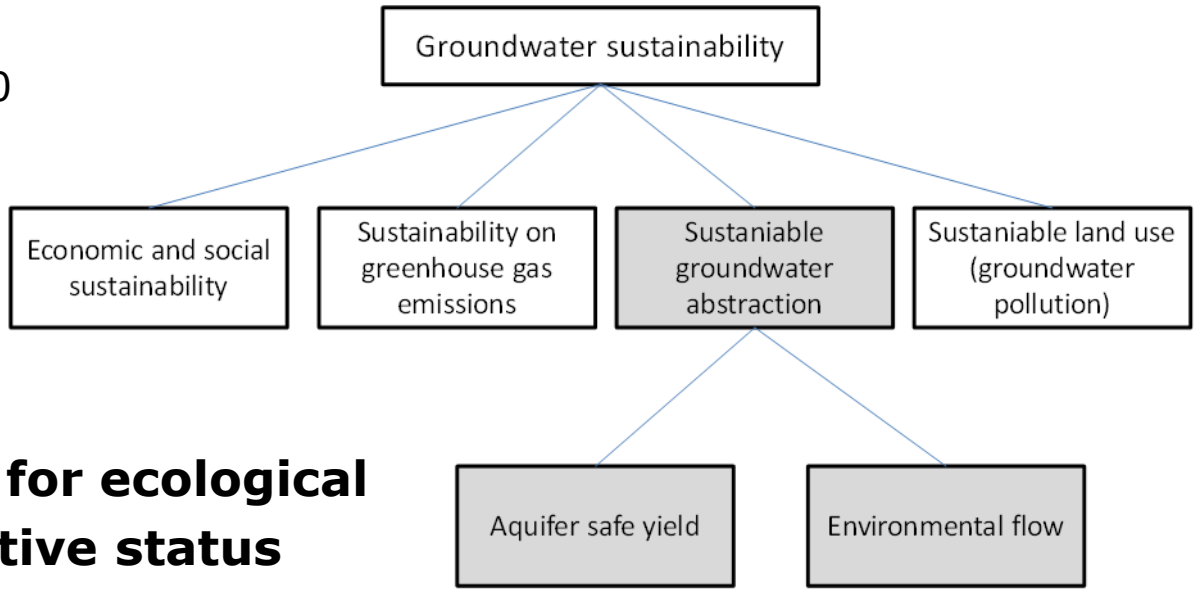
Content

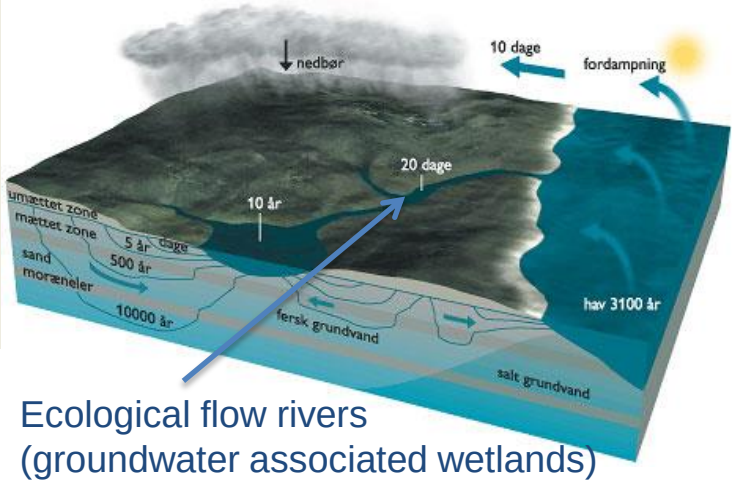
- **Background**. Sustainable groundwater abstraction. Environmental flow and aquifer sustainability. The national hydrological model (DK model). Transient GW-SW numerical model.
- **Aquifer sustainability and environmental flow** (GW Directive/WFD):
  - Aquifer sustainability (max 30 % abstraction of recharge to groundwater aquifers)
  - Ecological flow sustainability (DVFI/macroinvertebrates, DVPI/macrophyttes and DFFVa/fish)



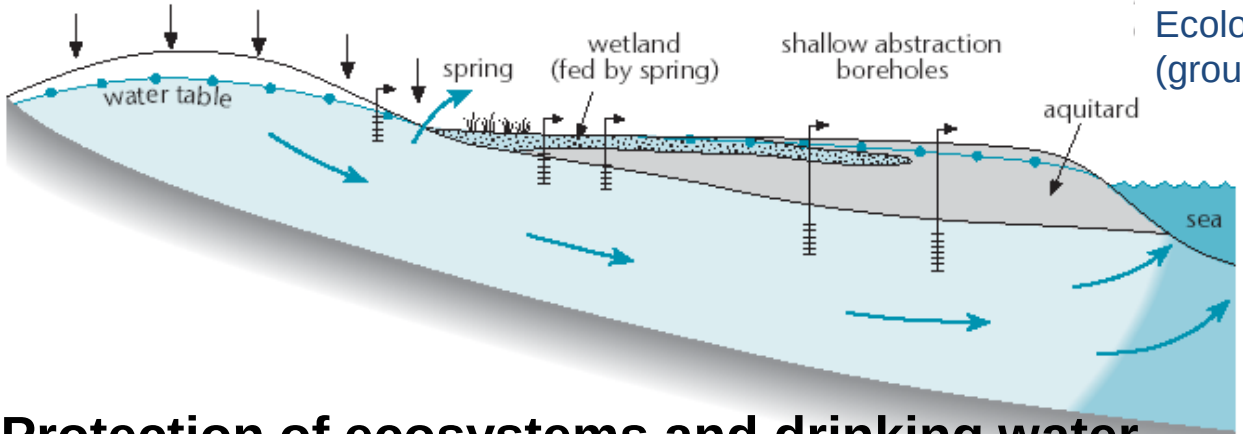
- **RBMP 2 new indicators for ecological flow and WFD quantitative status**
- **Results** of new indicators implemented based on national hydrological model (RBMP2-Denmark), and pre-project consolidation (web-interface)
- **Discussion and conclusions**

Assessing groundwater quantitative and chemical status

(according to EU directives – WFD/GWD)



Ecological flow rivers
(groundwater associated wetlands)



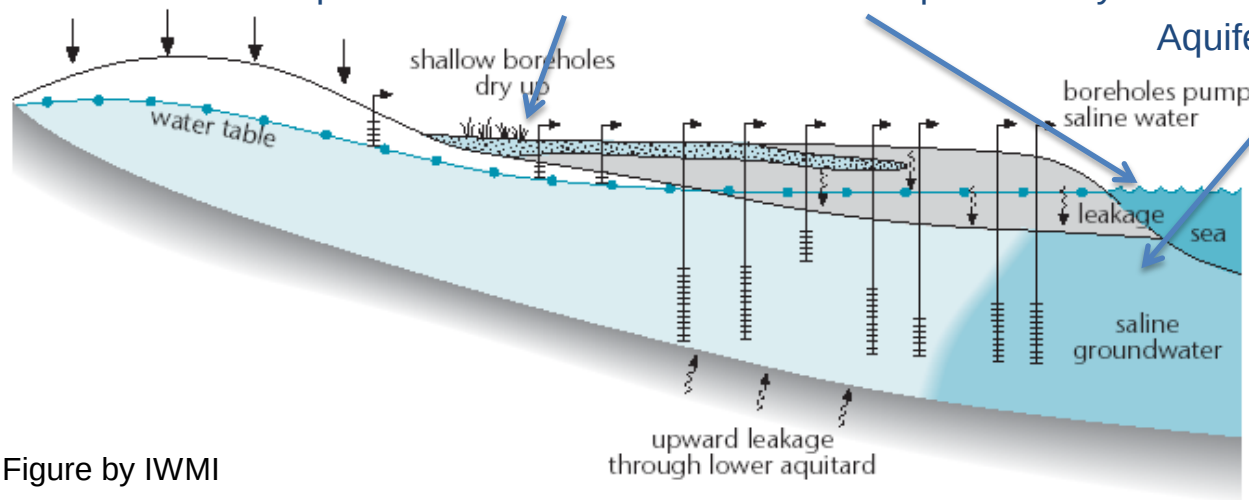
Stage A : Initial condition

- groundwater flows from outcrop to coast
- springs help maintain wetland
- limited abstraction from shallow boreholes occurrs

Protection of ecosystems and drinking water

Groundwater dependent terrestrial and associated aquatic ecosystems

Aquifer sustainability (saltwater intrusion)



Stage B : Groundwater abstraction increases leading to:

- groundwater level decline in aquifer
- springs feeding wetland cease
- shallow wells dry up
- coastal boreholes become saline
- leakage through upper and lower aquitards (if present) begins

Figure by IWMI

Definitions of aquifer safe yield and environmental flow requirements

BOX 2.1 Definition of sustainable groundwater abstraction

Aquifer safe yield can be defined according to (modified from Henriksen et al. 2008):
The safe yield of a groundwater aquifer is the amount of groundwater which can be pumped from an aquifer without unacceptable negative impacts on groundwater level and water quality, compared to the pre-developmental, virgin situation.

Environmental flow requirements can be defined as (modified from Navarro and Schmidt, 2012; Arthington & and Tharme, 2003):
The environmental flow requirements are the important flow regime characteristics, i.e. the quantity, frequency, timing and duration of flow events, rates of change and predictability/variability, that are required to maintain or restore the natural flow regime in order to maintain specified, valued features of the ecosystem.

Environmental flow requirements

Table 2.5 Standards for UK river types/sub-types for achieving good ecological status as % allowable abstraction of natural flow. Tresholds are for annual flow statistics (Acreman and Ferguson, 2010). Qn_{95} is the flow which is equalled or exceeded for 95 % of the time.

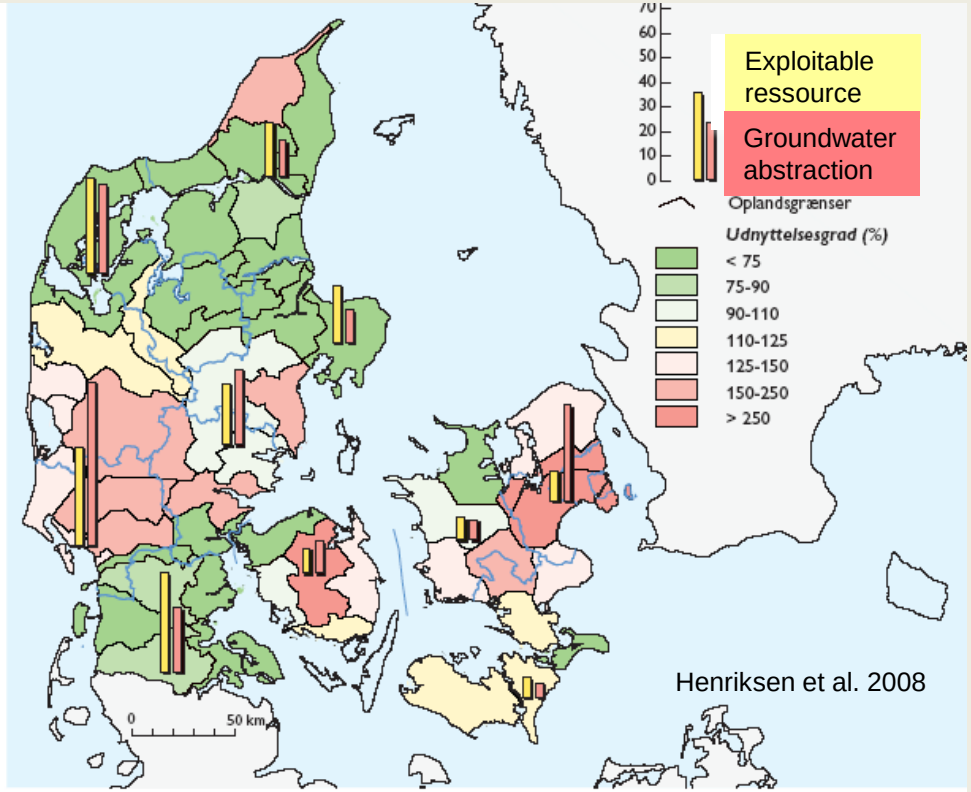
Type or sub type	Season	Flow > Qn_{60}	Flow > Qn_{70}	Flow > Qn_{95}	Flow < Qn_{95}
A1	Apr.–Oct.	30	25	20	15
	Nov.–Mar.	35	30	25	20
A2 (ds), B1, B2, C1, D1	Apr.–Oct.	25	20	15	10
	Nov.–Mar.	30	25	20	15
A2 (hw),	Apr.–Oct.	20	15	10	7.5
C2, D2	Nov.–Mar.	25	20	15	10
Salmonid spawning &	June–Sep.	25	20	15	10
nursery areas	Oct.–May	20	15	Flow > Q_{80}	Flow < Q_{80}
(not chalk rivers)				10	7.5

Table 2.2 Framework for classifying environmental flow requirement methods (simple, intermediate, complex)

Complexity level	Foundation	System components	Data needs	Knowledge base
Simple	Hydrological	Whole ecosystem, nonspecific.	Historical flow records. Abstraction and low flow reduction relationships.	Existing databases. Integrated groundwater and surface water flow model. Mainly hydrological and only some ecological expertise.
Complex	Hydraulic / habitat, holistic	Target biota specific instream habitat. Hydromorphology, temperature & water quality issues handled to some degree. The whole ecosystem all/most individual components including groundwater/floodplain and terrestrial interactions.	Historical flow records. Abstraction and low flow reduction relationships. Hydraulic variables of representative/numerous cross sections data. Suitability habitat data for target species. Biological data on flow and habitat-related requirements of all biota and ecological components.	Existing databases and limited or extended new field data campaigns. Integrated groundwater and surface water flow, hydraulic/habitat model and/or ecological models. Specialist expertise on hydrological, hydraulic, habitat and ecosystem components.

Historical background for Denmark

Assessment of sustainable groundwater abstraction 2003



Last nationwide exploitable gw ressource assessment (2003)

- Sustainable groundwater abstraction has been assessed based on simple indicators, and DK model-
  (Henriksen et al. 2008; Olsen et al. 2013)
- GWDTE has not been included yet in WFD RBMP quantitative status assessment
- New ecological flow hydrological regime indicators for fish, macrophytes and plants were implemented based on NOVANA data (GEUS report 2014/74)
- Need for scientifically based sustainability indicators for aquifer sustainability, GWDTE and ecological flow (GEUS report 2013/30)
- Small streams (75 % of all Danish streams) are considered as the most vulnerable to groundwater abstraction; these have not been included in RBMP2

->pre-project Web-interface/small streams and further consolidation

RBMP2: Modelled based assessment of quantitative status of groundwater

Goals:

- More transparent and harmonised methodology
- DK model quantify impacts of abstractions on eco-hydrological indicators and groundwater safe yield

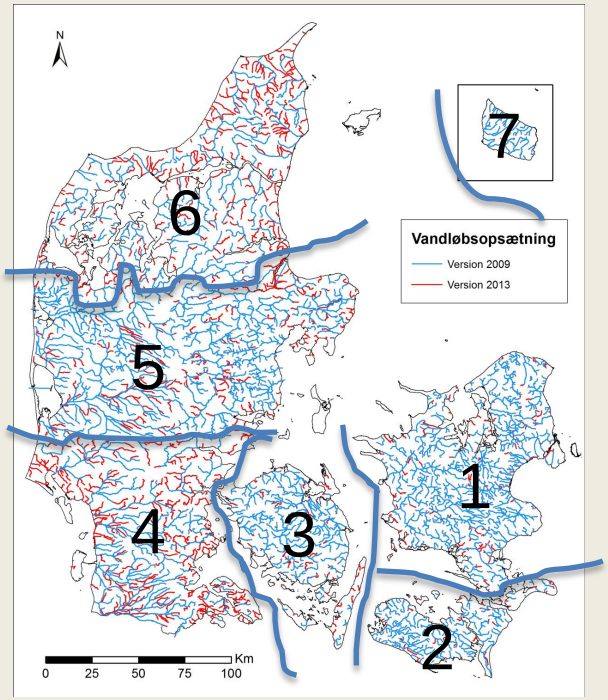
DK-model

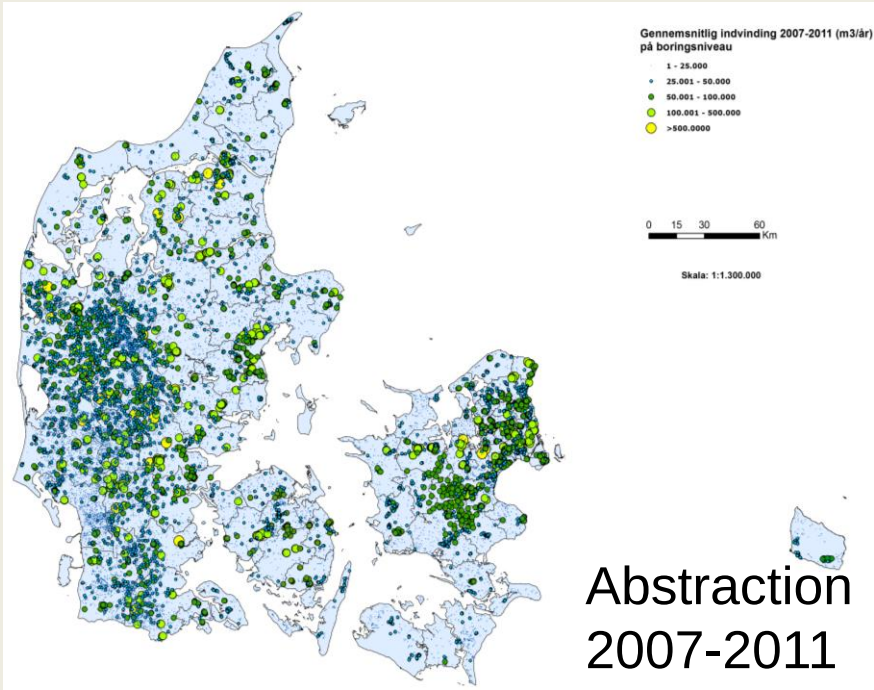
National hydrological model based on 7 sub-models

