Bayesian network for integrated assessment of ecological flow status in Danish rivers based on observed hydrological regime variables ©

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Background

Abstraction of groundwater is a major stressor for terrestrial and aquatic ecosystems especially in countries like Denmark where close to 99% of the water supply is based on groundwater. During the past decades overexploitation in Denmark and many other places has resulted in deterioration of aquifers and poor status of receiving ecosystems. Recently, the first River Basin Management Plans (EU Water Framework Directive) classified groundwater abstraction near the larger Danish cities to have severe sustainability problems due to over pumping. Criteria's in the first round were related to median minimum flow reductions due to groundwater abstraction, typically with thresholds of max 5 % reduction (high status) and max 10-25 % reduction (good status), depending on rather old guidelines from 1979 by the Danish EPA for ecological goals for fish for various stream reaches (Henriksen and Refsgaard, 2013).

Data bases with indicators for acceptable stream flow depletion for low flow are up till now the most common methods for assessing whether groundwater abstraction leads to unacceptable conditions for riverine ecosystems (Henriksen et al., 2008; Olsen et al., 2013). However, ecosystem conditions are known to depend on other factors than minimum stream flow (like median minimums flow Q_{mm}, Q95 or Q90). For the second River Basin Management Plans in Denmark, DCE (former NERI) therefor developed a new model for the relationship between flow variables and index scores for three biological quality elements fish (DVFFa/61 sites), macro-phytes (DVPI/91 sites) and macro-invertebrates (DVFI/122 sites), based on an analysis of ecological and measured flow data from 2004 to 2010 (Graeber et al., 2014). The effect of physical condition of the sites was included by using the quality of the cross-sectional profile and sinuosity. The final models for the three quality elements included six other flow variables: Q90 (flow below 90^{th} percentile), Fre1 (annual frequency of events above median discharge), Fre25 (annual frequency of flows above Q25), Fre75 (annual frequency of flows below Q75), Dur3 (annual duration of extreme flow events three times above median flow) and BFI (base flow index), (Graeber et al. 2014; Riis et al. 2008). GEUS implemented the new indicator for EU WFD RBMP2 for Denmark and even though median minimum flow Q_{mm} was evaluated as having less importance (Graeber et al. 2014), this variable was used for screening of the most impacted reaches (based on 2700 stations defining ID15 sub-catchments of approximate area of 15 km^2), and also for analysing relationships between impacted reaches and 400 groundwater bodies (Henriksen et al. 2014). In addition to this, in some streams water quality and temperature, will depend on impacts on median minimum flow, so for various reasons this indicator has a regulatory importance, and is therefore included in the calculations.

The approach is useful for highlighting where groundwater abstraction is likely to prevent full-filling good ecological status – taking physical conditions into account, and for designating sites, where it should be possible to establish how much abstraction must be reduced, or alternatively measures must be taken to improve ecological flows conditions. DCE derived the indicators for DVFI (macroinvertebrates), DVPI (macrophytes) and DFFVa (generalised fish index from Lithuania for three or more species) based on symbolic regression (EUREKA) - a genetic algorithm for identifying an optimal equation (in the formula SIN is the class of sinuosity (a value ranging from 1 to 4 where 1 is channelized river and 4 is meandering river):

$$\mathbf{DVFI_{EQR} = 0.217 + 0.103*Sin + 0.020*Q90*Fre_1} \quad \text{(R2 =0.44 based on 122 Danish sites)}$$

$$\mathbf{DVPI_{EQR} = 0.546 + 0.020*Fre_{25} - 0.019*Dur_3 - 0.025*Fre_{75}} \quad \text{(R2 =0.49 for 91 sites)}$$

$$\mathbf{DFFVa_{EQR} =0.811*BFI + 0.058*Sin + 0.050*Fre25 - 0.319 - 0.0413*Fre_{75}} \quad \text{(R2 = 0.53 for 61 sites)}$$

The above equations are the best option for evaluating the ecological status for the three indicators. However, I want to play a bit around with these equations in the following Bayesian network analysis, in order to show how uncertainties can be added to these equations for integrated assessment purposes.

Based on the calculated values of DVFI, DVPI and DFFVa for the 61-122 stations and the observed values of DVFI, DVPI and DFFVa, and implemented model results with the national water resource model (DK model) for Q90 (dkQ90S), BFI (dkBFI) and Q_{mm} (dkQmm) for the same stations, a dataset was prepared which was further analysed with HUGIN structural and EM learning tools. Hereby the Bayesian network shown in Figure 1 was developed and validated for the stations with observed DVFI, DVPI and DFFVa.