- 500x500 m
- 10-15 layers

– www.vandmodel.dk

Delmodel	Samlede landareal (km^2)	Aktive grids pr. lag
Omr. 1 – Sjælland	7163	37569
Omr. 2 – Sydhavsøerne	2042	13885
Omr. 3 – Fyn	3473	24009
Omr. 4 – Sønderjylland	7897	35869
Omr. 5 – Midtjylland	11578	49993
Omr. 6 – Nordjylland	9934	47649
Omr. 7 – Bornholm	590	2360





Abstraction 2007-2011

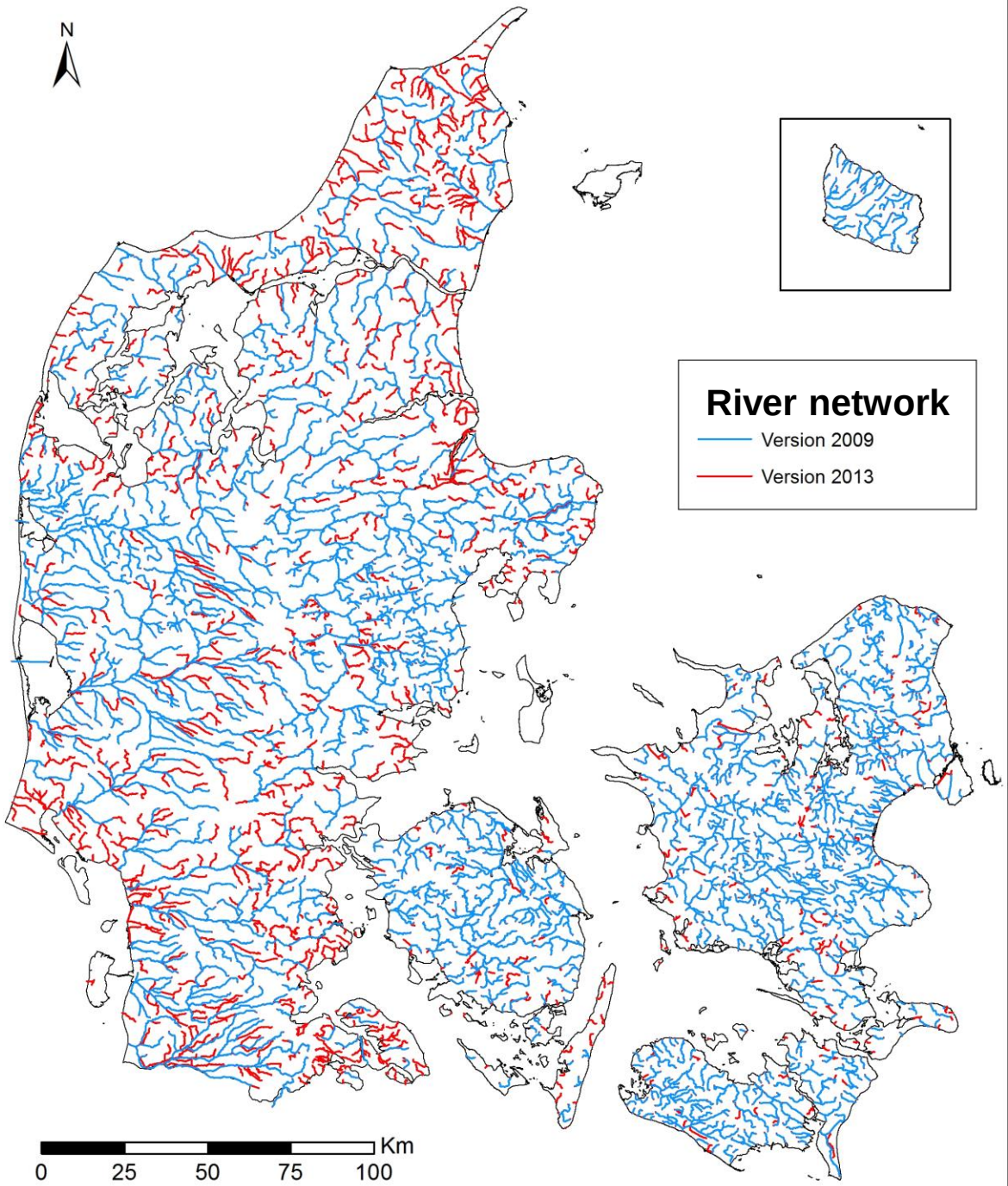
Development of DK model 2013/14

Updating

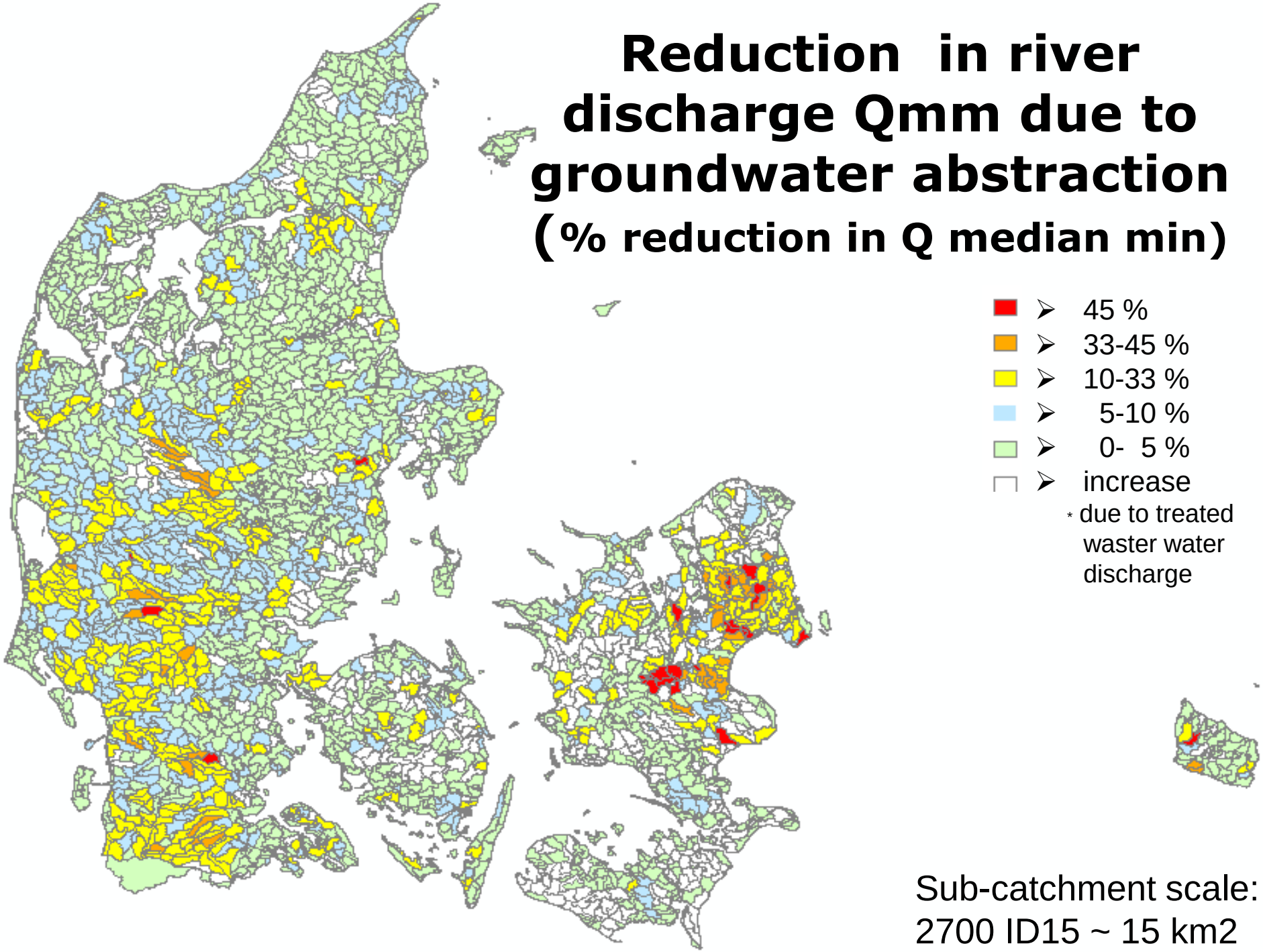
- Extension of river network > 850 streams, ~ 6.000 km (in total 15.770 km)
- New waste water discharge data (AU-bioscience)
- New dynamic precipitation correction
- New soil parameters (AU-agroscience)
- 400 New groundwater bodies (3D)
- Inverse calibration with PEST

Opportunity

- Daily flow for different scenarios => ecological flow
- Safe yield and water balance assessments for aquifers and catchments

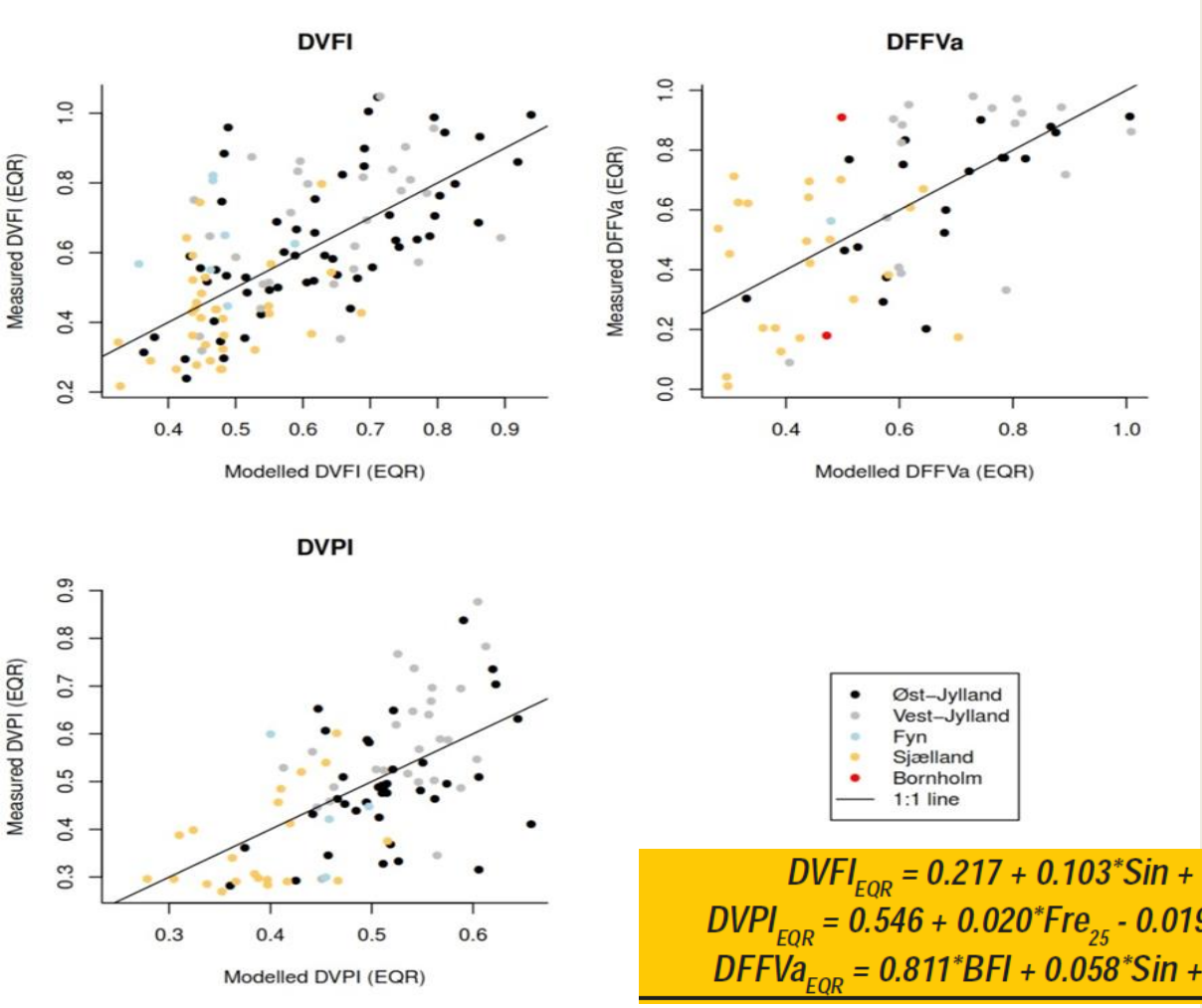


Reduction in river discharge Qmm due to groundwater abstraction (% reduction in Q median min)



Sub-catchment scale:
2700 ID15 ~ 15 km2

Empirical equations for larger rivers



Empirical equations was derived from observed biological quality elements and daily discharge data for 2004-2010 for 61-122 monitoring stations from the NOVANA program:

- *DVFI (N=122/R2=0,44),*
- *DVPI (N=91/R2 =0,34)*
- *DFFVa (N=61/R2=0,49)*

Aarhus University - Bioscience

(Graeber et al., 2014)

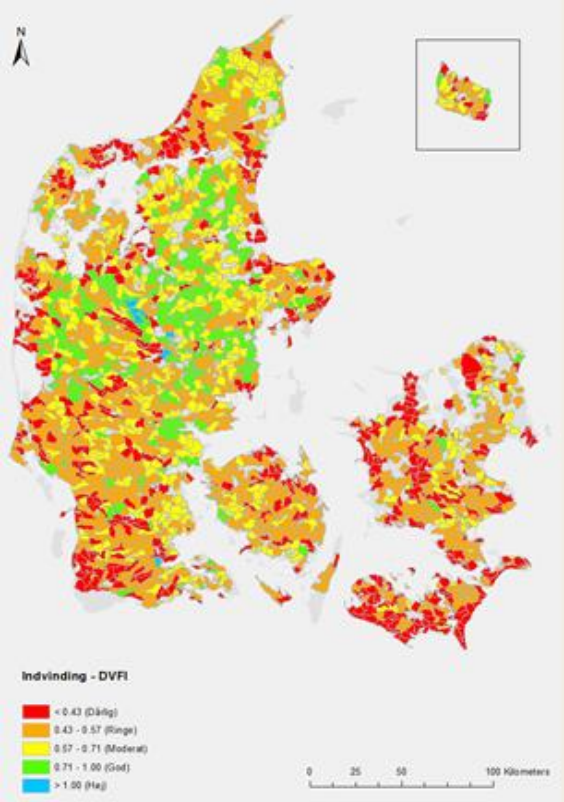
$$DVFI_{EQR} = 0.217 + 0.103 * Sin + 0.020 * Q_{90\text{-}n} * Fre_1$$ **Macroinvertebrates**

$$DVPI_{EQR} = 0.546 + 0.020 * Fre_{25} - 0.019 * Dur_3 - 0.025 * Fre_{75}$$ **Macrophyttes**

$$DFFVa_{EQR} = 0.811 * BFI + 0.058 * Sin + 0.050 * Fre_{25} - 0.319 - 0.0413 * Fre_{75}$$ **Fish**

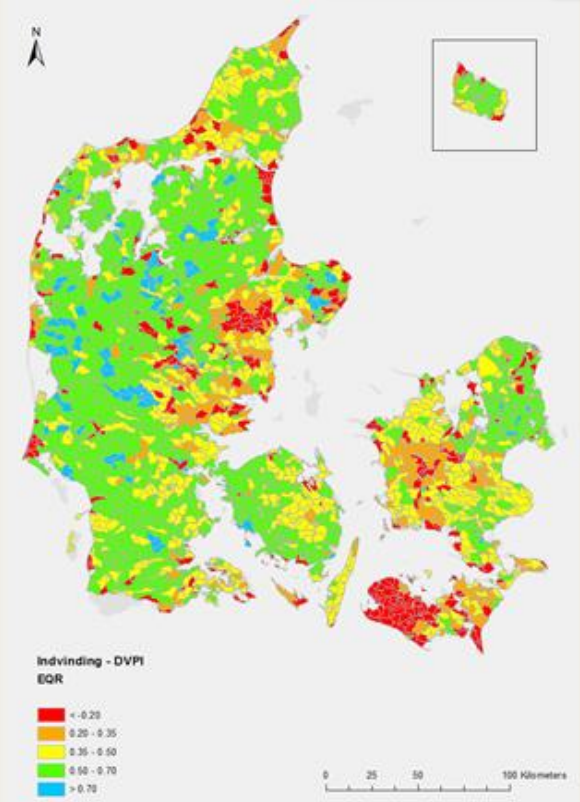
Simulated ecological flow based on DK model and empirical equations

Status	DVFI	DVPI	DFFVa
High	> 1,00	> 0,70	> 0,94
Good	0,71 – 1,00	0,50 – 0,70	0,72 – 0,94
Moderate	0,57 – 0,71	0,35 – 0,50	0,40 - 0,72
Poor	0,43 – 0,57	0,20 – 0,35	0,11 – 0,40
Bad	< 0,43	< 0,20	< 0,11



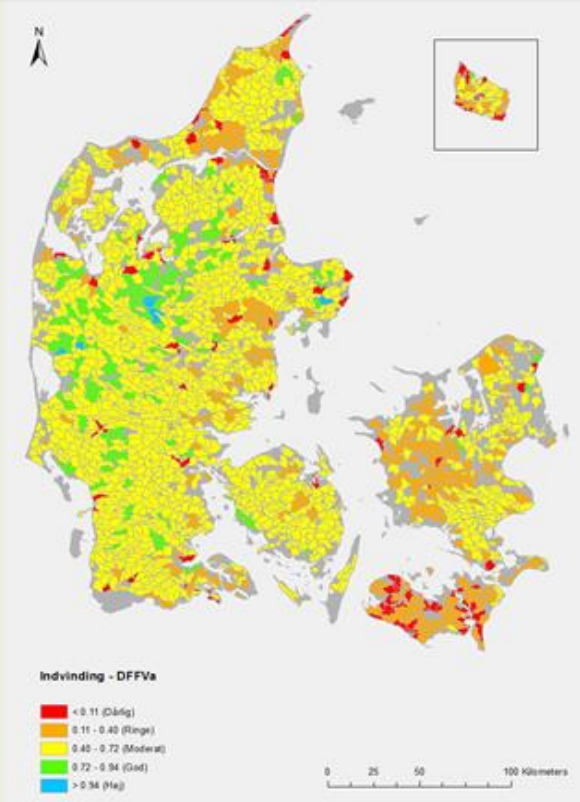
DVFI

Current abstraction



DVPI

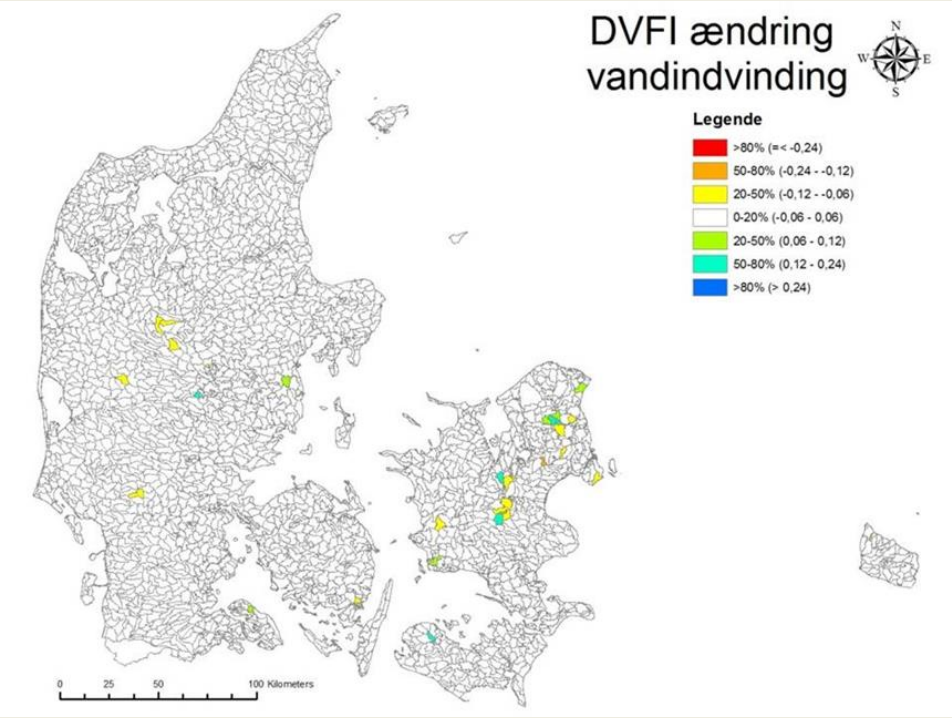
Current abstraction

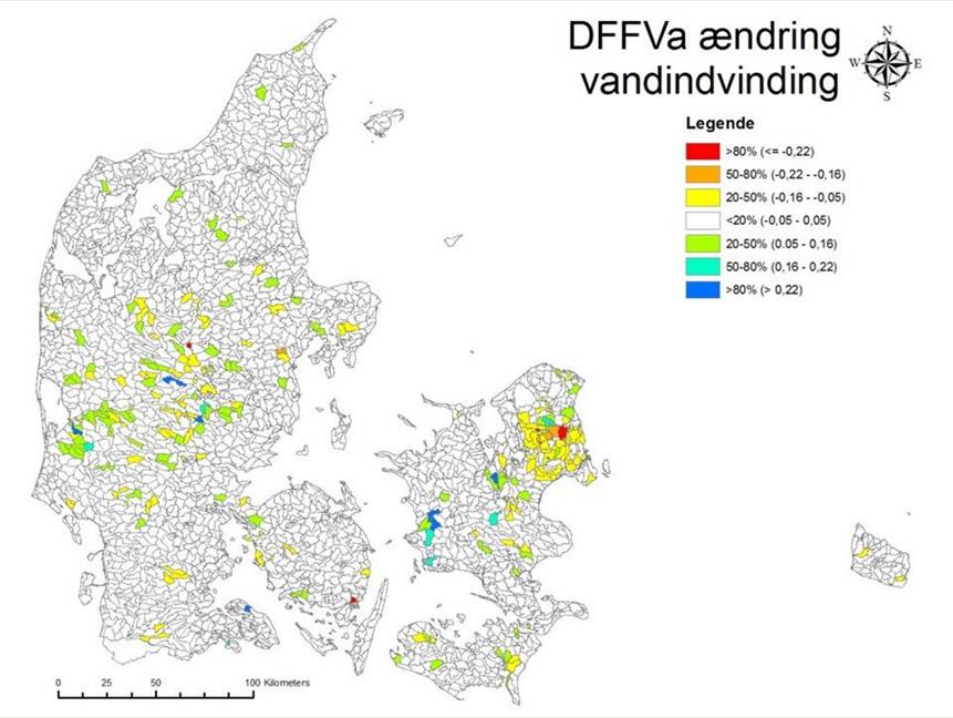


DFFVa

Current abstraction

Model simulated changes in DVFI (macroinvertebrates) and DFFVa (fish)



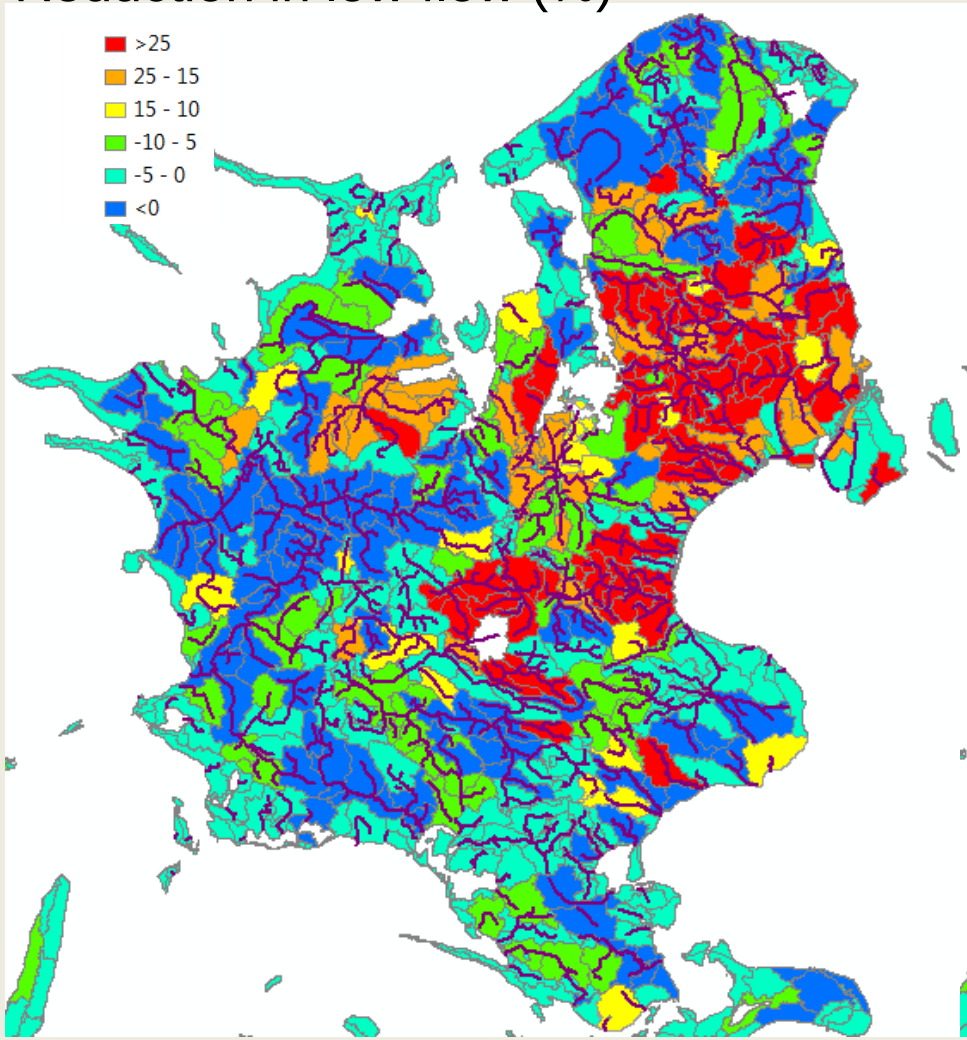


Model simulated changes in DVFI and DFFVa. Sub-catchments with red color has > 80 % probability for reduced ecological status (e.g. from good to moderate), orange colors has 50-80 % probability and yellow 20-50 % probability for reduced ecological state (by one class)

EQR threshold values	DVFI Max reduktion af EQR værdi	DVPI Max reduktion af EQR værdi	DFFVa Max reduktion af EQR værdi
80 %	0,24	0,23	0,22
50 %	0,12	0,11	0,16
20 %	0,06	0,03	0,05

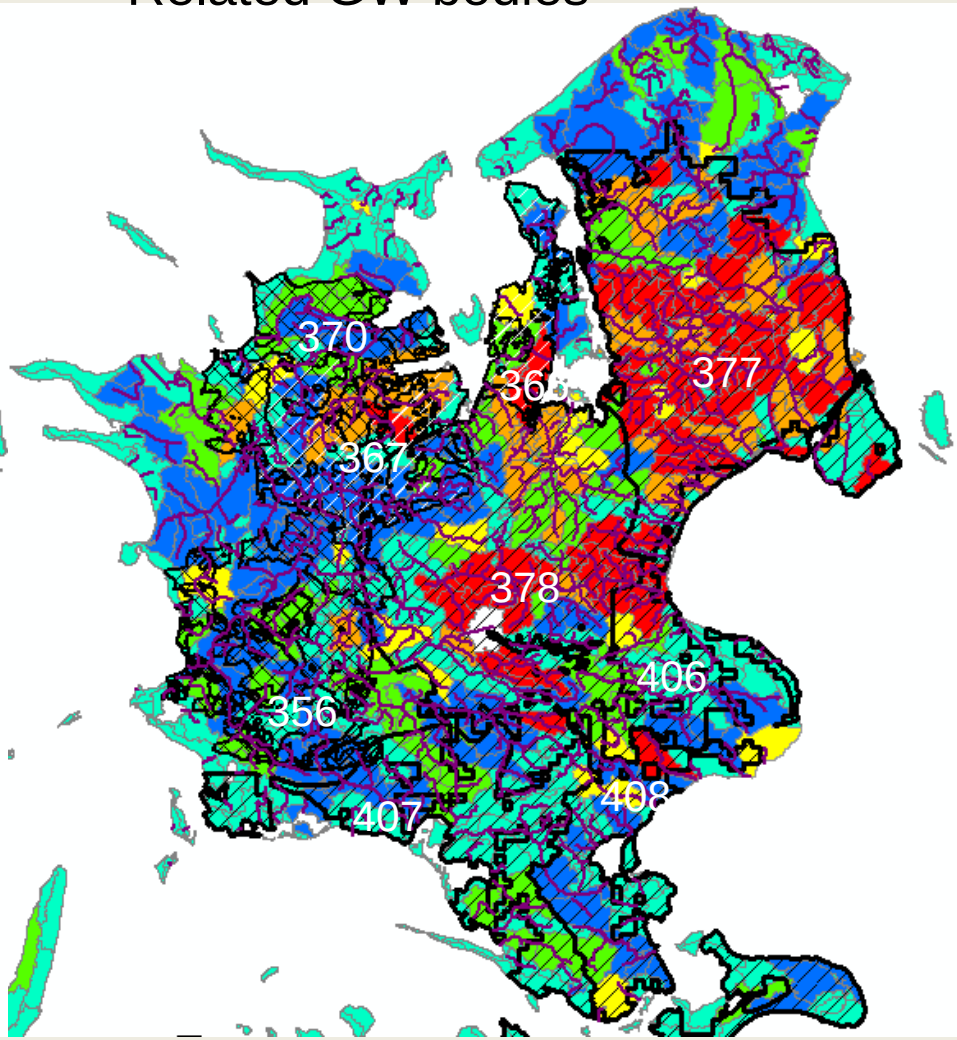
Sjælland

Reduction in low flow (%)



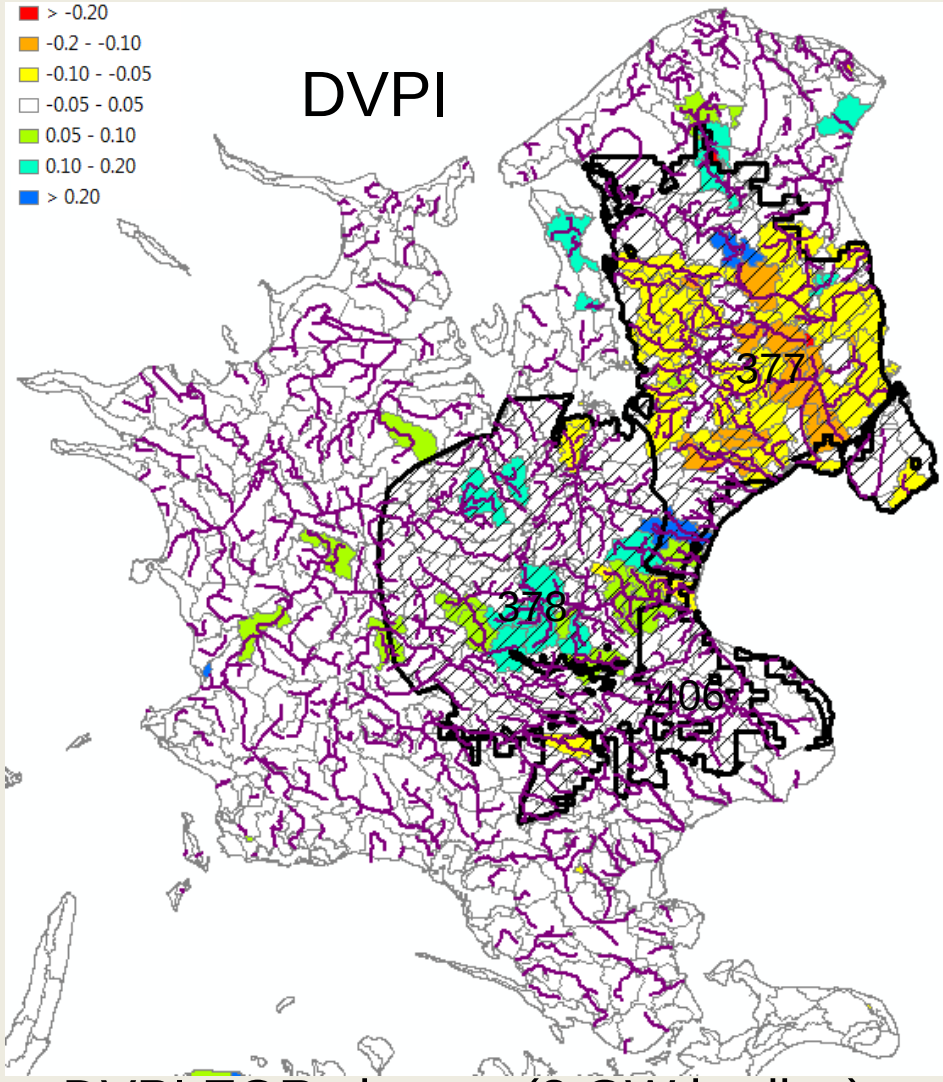
Reduction median min Q (%)