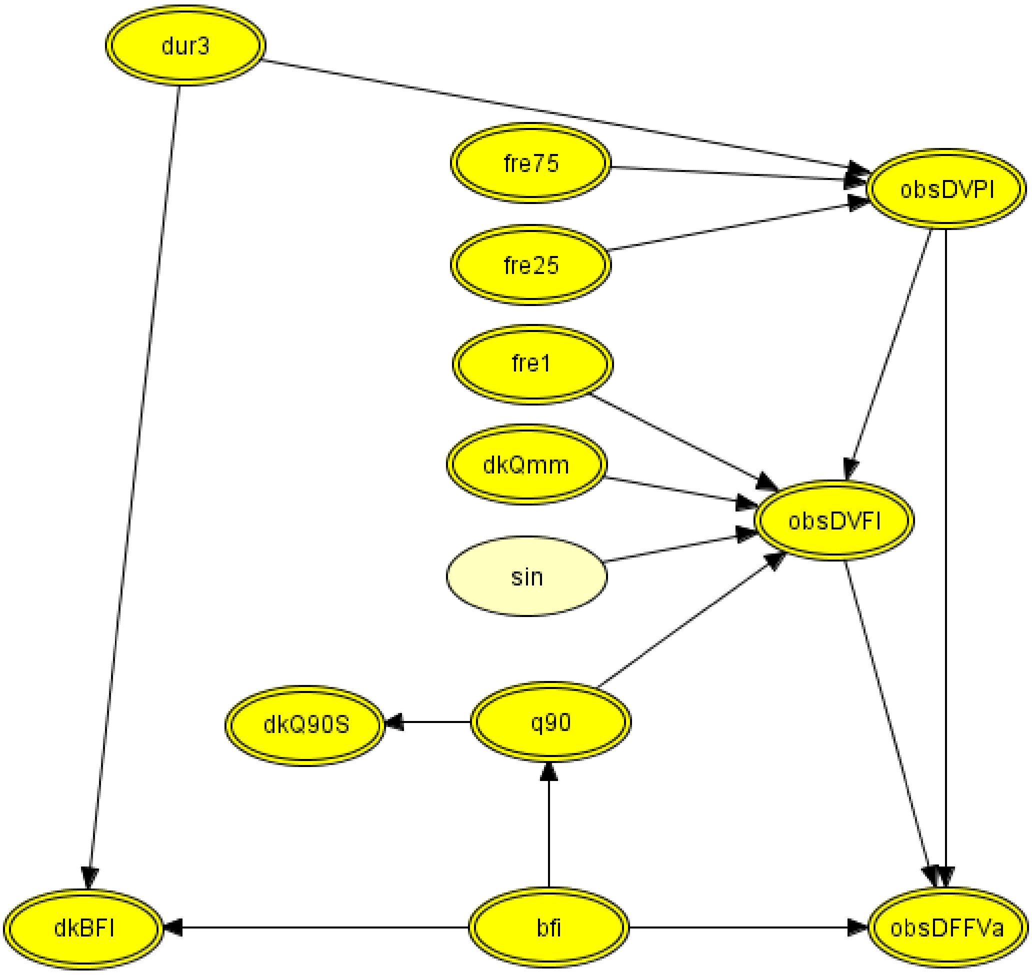

Figure 1 Developed BN for integrated assessment of ecological status in Danish rivers

In the final prototype Bayesian network all variables (except SIN which has four discrete states that can have the values 1-4) have been implemented as continuous variables. Hereby casual relationships e.g. that obsDVPI depends on Fre_{25}, Fre_{75} and Dur_3, where each variable is represented by a linear relationships of mean values plus a constant, and assuming a normal distribution whereby uncertainties bounds (variance) is explicitly represented by the Bayesian network. For DVPI the formula on page 1 has been directly incorporated, since it is assumed that DVPI only depends on these three variables, and furthermore that macrophytes ecological state can been assumed as a parent variable for macroinvertebrates (DVFI) and fish (DFFVa), which is represented by the BN with the arrows to obsDVFI and obsDFFVa.

This means that the constructed Bayesian network for DVFI and DFFVa is an alternative way of calculating ecological status compared to the equations for the three ecological quality elements shown on page 1. The calculated results (mean values) will therefore differ from results obtained by the equations, and below I have tested the constructed Bayesian network against selected data (all stations with all there observed data). However, the main idea of the Bayesian network is to include the uncertainty assessment, and also to provide a more holistic model, compared to the symbolic regression derived formulas on page 1, e.g. a more integrated model, also honoring relationships (DVPI-> DVFI, DVFI-> DFFVa and DVPI-> DFFVa). Here I assume that the plants in the river, will positively affect habitat conditions for macroinvertebrates and fish, and also that a good status of macroinvertebrates will positively effect the status of fish.

For DVFI where the formula assumes a multiplication of q90 and fre_1 I can't include this mathematical relationship in the Bayesian network, due to limitations when using continuous variables (only linear relationships are permitted). Therefore, the constructed BN do not fully incorporate the multiplication of q90 and Fre^1, and this will increase the uncertainty of the prototype. In the structural learning and EM learning (training of network with the 61-122 data which is available for the three indicators), I in addition to observed values and simulated DCE indicators, also included DK modelled data for the variables which is most accurately described by the DK model (dkQ90S, dkBFI, dkQ_{mm}), see Henriksen et al. 2014. I decided to skip the most uncertain DK modelled variables (Fre_1, Fre_{25}, Fre_{75} and DUR_3). These frequency variables are typically underestimated by the national model compared to observed variables derived from observed time series. In the implementation as part of WFD RBMP2 this bias was compensated for by a bias-correction (Henriksen et al., 2014). When carrying out the structural analysis and EM learning variables with 'high noise' inaccurate variables are often not identified by the learning algorithm and therefore not included in the constructed networks unless inclusion their representations is forced by the expert. This was not done here. The analysis revealed that actually Q_{mm} could be included, even though it did only add minor explanation, whereby a suitable linear relationship for calculating obs-DVFI was obtained. Hereby, it could be calculated by the Bayesian network by which degree the evaluated DVFI depends on the value of the median minimum flow.

Since the equations for DVPI and DFFVa contains almost the same terms for x Fre_{25} – y Fre_{75}. In the developed Bayesian network, these two variables only impact obsDVPI, but since DVPI is a parent to DFFVa, once the value of DVPI has been calculated by the Bayesian network, this subsequently impact DFFVa and the calculated ecological status for fish.

Since the *sin* term already has been included in obsDVFI, this variable therefore in a similar way has a knock on effect on DFFVa through obsDVFI. Due to these already incorporated relationships, only the variable bfi (baseflow index - provide another parent variable to obsDFFVa) give direct input to obsDFFVa, all the other terms comes via DVPI and DVFI. In this sense the network is more integrated.