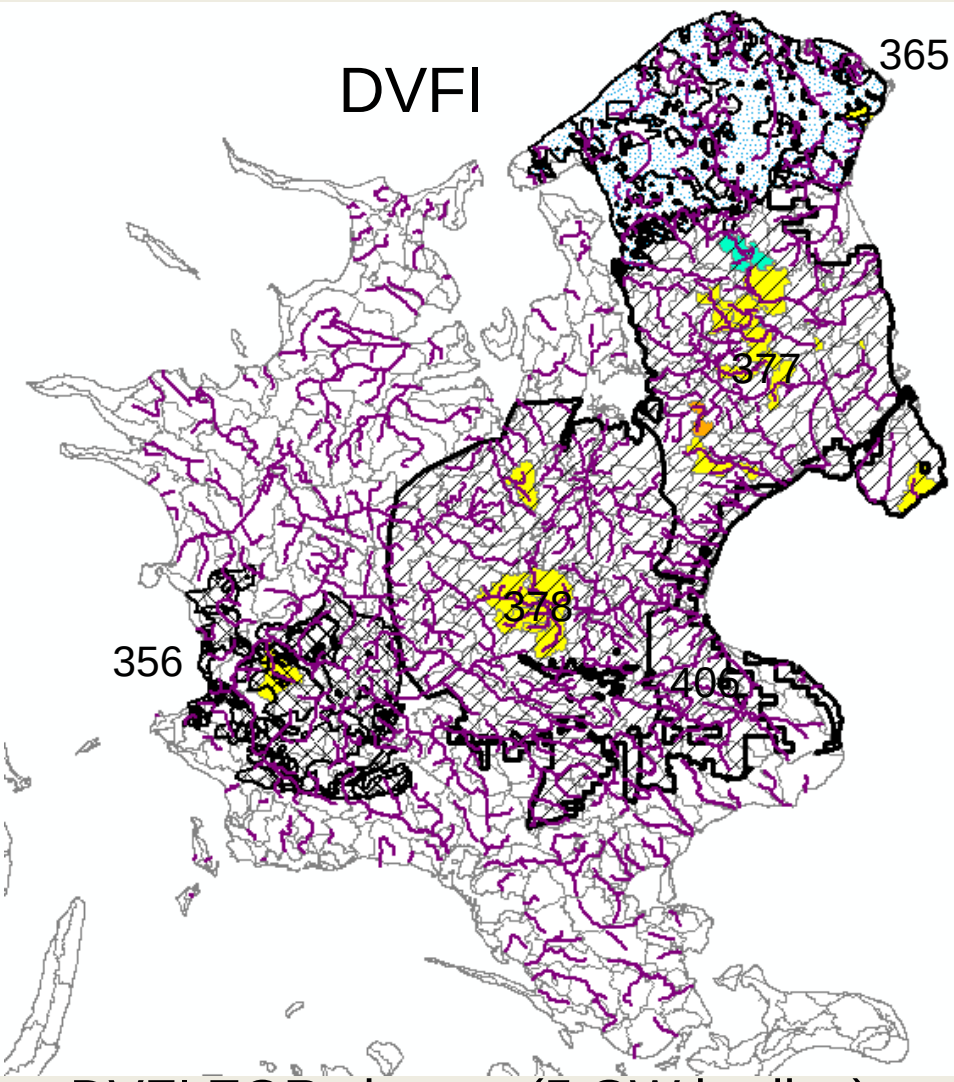
Related GW bodies



Related groundwater bodies (9)

Sjælland

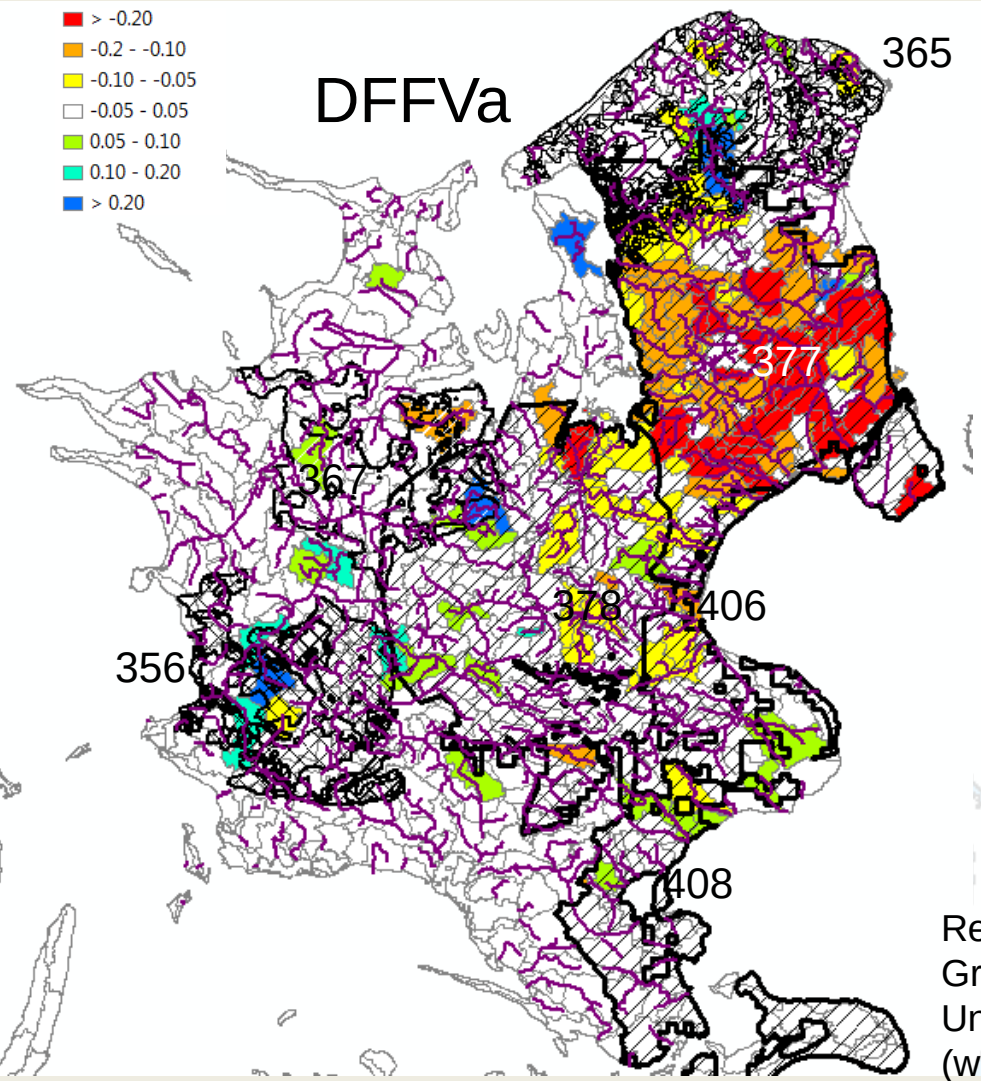


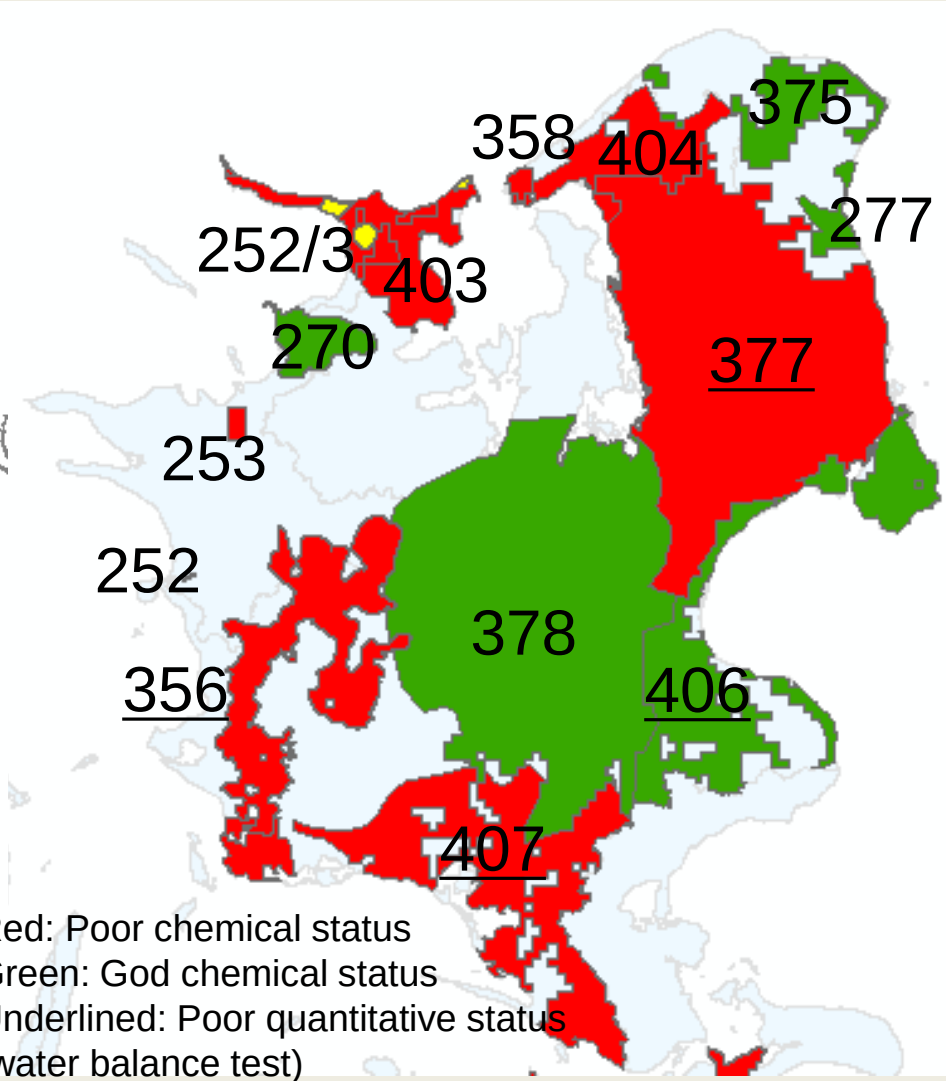


DVPI EQR change (3 GW bodies)

DVFI EQR change (5 GW bodies)

Sjælland



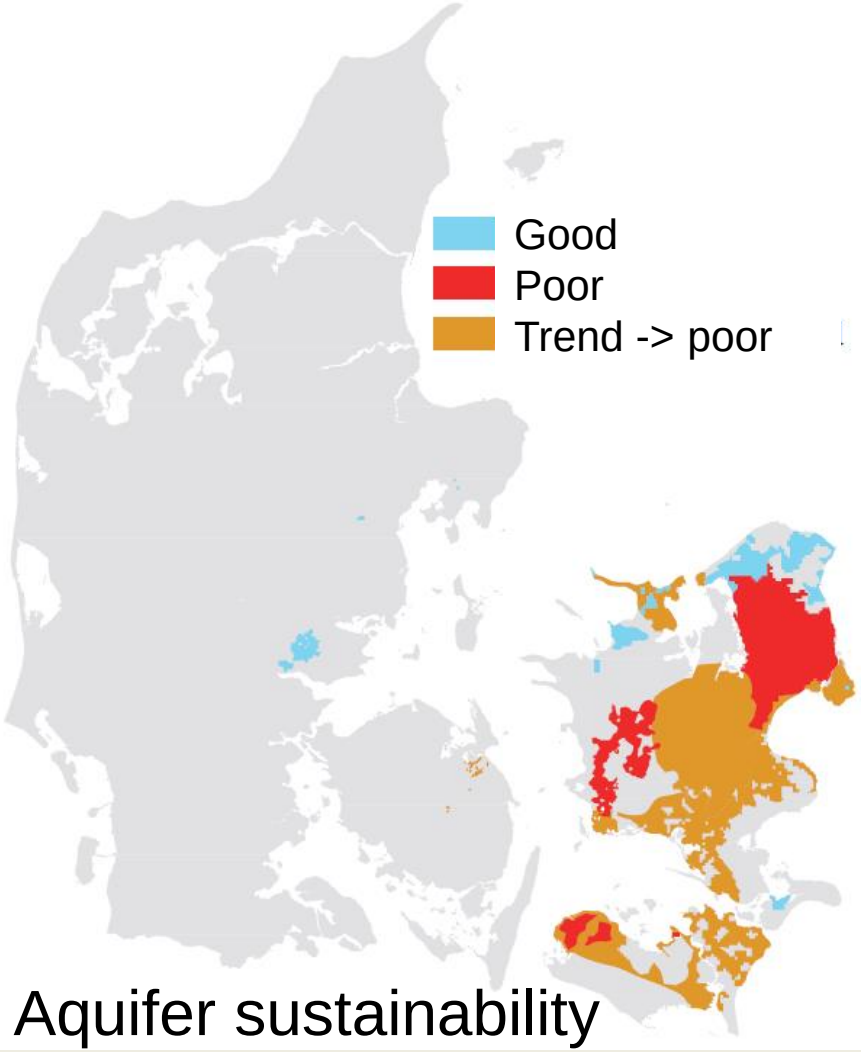


Red: Poor chemical status
Green: God chemical status
Underlined: Poor quantitative status
(water balance test)

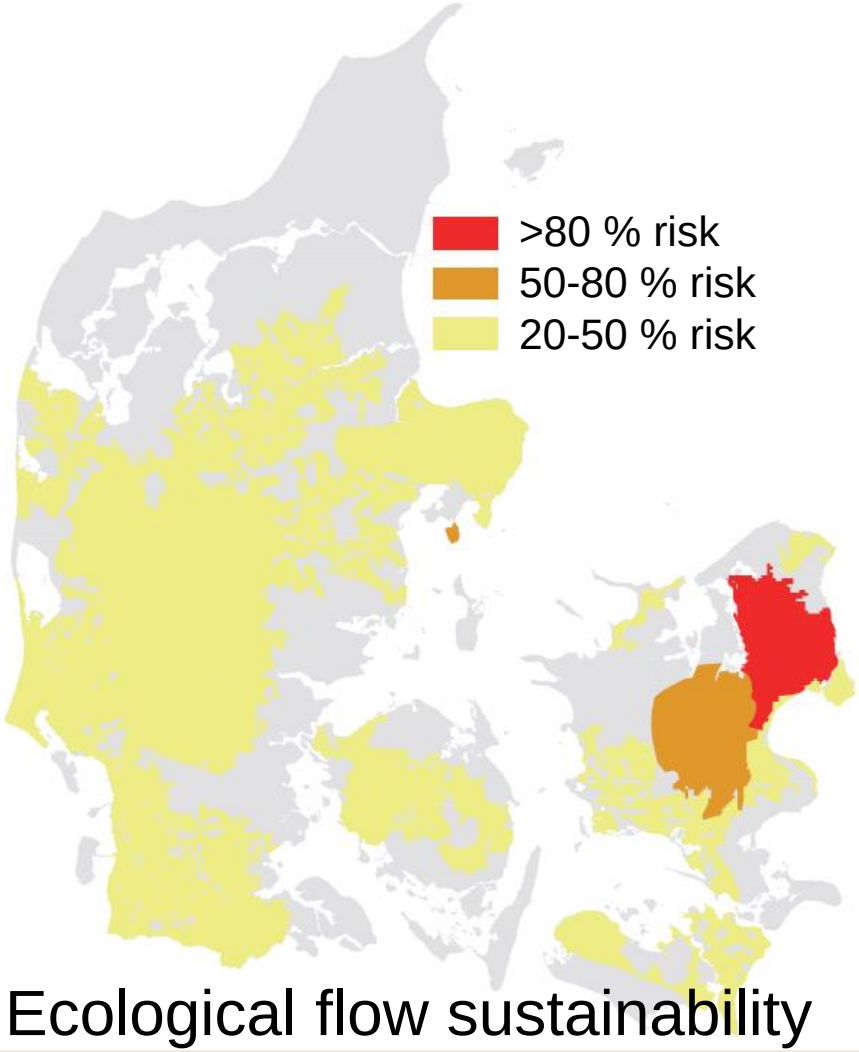
DFFVa EQR change (7 GW bodies)

GW Abstraction > 30 % of Recharge

RBMP2 in Denmark – Overall result for groundwater bodies



Aquifer sustainability



Ecological flow sustainability

Pre-project 2015-2016

Background

- Web-interface for municipalities for screening purposes with new indicators for DVFI, DVPI and DFFVa. User needs and small rivers?

New eco-hydrological indicators (WFD-RBMP2)

- Large rivers (> 2 m width/ ~ ID30 km2 scale or larger):
  - Ecological flow for type 2 and 3 rivers Hydrological regime indicators for DVFI/macroinvertebrates, DVPI/macrophyttes and DFFVa/fish
- Small rivers (<= 2 m width/ ~ ID10 km2 scale):
  - How can river flow be estimated, and how to best implement methodology for such rivers (including new relevant indicators for DFFVø/trout and macroinvertebrates)

Methodology

- Questionnaire (98 municipalities) -> what do municipalities need?
- Interviews/focus group (5 municipalities) -> in depth exploration
- Uncertainty assessment (Test case Karupå-Storå-Skjernå-Gudenå-Nørre å; test of DK model performance for large and small rivers; Decision making under uncertainty by use of Bayesian network)

Results and discussion

Goal and objective
(in Danish)

Der er med dette projekt tale om et for-projekt forud for et hovedprojekt om operationalisering af den nye viden til vurdering af vandindvindingens betydning for den økologiske tilstand i vandløb.

For-projektet har følgende formål:

- at afklare kommunernes behov og mulighed for at gennemføre beregninger til vurdering af vandindvindings kvantitative påvirkning af vandløbenes økologiske forhold
- at konsolidere det eksisterende modelkompleks med henblik på at skabe grundlaget for i et efterfølgende hovedprojekt at udvikle et landsdækkende screeningsværktøj til brugfor kommunernes vurdering af vandindvindings betydning for målopfyldelse i vandløb
- at identificere alternative metoder/data til at modellere vandindvindings betydning for målopfyldelse i mindre vandløb.

- What are the needs of municipality for Web-interface and screening tool?
- Consolidation of modelcomplex + small rivers?

Results survey (20 questions)

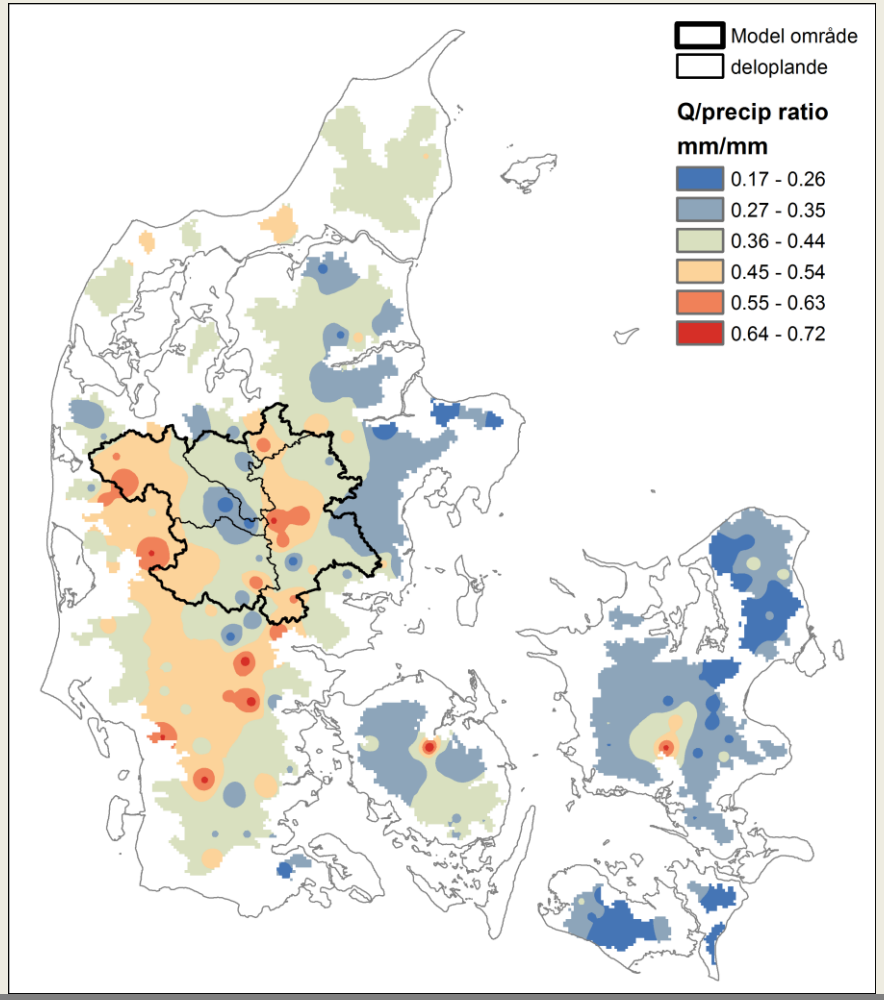
Svarvalg	Besvarelser	
Mulighed for at man kan definere et eller flere scenarie (for en eller et større antal indvindinger), bestille en modelkørsel med DK model via web interface (hvor så en modellør fra GEUS eller rådgiver kvalitetssikrer leverancen som en del af processen), hvorefter resultater kan hentes fra interface af kommunen eller rådgiver (API)	**61,19%**	41
Mulighed for at kommunen selv kan de definere et eller flere scenarier, med standardiserede udtræk af resultater på interface, der kan hentes af kommunen eller rådgivere (API)	**86,57%**	58
Mulighed for at kommunen kan uploade lokale data og administrative informationer, der kan indgå i kalibrering, usikkerheds- og risikovurdering	**73,13%**	49
Mulighed for analyser af følsomme parametre på det nuværende datagrundlag og i forhold til økologiske flow variable	**53,73%**	36
Mulighed for at kommunen kan bestille en målrettet kalibrering af DK model til økologiske flow indikatorer, med automatiseret løsning via web interface	**43,28%**	29
Mulighed for automatiseret udtræk af submodel af DK model som kommunens rådgiver kan arbejde videre med (fx 100 m model)	**58,21%**	39
Mulighed for at hente landsdækkende scenarier (0 indvinding, aktuel, tilladelse, klimaeffekter, vegetation etc.)	**35,82%**	24
Mulighed for beregning af økologiske flow indikatorer	**58,21%**	39
Mulighed for udtræk af moniteringsdata vedr. økologiske flow indikatorer	**40,30%**	27
Respondenter i alt: 67		

example

Uncertainties related to model based screening approach? Test case

- Skjern Å, Storåen, Karup Å, Nørre Å and Gudenåen
- focus on irrigation and ecological flow indicators

- PhD work of Mehrdis Danapour (spatial parameterisation and evaluation of groundwater models)
- Model optimised for fast runs (MSHE 2016, 500m grid, 4 model layers)
- Suitable for PEST inverse calibration
- Focus on irrigation and ecological flow indicator calibration

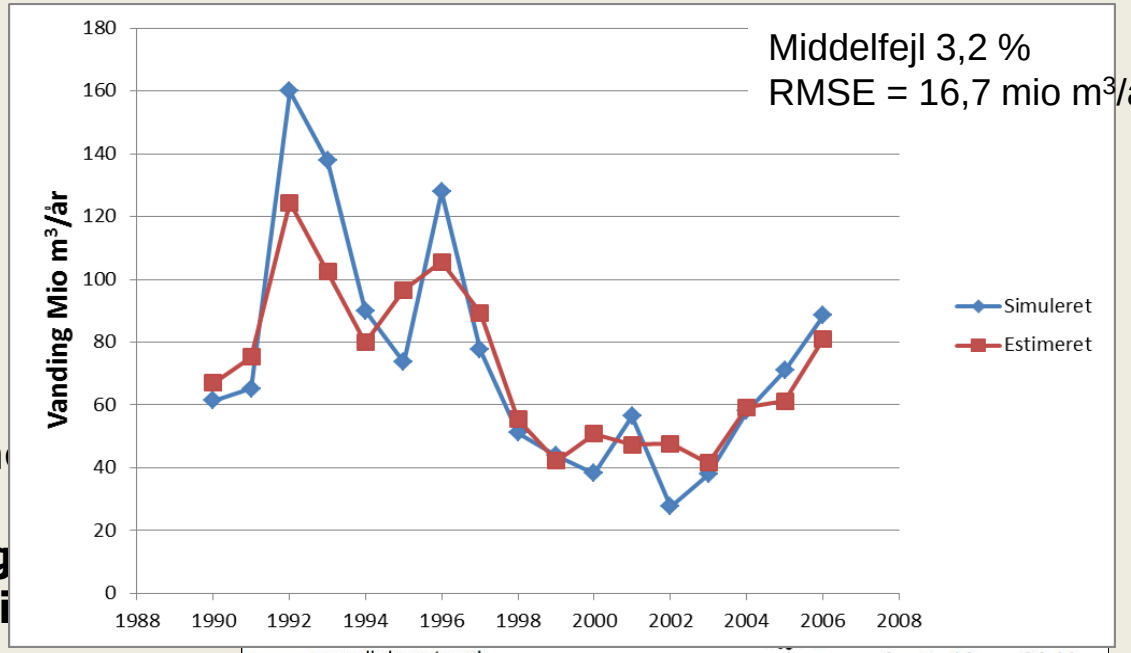


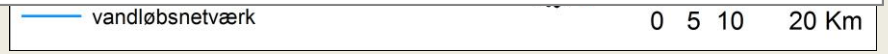
Integrated modelling in Central Jutland

- Focus on irrigation and ecological flow

Calibrated toward:

- **25 river discharge stations (>30 km²)**
- **Piezometric head observations (2640 boringer)**
- **Estimeret årlig markvandin**





Kalibreret i PEST med forskellig objektiv funktioner for vandføri (kalibreringsmål)

- **Traditionel (NSE, Fbal, $Fbal_{sommer}$)**
- **28 Økologiske flowindikatorer (BFI, DVFI, DVVFa osv.)**

Integrated modelling in Central Jutland

- Focus on irrigation and ecological flow

Calibration:

- **Calibration 2000-2006**
- **Validation 1995-1999**

- **13 calibration parameters (Ks, rootdepth, irrigation, drains, leachage)**

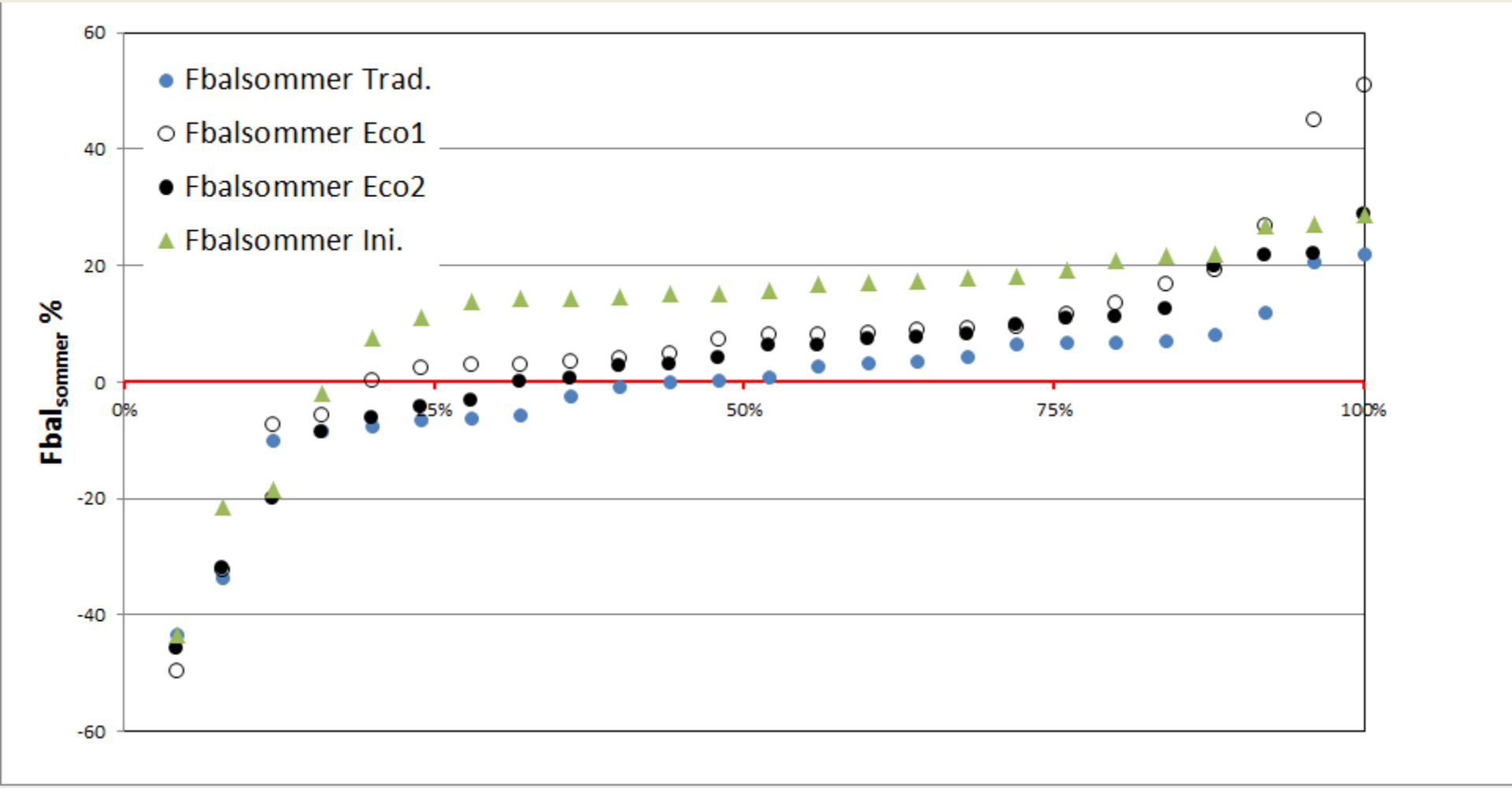
- **Calibrated in PEST with different objective functions for discharge (calibration goals)**

- **Traditionel (NSE, Fbal, $Fbal_{summer}$)**

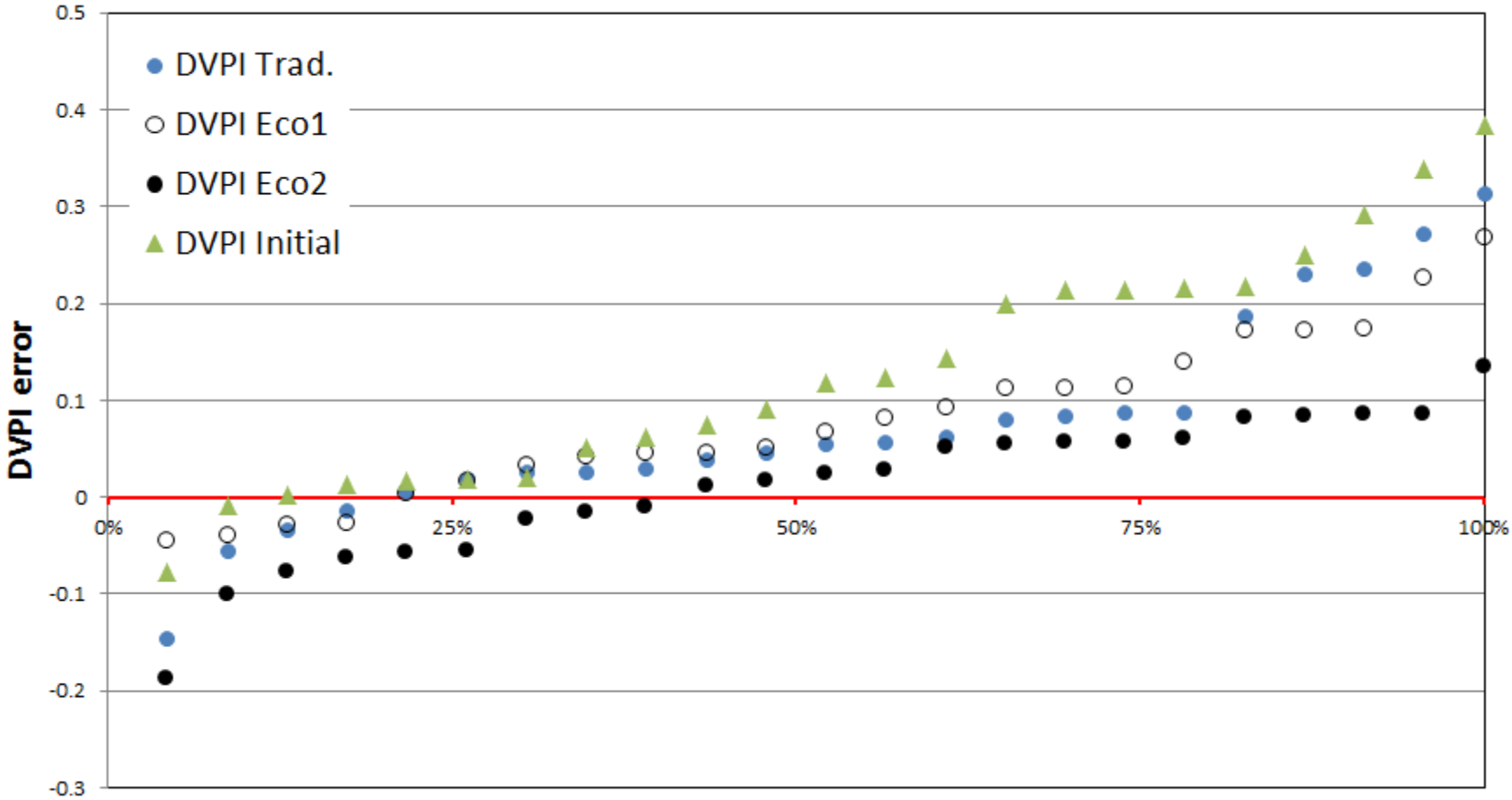
- **28 Økologiske flowindikatorer (BFI, DVFI, DVVFa ovs.)**