The final network show that the result of the DK model variable (dkBFI) is mainly dependent on measured bfi but also slightly dependent on measured Dur_3 (duration of events three times Q90). These observed parent variables can translate measured bfi and dur3 to a distribution (update mean and variance) of dkBFI values. The same yield for dkQ90S (dkQ90/dkQ50), but here the relationship is directly translated by a linear combination with q90 as the single parent variable.

The idea of the network is to enable an exploratory analysis and integrated assessment of the state of ecological flow variables. In the initial situation the network describe the overall results "in average" based on initial distributions of all variables based from the 61-122 sites. So the initial Bayesian network show distributions for all variables, but here the main uncertainty is due to the variability of the 61-122 sites, and to a less degree measurement and model uncertainty, which first are analysed after having entered fixed mean values for the 8 observed variables (dur_3, Fre_1, Fre_{25}, Fre_{75}, Q_{mm}, Sin, q90, bfi), see Figure 2.

Due to the importance of the discrete variable (Sin) the probability distributions for obsDVFI and obsDFFVa reflect an impact of the discrete nature of Sin. Once sinuosity has been fixed, and other variables has been entered, the Bayesian network is updated and by use of Bayes theorem and now show a posterior assessment of the three indicators obsDVFI, obsDVPI and obsDFFVa.

Entering evidence also affect the variance and the uncertainty bounds, and after entering site specific data for a station by the user, the Bayesian network now show the results of the three quality elements based on the entered 8 hydrological regime variables as evidence.

Due to the ability of doing exploratory analysis by changing single or all hydrological regime variables by the user, the BN can analyse how a change due to groundwater abstraction (reduced or increased) will affect the three ecological flow indicators (obsDVFI, obs DVPI and obsDFFVa), by entering updated values of regime variables based on detailed model analysis. Below in Figure 2 an example is shown of the initial BN estimates of mean values and variance, and the normal distributions (within a window of 2*STD).

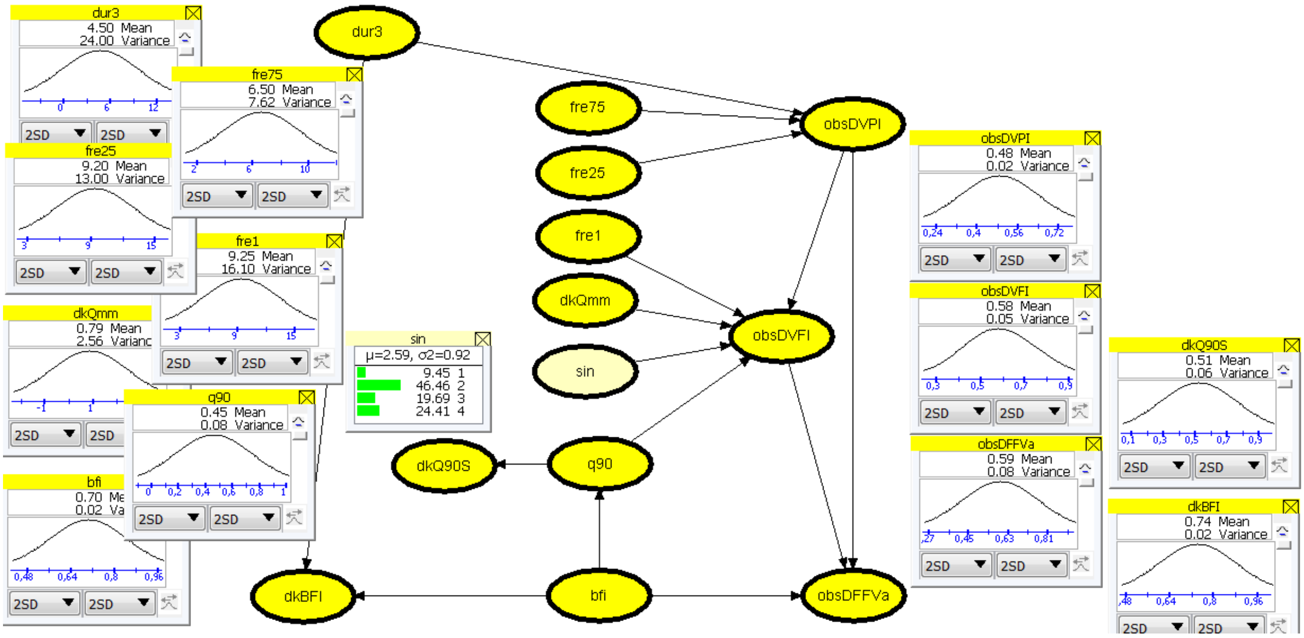

Figure 2 Example with initial network showing calculated mean values and variance (show with monitor windows for all variables). For the initial network the uncertainty bounds reflect the overall variability.

Inference with the constructed Bayesian network

Inference is the act or process of deriving logical conclusions from premises known or assumed to be true. Let's try to enter the following hydrological regime variables (for station 220062):

Example A large downstream catchment in Jutland (220062)

- $Dur_{3\,=}$ 5 days
- Fre_{75} = 6.56 (events per year below Q75)
- Fre_{25} = 8.22 (events per year above Q25)
- Fre_{1} = 8.22 (events per year above Q50)
- dkQ_{mm} = 9.07 (m3/sek)
- Sin = 3 (slightly meandering)
- q90 (Q90/Q50) = 0.62
- bfi = 0.84

For example A the following observed data are available: DVPI = 0.46, DVFI = 0.87 and DFFVa = 0.95. From the DK model (new baseline Henriksen et al. 2015) the following results for 2004-2010: dkQ50 = 15.9 m3/s, dkFre1 = 7.14, dkFre25 = 6.85, dkFre75 = 5.42, dkQ90 = 0.64, dkBFI = 0.87 and dkDur3 = 3.2. DK model has estimated dkQ25 to 22.5 m3/s and dkQ75 to 12.07 m3/s for 2004-2010.