	Trad.	Eco1	Eco2
Traditionelle			
Trykniveau	4	4	4
$Fbal_{sommer}$	1		1
Fbal	1		1
NSE	2	2	2
Vanding RMSE	2	3	2
Økologiske			
BFI		2	2
DFFVa		2	
DVFI		2	
DVPI			
Q25			
Q50			
Q75			
Q95			
Sum	**10**	**15**	**12**

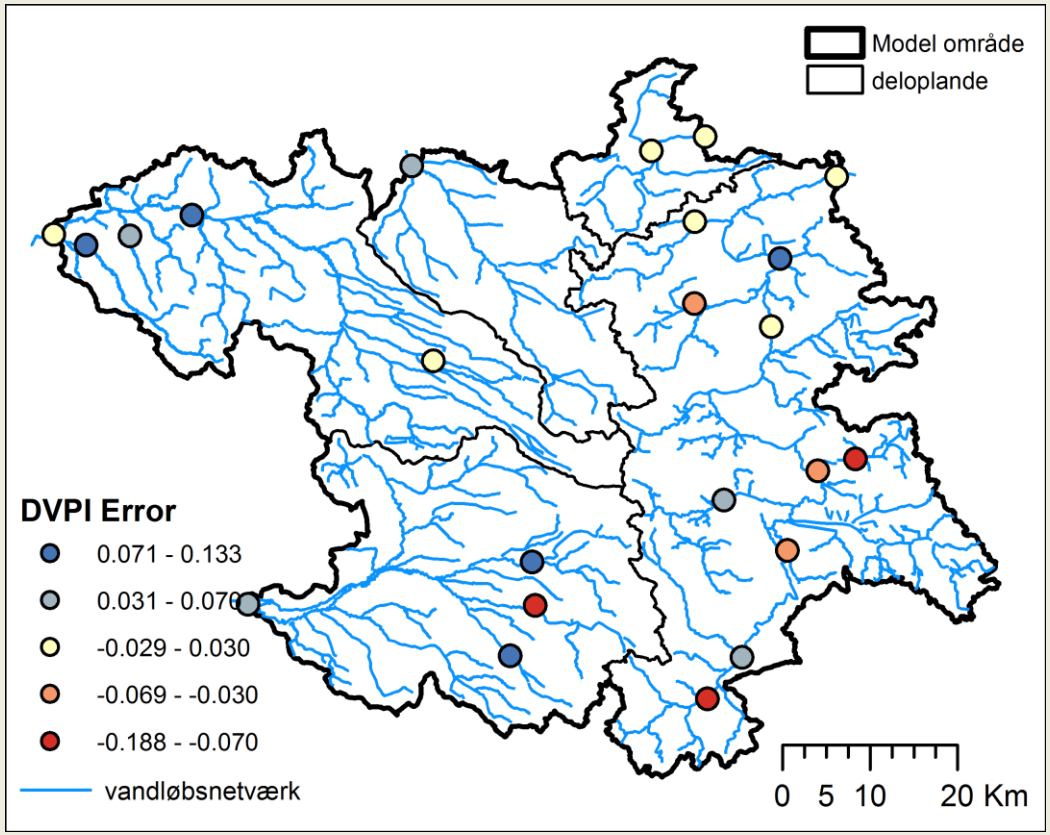
Calibration results
Traditional OBF



Calibration results
Ecological flow OBF



Calibration results ECO2



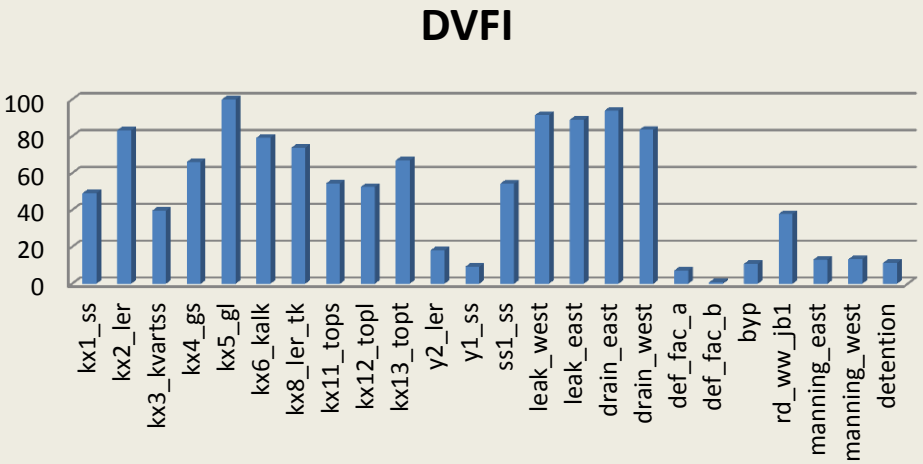
Results

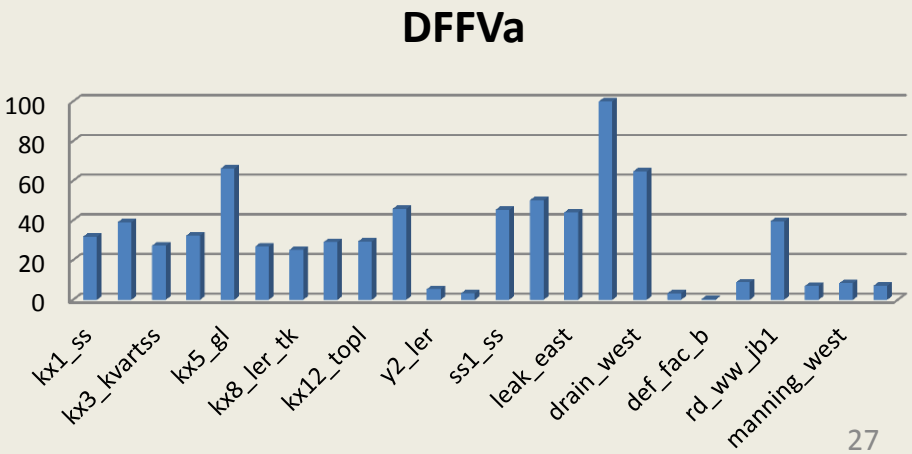
	Initial	Trad.	Eco1	Eco2
Markvanding				
RMSE [mio m^3/år]	36.7	12.5	14.4	14.8
Traditionelle kalibreringsmål				
NSE > 0.70	36%	52%	52%	52%
NSE > 0.50	68%	84%	72%	80%
Fbal ± 10%	52%	64%	56%	56%
$Fbal_{sommer}$ ± 15%	28%	84%	72%	72%
Økologiske indikatorer				
RMSE BFI i %	10%	9%	9%	5%
RMSE DVFI i %	17%	15%	11%	10%
RMSE DVPI i %	36%	26%	23%	15%
RMSE DFFV i %	25%	21%	19%	14%
Trykniveau				
RMSE Lag 1 [m]	3.3	3.2	3.1	3.2
RMSE Lag 2 [m]	8.0	7.7	7.9	7.8
RMSE Lag 3 [m]	6.2	5.4	5.0	5.2
RMSE Lag 4 [m]	6.6	5.8	5.7	6.1

Composite sensitivity

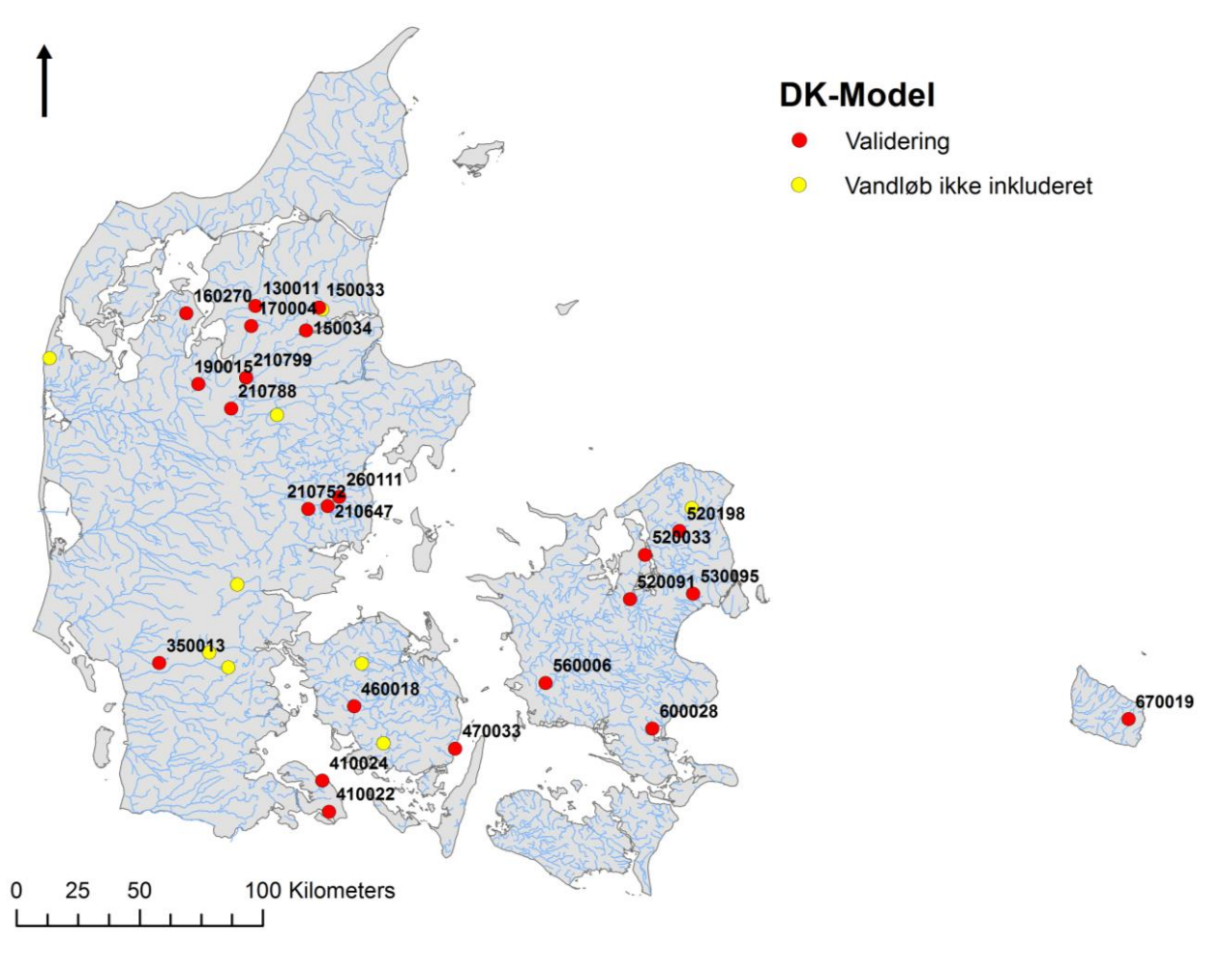
Tabel 6.6 Relativ følsomhed/composite sensitivity (0-100)

Kalibrerings-\ mål Parameter	RSME vanding	NSU	Fbal	Fbal-S	Tryk-niveau	DVFI	DFFVa	BFI
Draen-east	19	22	50	**41**	75	**94**	**100**	**100**
Draen-west	**52**	**57**	**93**	15	**95**	84	**65**	**79**
kx5-gl	15	**49**	**97**	32	**85**	**100**	**66**	40
Leak-west	5	9	16	15	52	**92**	50	40
Rd_ww_jb1	**100**	45	**100**	**93**	49	38	40	27
Leak-east	3	9	41	**55**	27	89	44	41
ss1-ss	0.4	5	17	19	27	54	45	29
kx13_topt	0.4	3	14	10	31	67	46	29
kx2-ler	**20**	**100**	45	38	**100**	83	39	41
kx1-ss	7	47	58	21	55	49	32	**60**





Small rivers – uncertainty

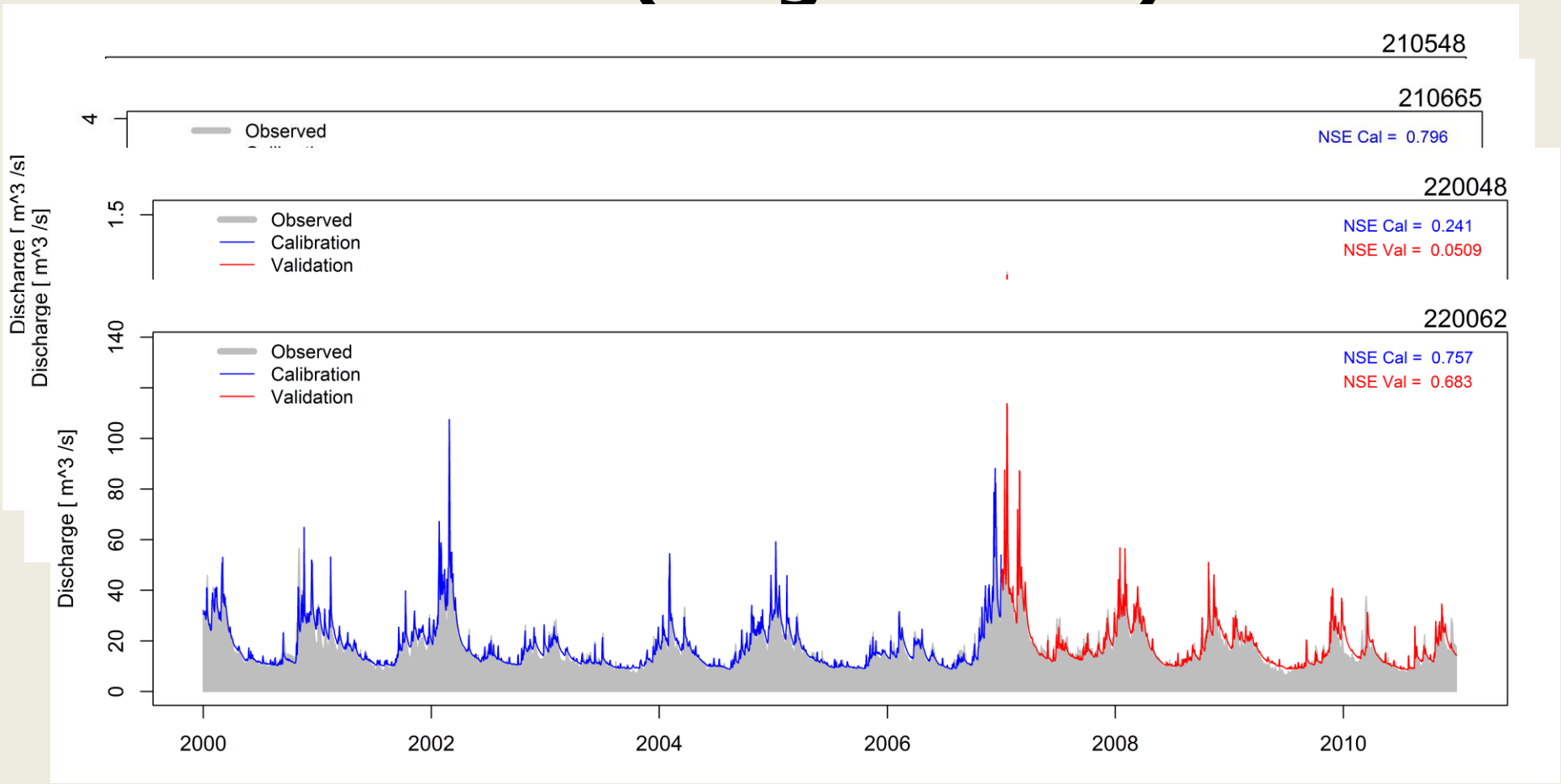


DCE methodology
SWAT

GEUS DK model
Approach

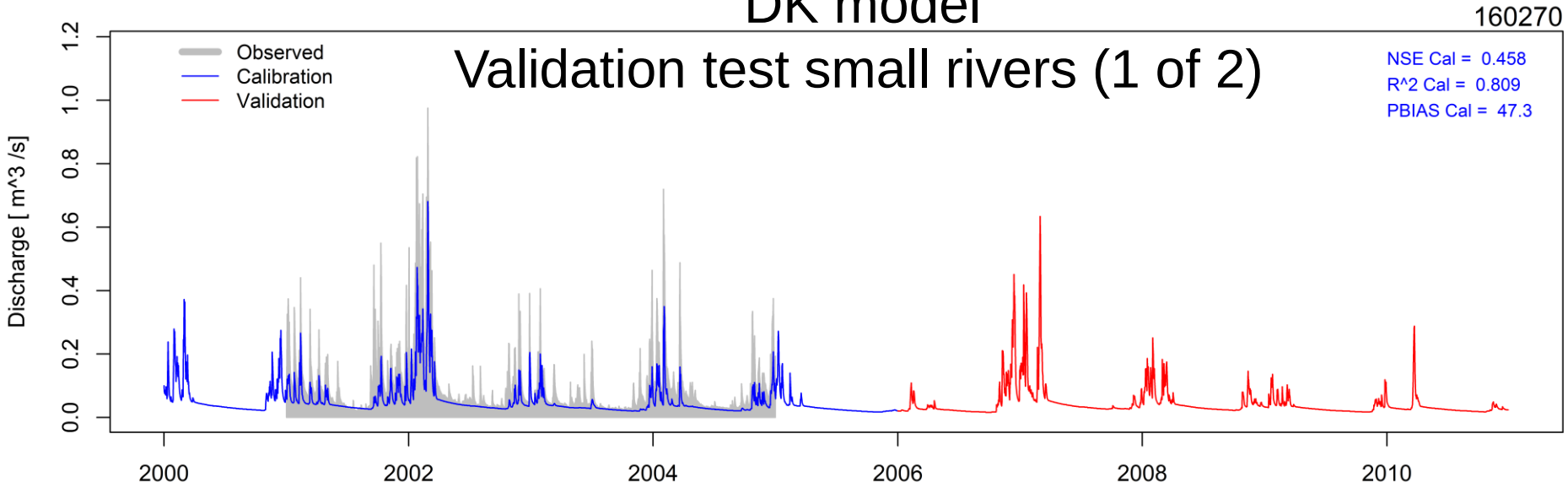
Test performance
(NSU + Fbal)
for DCE stations
(observed
Discharge)