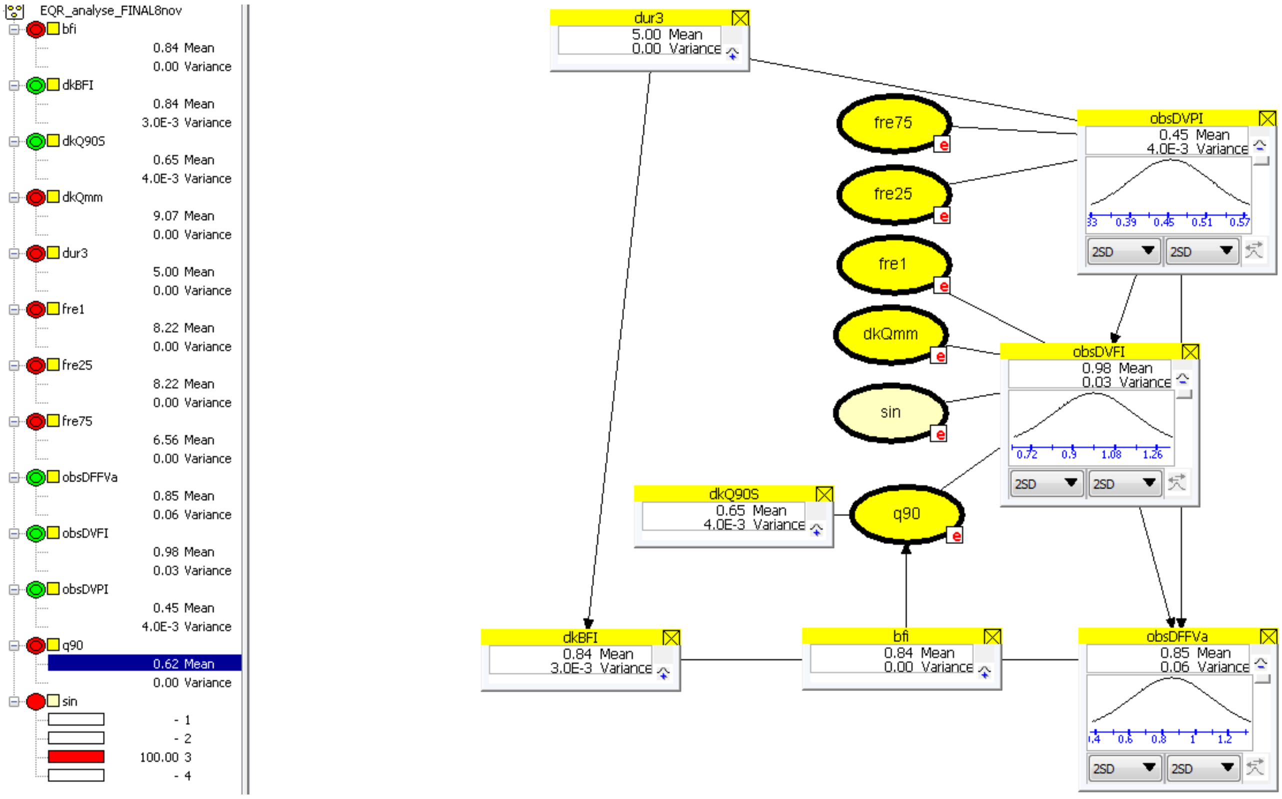

Figure 3a Example St 220062 Estimated distributions of obsDVPI, obsDVFI and obsDFFVa after entering site specific knowledge for large river in Jutland

As can be seen for example A the BN simulates the mean value for obsDVPI to 0.45 and the variance 0.0004 (observed DVPI is 0.46). BN simulates obsDVFI to 0.98 with variance 0.03 (observed DVFI =0.87) and finally BN simulates obsDFFVa to 0.85 with variance 0.06 (observed DFFVa is 0.95).

Example B small catchment on Sjælland (540002):

- $Dur_3 = 9$ days
- Fre_{75} = 4.67 (events per year below Q75)
- Fre_{25} = 7 (events per year above Q25)
- Fre_1 = 5.55 (events per year above Q50)
- dkQ_{mm} = 0.0012 (m3/sek)
- Sin = 1 (channelized)
- q90 (Q90/Q50) = 0.08
- bfi = 0.50

For example B the following observed data are available: obsDVPI = 0.46, obsDVFI = 0.21 and obsDFFVa = 0.01. From the DK model the following results are available: dkQ50 = 0.035 m3/s, dkFre1 = 2.71, dkFre25 = 4, dkFre75 = 1.57, dkQ90 = 0.0385, dkBFI = 0.65 and dkDur3 = 15.1. Data for dkQ25 and dkQ75 has not been calculated in Henriksen et al. 2014. DK model has estimated dkDVPI = 0.49, dkDVFI = 0.23 and dkDFFVa = 0.35.

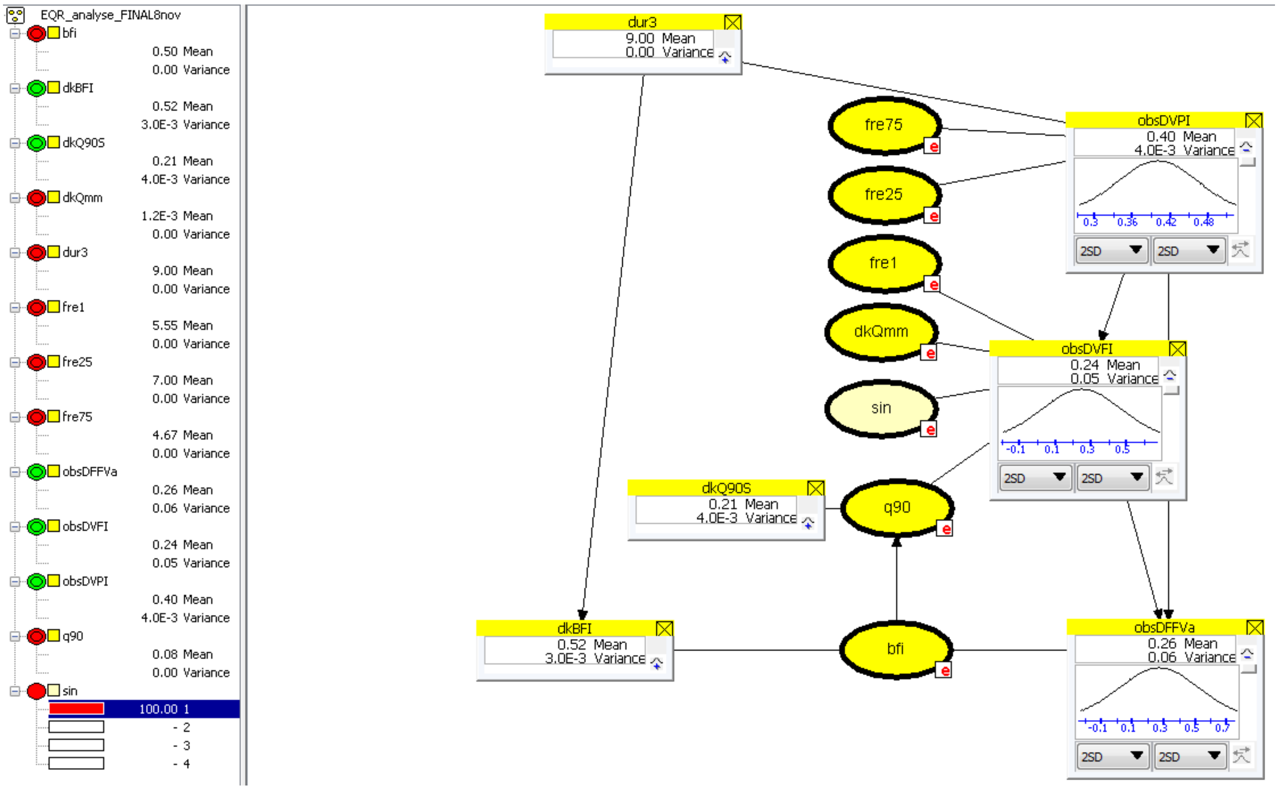

Figure 3b Example St 540002 Estimated distributions for obsDVPI, obsDVFI and obsDFFVa for small river from Sjælland

Inference can be provided in case we want to investigate how much a change in Q_{mm} for the station in example b would affect the DVFI and DFFVa indicators. If we increase Q_{mm} from 0.001 m3/s to 0.050 m3/s (~from 1 to 50 l/s), the updated BN reveals that an increase of Q_{mm} to 50 l/s still most likely will result in an obsDVFI and obsDFFVa of 0.24 and 0.26. First if we increase Q_{mm} to 500 l/s we can see a significant effect on the two quality elements since obsDVFI and obsDFFVa hereby both is increased to 0.29. But this is still significantly below the good status limit threshold (threshold for DVFI is 0.71). Other variables or Sin need also to be changed in order to reach a good ecological status for this river site. Of cause all variable sensitive to changes in low flow especially q90 and fre75 would also change significantly in case we increased the flow to 50 or 500 l/s, so these changes should be estimated by the model or expert elicitation. Since DVPI, DVFI and DFFVa are casually related (DVPI impact the two other variables, and DVFI impact DFFVa), measurement of DVPI can be valuable for a proper calculation of DVFI and DFFVa, and the Bayesian network allows such an analysis which is a strength of this assessment tool. In that case evidence is entered for obsDVPI. Since there is a lot of data for obsDVFI, this can also be entered as evidence for stations where such data are available in order to updated the BN and reduce uncertainties on estimates of obsDVPI and obsDFFVa.

Since only a limited number of river stations in Denmark with observed discharge time series the above example of entering results of time series with complete daily discharge show how this information can reduce the uncertainty bound of the estimated DVFI, DFFVa and DVPI, compared to when using model results from DK model. It has been evaluated by GEUS that simulated values of dkFre1, dkFre25, dkFre75 and dkDUR3 should only be used for analyzing differences in simulated EQR values, not for estimate of absolute values. This is the reason behind the Bayesian network where only variables that can be sufficiently accurately determined by the DK model e.g. dkQ90, dkQmm and dkBFI. But since a BN allows evidence to be entered for all variables, we can also enter data for stations where we have calculated estimates of the three variables from the DK model and including observed sin if available. In the following let us demonstrate this for example B. First we initialize the BN, and enter the following three variables as evidence:

- sin = 1
- dkQmm = 0.0012 m3/s
- dkBFI = 0.65
- dkQ90S= 0.0385

Hereby the following estimates of other variables is estimated by the BN, see Figure 4.