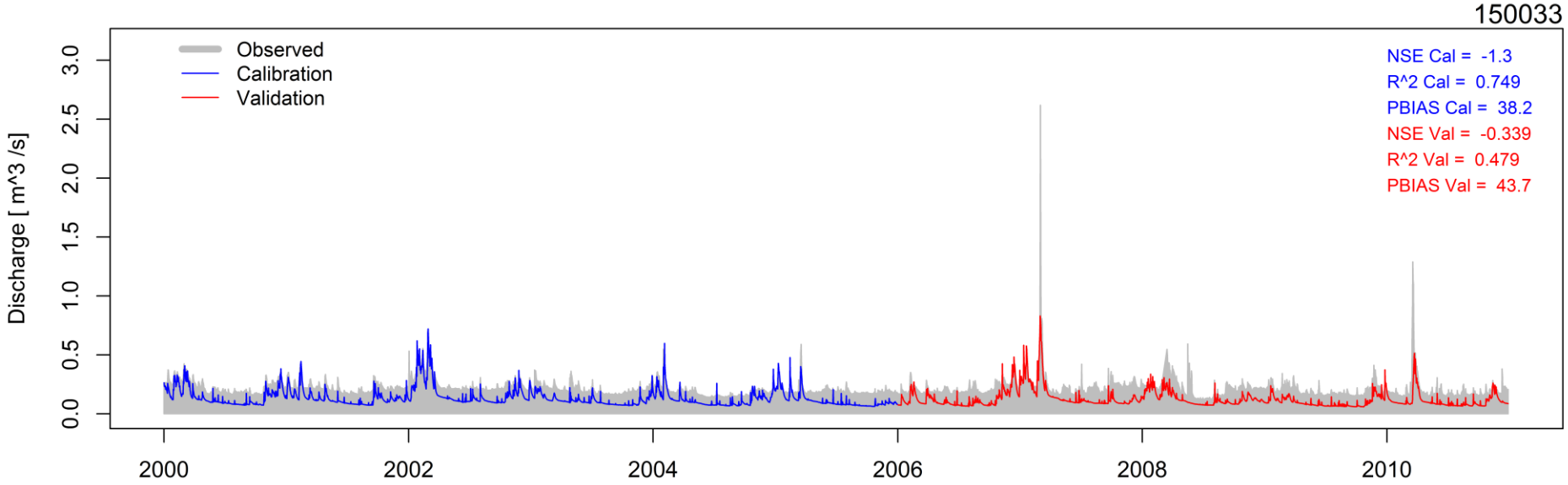
Hydrographs – examples from DK model (large rivers)



DK model

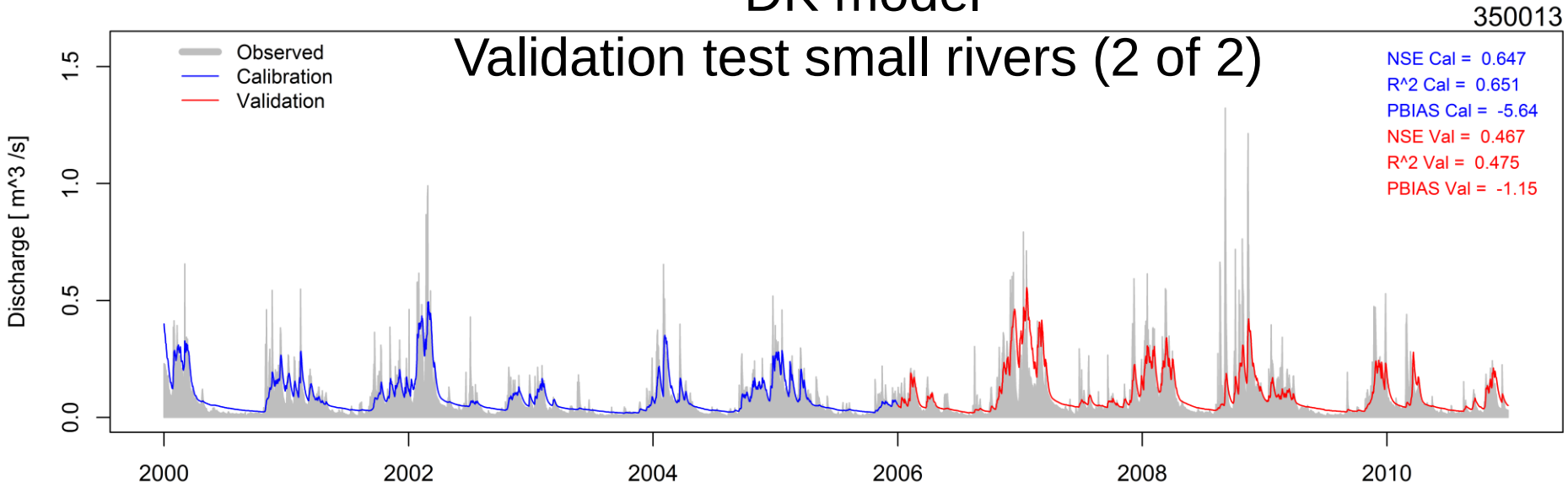
Validation test small rivers (1 of 2)

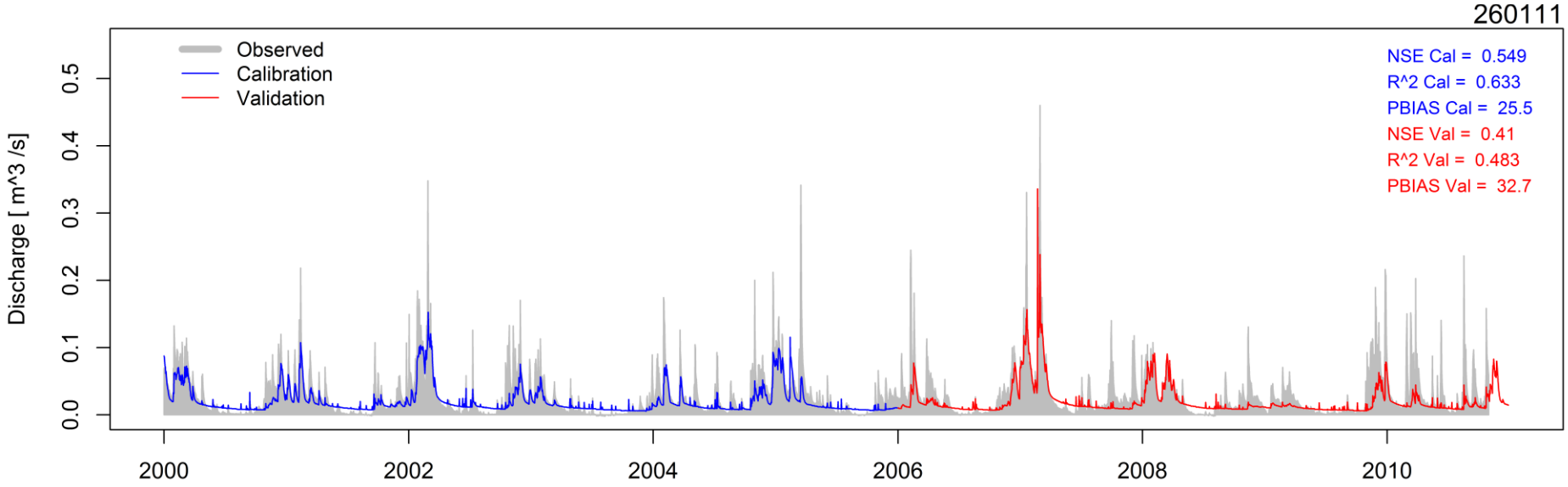




DK model

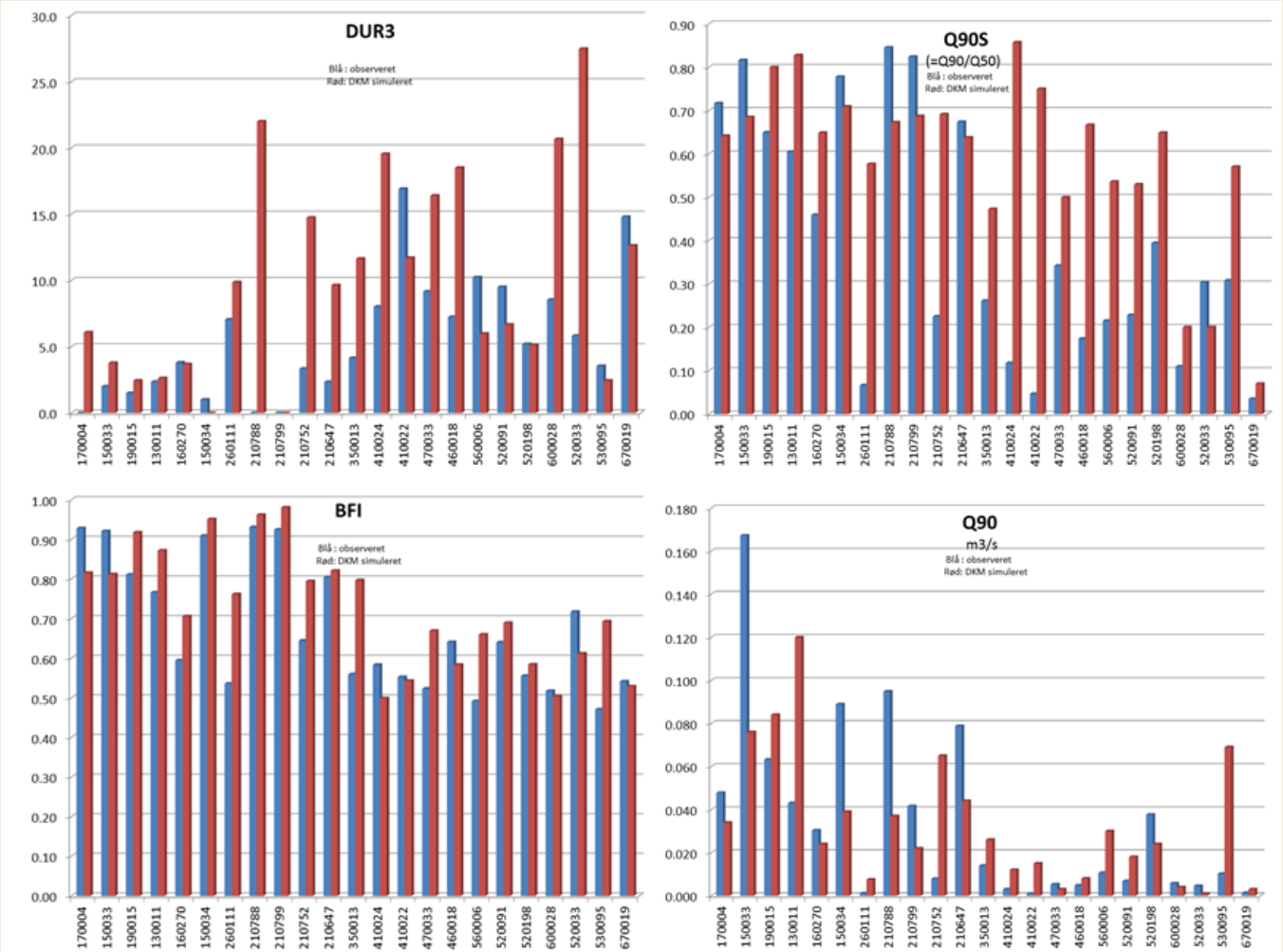
Validation test small rivers (2 of 2)