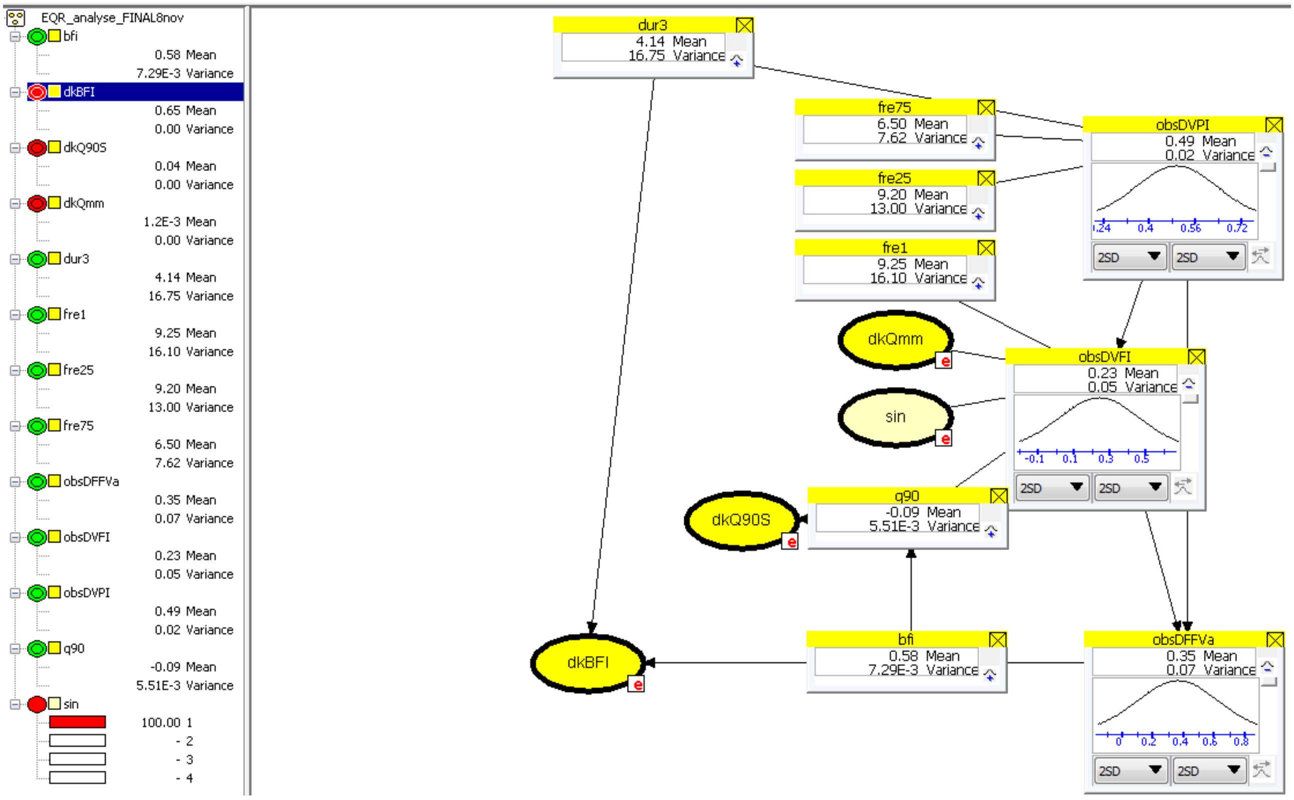

Figure 4 Example of entering evidence based on DK model for station without observed discharge

Note that compared to Figure 3b (obsDVPI = 0.4, obsDVFI = 0.24 and obsDFFVa = 0.26), the BN has estimated obsDVPI$_{\text{dk model variable}}$ = 0.49, obsDVFI $_{\text{dk model variable}}$ =0.23 and obsDFFVa $_{\text{dk model variable}}$ = 0.35 which still gives a relevant hint about the correct value, even though the variance due to the higher uncertainty is higher compared to when using observed discharge data. Since the bfi, q90, fre1, fre25, fre75 and dur3 is also calculated, this gives the user an additional possibility to evaluate what can be expected in terms of the mean values of the frequency and duration variables.

Try it out to learn more about which variables are the most important for good ecological status on the following HUGIN web-site, where you can enter sinuosity and either modelled flow data from DK model or flow data based on observed river flow from gauging stations in rivers in order to get an estimate of DVPI, DVFI and DFFVa:

http://demo.hugin.com/example/EcologicalIndicators

On the web-site a traffic light finally calculate the probability distribution derived from the modelled mean value and variance when using threshold values shown in Table 2.

Table 2 Threshold values for DVPI, DVFI and DFFVa (Henriksen et al., 2014)

Ecological status	DVPI	DVFI	DFFVa
High	*> 0.70*	*> 1.00*	*> 0.94*
Good	*0.50 – 0.70*	*0.71 – 1.00*	*0.72 – 0.94*
Moderate	*0.35 – 0.50*	*0.57 – 0.71*	*0.40 – 0.72*
Poor	*0.20 - 0.35*	*0.43 – 0.57*	*0.11 – 0.40*
Bad	*> 0.20*	*< 0.43*	*< 0.11*

Validation test of constructed Bayesian network

The table 1 below summarise the overall results of the DVFI-DFFVa-DVPI BNs compared to observed DVFI-DFFVa-DVPI and DCE calculated values (using formulas on page 1).

Overall, the Bayesian network integrated assessment gives nearly equally valid results compared to DCEs model, so it is an alternative model with approximately same performance level. As can be seen from data for DVPI the two methods gives almost the same estimated values, due to the similar linear relationships for DVPI in the Bayesian network and in formulas on page 1. The R2 values of the BN for the stations shown in the table is 0.48 for DVFI, 0.38 for DFFVa and 0.42 for DVPI.

There is also a need for further validation of new indicators based on time series of observed data. The developed prototype illustrates an example of a more comprehensive uncertainty analysis which this tool can provide. However, further work is required in order to turn the prototype into a practical tool for water managers. The possibilities of inference and of adding additional variables to the BN, which can provide assessment of changes in EQR values due to changed abstraction makes Bayesian networks a promising tool, especially if the exploratory analysis also can support dialogues with stakeholders, in order to further advance the resource assessment, and to add adaptation measures like river restoration, water quality, temperature/trees, horizontal or longitudinal barriers for fish, and maintenance of rivers. Bayesian networks are ideal for handling the knowledge with explicit incorporation of uncertainty.