Results with DK model for small streams compared to observed flow

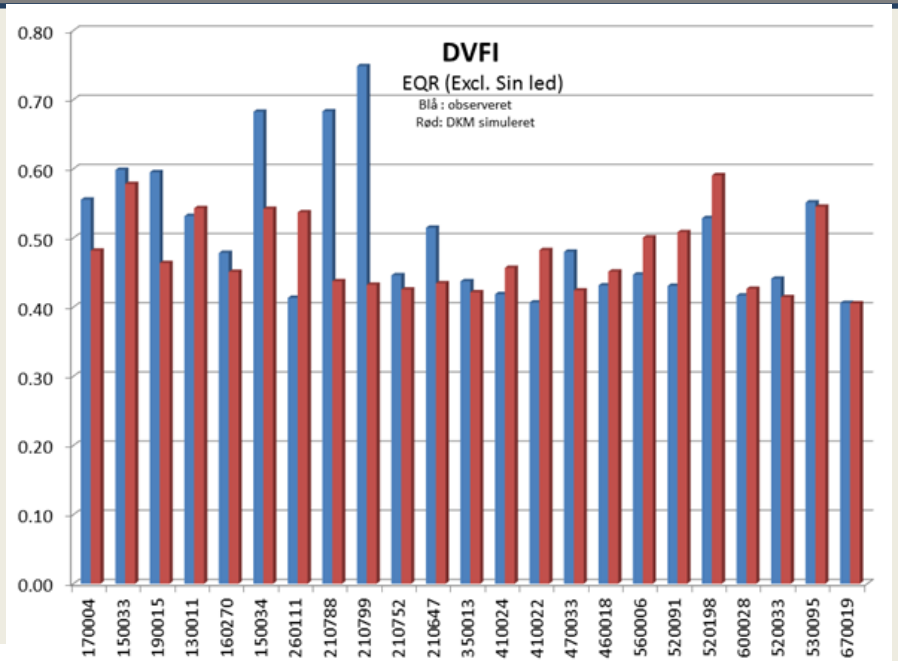
Results DK model small streams

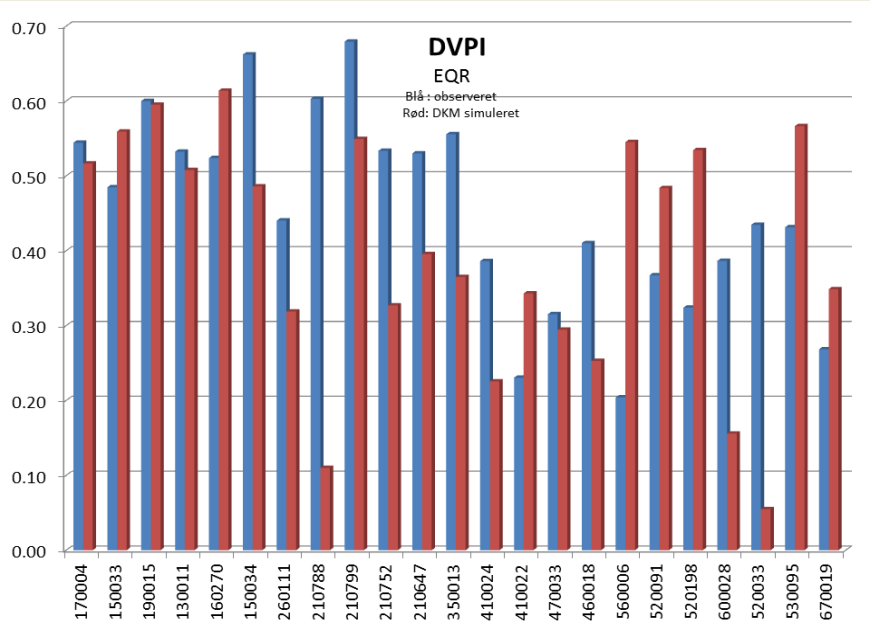


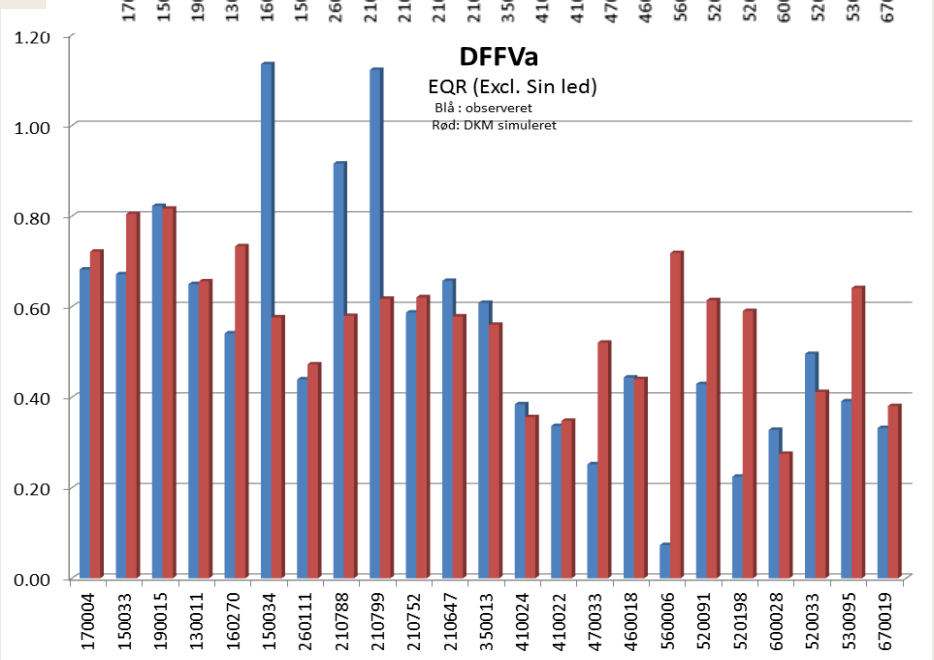
DVFI, DFPI DFFVa

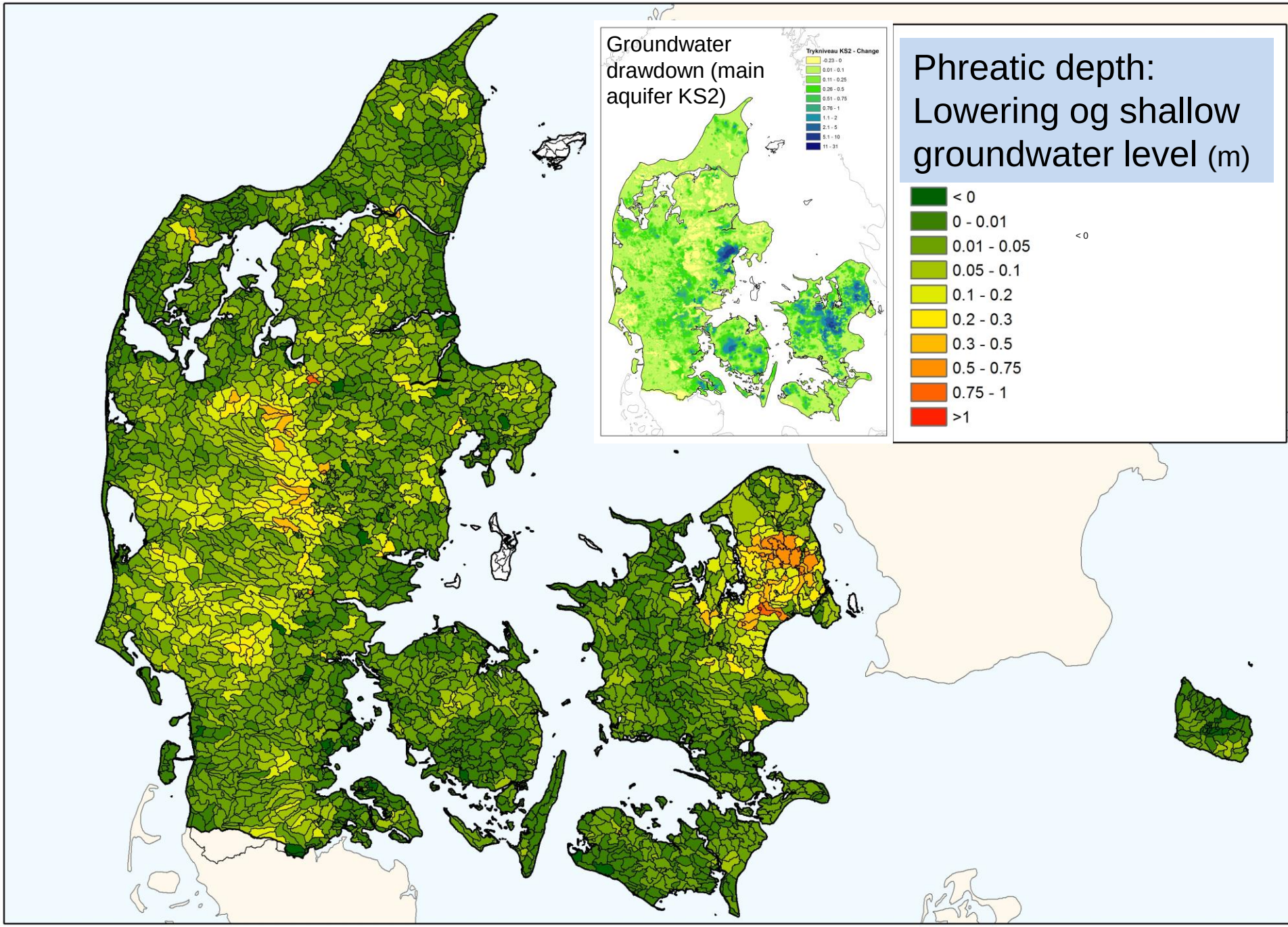
Calculated from observed discharge compared to DK model simulated

small rivers
(~10 km2)








Groundwater drawdown (main aquifer KS2)
Trykniveau KS2 - Change
-0.23 - 0
0.01 - 0.1
0.11 - 0.25
0.26 - 0.5
0.51 - 0.75
0.76 - 1
1.1 - 2
2.1 - 5
5.1 - 10
11 - 31
Phreatic depth: Lowering og shallow groundwater level (m)
< 0
0 - 0.01
0.01 - 0.05
0.05 - 0.1
0.1 - 0.2
0.2 - 0.3
0.3 - 0.5
0.5 - 0.75
0.75 - 1
>1
< 0

Discussion: Science-(policy)

- Today, screening methods with in-built precautionarity are used for evaluating aquifer safe yield and environmental flow. Such methods are simple to administrate, but they lack flexibility to incorporate local data and knowledge and they therefore have a high uncertainty
- More comprehensive (investigative) methods that better utilize new scientific knowledge and site (reach) specific hydrogeological and ecological data, allowing for a higher transparency and accuracy in assessment of sustainable groundwater abstraction, are needed
- New risk-based strategies for well field operation and water management taking into account the uncertainties in the sustainability criteria, should be developed
- Methodologies and tools that can support management of sustainable groundwater abstraction is needed

Conclusion (RBMP2)

- There has been **established a model system that implements new hydro-ecological regime indicators**
  - 6 eco-flow variables for DFFVa/fish, DVFI/macro-invertebrates and DVPI/macrophyttes-plants, and sinuosity/meandering as a proxy for physical index score).
- The scale of assessment is based on ID15 catchment areas (2700 sub-catchments ~ 15 km2 on average) and with **impacts related to groundwater bodies** (a total of 400).
  - 3 groundwater bodies was evaluated in poor status, and 6 at risk in relation to aquifer sustainability
  - 1 groundwater body had poor status in relation to ecological flow (> 80 % probability for reduced ecological status, many more if threshold is lower)
- The used **low flow indicator (Qmm)** used since 1979 was evaluated to have only secondary importance (R2 max 0.15 for the three indicators)..
- The indicators was **used for WFD/draft RBMP2**
  - Indicators for GWDTE's and ecological flow for type 1 rivers (< 2 m width, juvenile trouths/DFFVø) need to be implemented. Uncertainty: 1) from hydrological regime varibles -> DVFI, DFFVa and DVPI, 2) national model

Conclusion: Knowledge gaps

- Development and validation of ***environmental flow/aquifer safe yield*** methods at RBMP scale and especially at a ***smaller scale relevant for groundwater abstraction licenses*** adm.
  - *Absolute flow magnitude is not included in 3 new ecological flow regime indicators – does flow have any importance? (only Q90/Q50, Fre1, BFI, Fre25, Fre75 and Dur3 included)*
  - *Water levels in groundwater and surface water not included*
  - *Water quality, temperature and sediments not included*
  - *Trout nursery and spawning grounds in upstream parts of rivers not included at scales < 15 km2 (trout density index, DFFVø not included)*
- ***Incorporation of GWDTE*** *in RBMP and administration of groundwater licenses*
  - *Soil moisture and/or shallow groundwater level and seasonal variation and importance for various indicators (vegetation/GWDTEs)*
  - *Need for development of methodology (evidence based)*
- ***Adaptive management***, based on innovative approaches for monitoring, polycentric governance, uncertainty assessment etc.
  - *Need for novel ways of managing new licenses (monitoring and model based but where uncertainties are addressed in different ways)*

Thank you for your attention!

(background litteratur)

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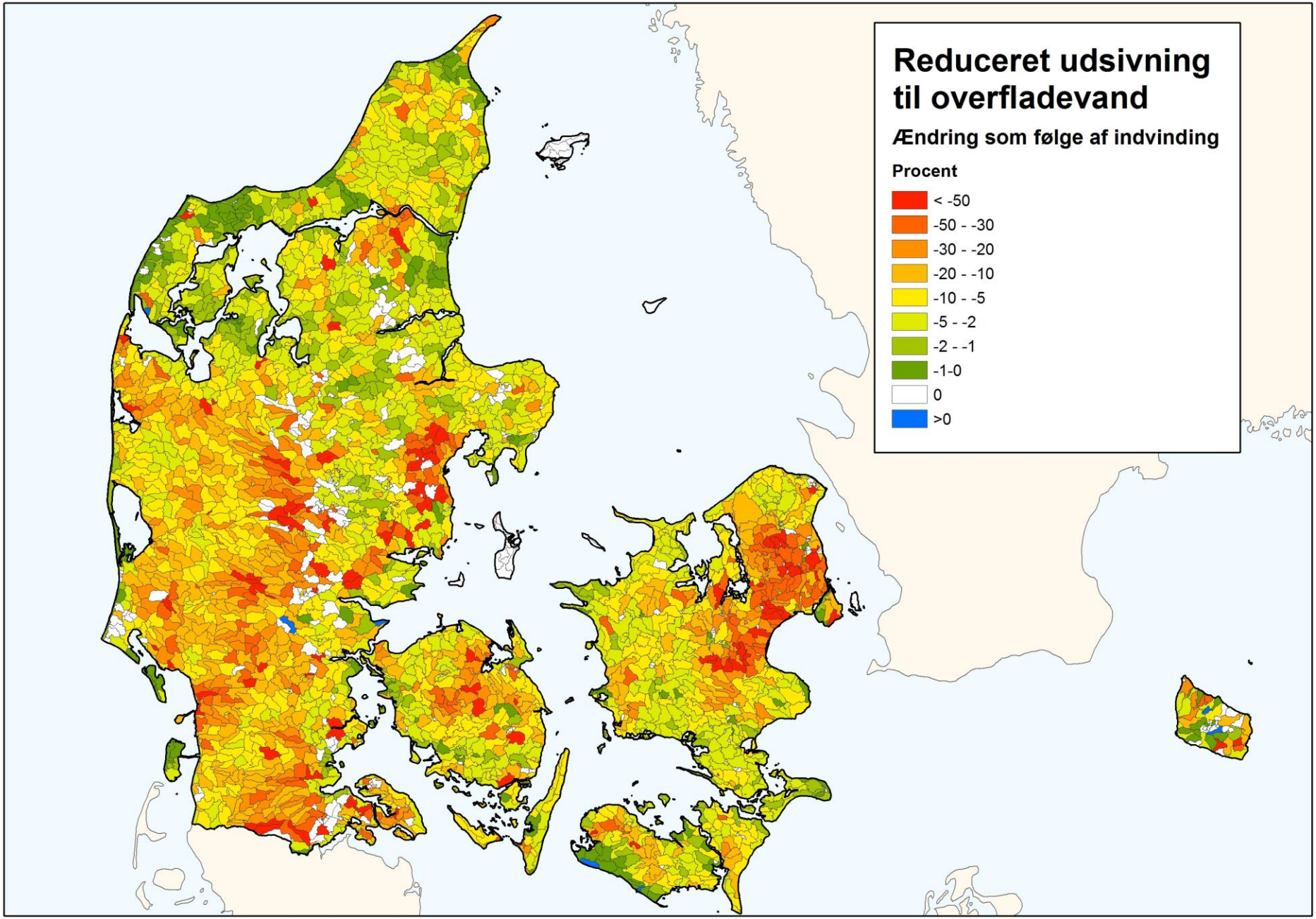
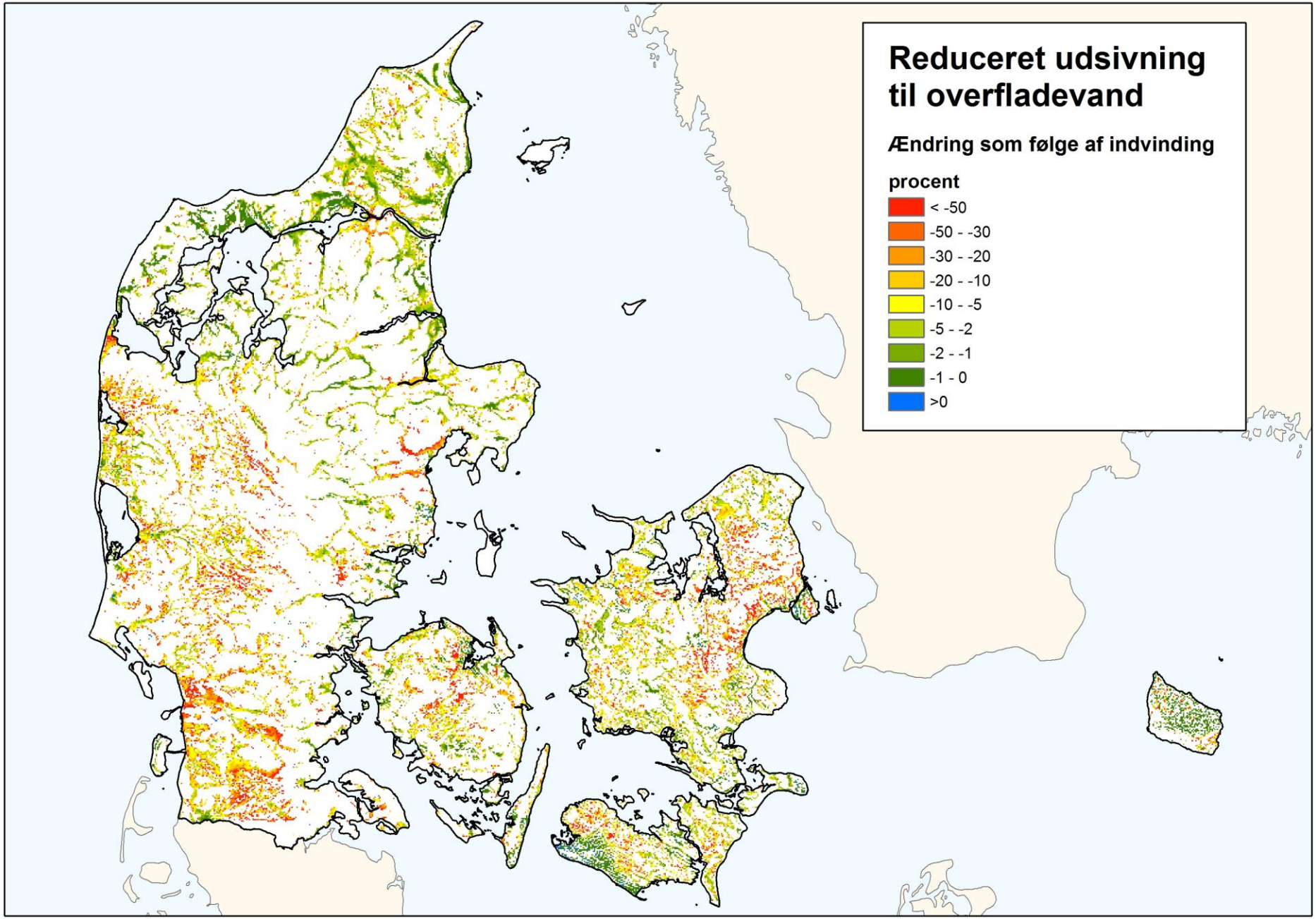

Reduceret udsivning til overfladevand
Ændring som følge af indvinding
Procent
< -50
-50 - -30
-30 - -20
-20 - -10
-10 - -5
-5 - -2
-2 - -1
-1-0
0
>0


Reduceret udsivning til overfladevand
Ændring som følge af indvinding
procent
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-1 - 0
>0