The constructed prototype is evaluated as useful for strategic reasoning including exploring cumulative, joint uncertain impacts of various hydrological regime variables and proxy for physical index for evaluating ecological indicators and their uncertainty bound, when estimated from different datasets (dk model, observed time series of daily discharge data and/or in combination with observed values of DVFI, DVPI and DFFVa). What is known is updated using observations related to the decision at hand so the constructed BN can also be of value when used tactically for exploring what will be needed in terms of hydrological regime variables, if a good status should be obtained, and to which degree changes in flow or physical index and due to groundwater abstraction might hinder good or high ecological status. It should be noted that high ecological status would require not only ecological flow, but also that the morphological regime is near to natural, e.g. that Qmm is not changed more than 5 % and that other Q's like Q75, Q25, Q50 etc. are also with only minor differences compared to natural conditions for river reaches with high status goals.

Table 1 Validation test of 35 stations with measurement of all three indicators (DVFI, DVPI and DFFVa). Comparison of results for BN model, observed EQR values and DCE simulated by use of equations.

DMU no	Sin	DVFI BN	DVFI obs	DCE SIM	DFFVa BN	DFFVa obs	DCE SIM	DVPI BN	DVPI obs	DCE SIM
20006	4	0.78	0.77	0.75	0.65	0.88	0.60	0.50	0.52	0.51
80001	4	0.73	0.53	0.68	0.67	0.52	0.68	0.50	0.59	0.50
100009	2	0.57	0.67	0.59	0.64	0.83	0.61	0.50	0.46	0.49
100014	2	0.49	0.44	0.67	0.70	0.60	0.68	0.51	0.49	0.51
110016	2	0.47	0.35	0.48	0.58	0.20	0.65	0.50	0.48	0.51
150034	3	0.72	0.64	0.81	0.84	0.91	1.01	0.61	0.71	0.62
150046	3	0.64	0.52	0.62	0.47	0.30	0.33	0.50	0.49	0.51
150073	2	0.61	0.51	0.61	0.81	0.86	0.88	0.60	0.51	0.61
150104	4	0.81	0.65	0.79	0.86	0.88	0.87	0.51	0.65	0.52
150109	3	0.70	0.64	0.77	0.76	0.77	0.78	0.52	0.64	0.52
160070	2	0.48	0.49	0.52	0.55	0.75	0.61	0.50	0.48	0.51
210077	4	0.79	1.05	0.71	0.87	0.78	0.78	0.57	0.5	0.57
220047	3	0.67	0.55	0.68	0.75	0.58	0.58	0.46	0.49	0.46
220053	3	0.52	0.44	0.54	0.57	0.41	0.6	0.45	0.56	0.44
220062	2	1.02	0.87	0.52	0.87	0.95	0.62	0.45	0.46	0.46
250021	2	0.46	0.69	0.69	0.62	0.89	0.8	0.51	0.62	0.52
250592	3	0.7	0.77	0.78	0.8	0.33	0.79	0.54	0.5	0.55
250727	4	0.91	0.97	0.79	0.91	0.72	0.89	0.58	0.49	0.59
310032	2	0.52	0.71	0.58	0.67	0.71	0.82	0.6	0.78	0.61
310374	2	0.73	0.86	0.6	0.76	0.98	0.73	0.55	0.67	0.56
370011	3	0.6	0.36	0.38	0.54	0.77	0.51	0.6	0.77	0.59
380107	3	0.61	0.83	0.59	0.7	0.97	0.81	0.57	0.59	0.57
500057	1	0.38	0.34	0.46	0.5	0.3	0.52	0.46	0.6	0.47
510002	2	0.38	0.42	0.55	0.26	0.71	0.31	0.16	0.45	0.17
520039	2	0.43	0.36	0.48	0.5	0.38	0.58	0.41	0.49	0.41
520068	2	0.37	0.59	0.44	0.36	0.13	0.39	0.33	0.29	0.34
530011	1	0.34	0.26	0.41	0.35	0.04	0.3	0.38	0.3	0.39
540002	1	0.28	0.22	0.33	0.28	0.01	0.3	0.4	0.46	0.41
550051	3	0.54	0.57	0.55	0.56	0.67	0.64	0.51	0.38	0.52
560005	2	0.43	0.44	0.47	0.39	0.63	0.32	0.37	0.29	0.37
570058	2	0.4	0.44	0.44	0.33	0.5	0.48	0.11	0.3	0.11
570179	3	0.52	0.45	0.55	0.41	0.21	0.38	0.31	0.3	0.3
570187	2	0.39	0.74	0.45	0.53	0.18	0.7	0.41	0.29	0.47
580057	2	0.37	0.43	0.44	0.32	0.54	0.28	0.32	0.4	0.32
600024	2	0.68	0.44	0.47	0.53	0.62	0.33	0.4	0.28	0.4

We can now plot the calculated results by the symbolic regression equations (DCE) and the Bayesian Network (BN) as shown below and compare the results (Nash-Sutcliff R2) as shown below in Figure 4 (X-axis modelled; Y-axis observed).

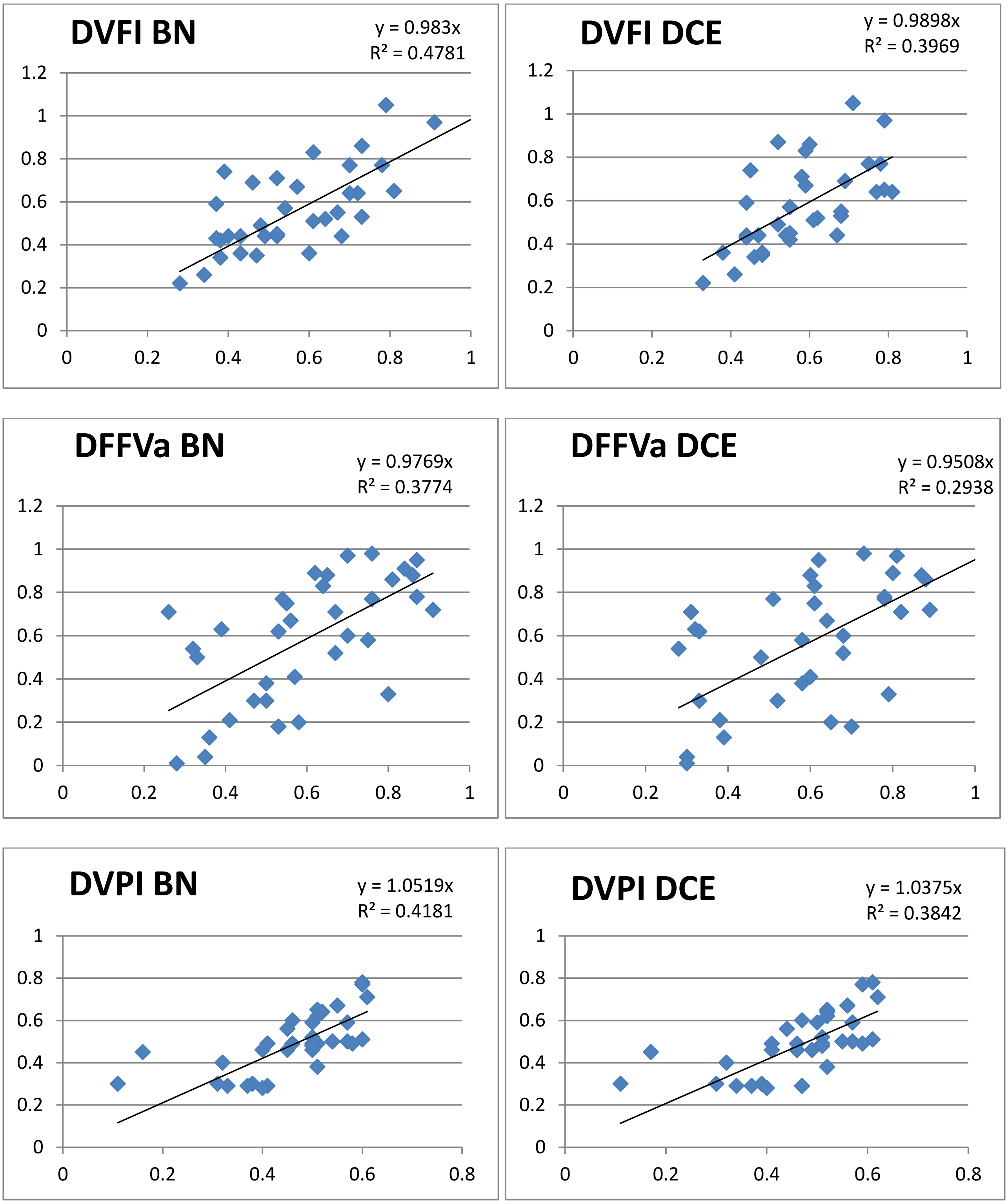

Figure 4 Observed DVFI, DFFVa and DVPI (y-axis) plottet against modeled DVFI, DFFVa and DVPI with Bayesian network (BN) and equations derived by DCE using symbolic regression (DCE).The two approaches have similar performance, with a bit higher R2 values for the Bayesian network N approach for the stations with all three observations shown in Table 1.

Discussion

A Bayesian network has been constructed which enable an integrated assessment of ecological status for macrophytes (DVPI), macroinvertebrates (DVFI) and fish (DFFVa). Results are based on seven hydrological regime variables and a proxy for physical index (sinuousity). Ecological flow sustainability is only one element in assessment of sustainable groundwater abstraction another element (not described here) is the aquifer sustainability assessment, where max 30 % abstraction compared to recharge is used as a screening criteria.

The constructed BNs was based on monitoring data from Danish streams (NOVANA), and based on indicators calculated for 2004-2011 (e.g. average conditions). It should be noted that groundwater abstraction can also affect groundwater dependent terrestrial or associated wet ecosystems and that small streams (75 % of all Danish streams) are considered as the most vulnerable to groundwater abstraction, and that the indicator for trout (DFFVø) first will be implemented in the third RBMP.

The new indicators has been implemented by the national water resource model for ID15 subcatchments (subcatchments of approximately 15 km^2), and the results has shown that there is a need for a 'better geological/riparian model in case the uncertainty by the model shall be reduced (especially the frequencies and the duration variables). Furthermore, a targeted calibration is needed, in order to provide a more accurate hydrological model and to reduce uncertainty bounds which are significant as shown.

It has been demonstrated how the BN can be used in different ways to estimate DVPI, DVFI and DFFVa. Where observed data of sin, fre1, fre25, fre75, dur3, bfi and q90 are available this will give the best estimates of DVPI, DVFI and DFFVa. If there is also observed DVPI or DVFI or DFFVa these measurements can also be entered as evidence, in order to update the BN and to reduce variances and uncertainty bounds. Furthermore, if no observed DVPI, DVFI and DFFVa, data from DK model can be entered as evidence for a estimate of DVFI, DVPI and DFFVa. Again, such estimates can be consolidated in cases where observed DVFI should be available, or DVPI or DFFVa, for determining the other two variables.

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