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Assessing the impacts of groundwater abstractions on flow regime and stream biota: Combining SWAT-MODFLOW with flow-biota empirical models

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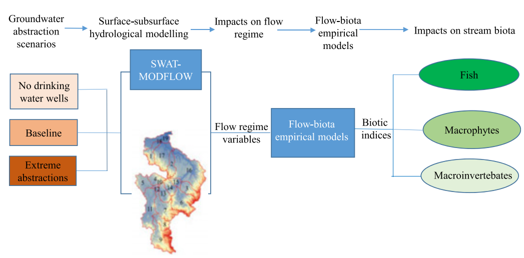
HIGHLIGHTS

- We took an integrated approach combining SWAT-MODFLOW with flow-biota models.
- Current groundwater abstractions had minor impacts on flow regime and stream biota.
- An extreme abstraction level had significant impacts on small streams.
- The fish index was most affected by groundwater abstractions.

GRAPHICAL ABSTRACT



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ABSTRACT

Assessing the impacts of groundwater abstractions on stream ecosystems is crucial for developing water planning and regulations in lowland areas that are highly dependent on groundwater, such as Denmark. To assess the effects of groundwater abstractions on flow regime and stream biota in a lowland groundwater-dominant catchment, we combined the SWAT-MODFLOW model with flow-biota empirical models including indices for three key biological taxonomic identities (fish, macroinvertebrates, and macrophytes). We assessed the effects of the current level of abstractions and also ran a scenario for assessing the effect of extreme groundwater abstractions (pumping rates of the drinking water wells were increased by 20 times in one subbasin of the catchment). Three subbasin outlets representing stream segments of different sizes were used for this evaluation. Current groundwater abstraction level had only minor impacts on the flow regime and stream biotic indices at the three subbasin outlets. The extreme abstractions, however, led to significant impacts on the small stream but had comparatively minor effects on the larger streams. The fish index responded most negatively to the groundwater abstractions, followed by the macrophyte index, decreasing, respectively, by 23.5% and 11.2% in the small stream in the extreme groundwater abstraction scenario. No apparent impact was found on macroinvertebrates in any of the three subbasin outlets. We conclude that this novel approach of a combined modelling system is a useful tool to quantitatively assess the effects of groundwater abstractions on stream biota and thereby support water planning and regulations related to groundwater abstractions. We highlight the need for developing improved biotic models that target specifically small headwater streams, which are often most affected by water abstraction.

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1. Introduction

The flow regime, i.e. the temporal pattern of stream and river flow, has been shown to be the key driver of river ecosystems as it fundamentally controls many physical processes (e.g. the movement of water and sediment within the channel) that have a major influence on the biotic composition and dictates the evolutionary adaptations and viability of many river biota (Bunn and Arthington, 2002; Carlisle et al., 2011). Because the flow regime is critical in shaping stream or river habitats, streamflow alterations due to anthropogenic activities, such as dam operations (Tonkin et al., 2018), water withdrawals (Arroita et al., 2017), land-use activities (Stein et al., 2017), and inter-basin water transfers (Petts, 2018), can heavily impact the structure and function of riverine ecosystems.

Formulating flow regime alteration-ecological response is a critical step in using ecological indicators to develop environmental flow standards at the regional scale (Poff et al., 2010). A number of studies have endeavored to develop relationships between flow regime and ecological integrity. In general, five critical components of the flow regime (magnitude, frequency, timing, duration, and rate of change) have been used to characterize flow alteration (Poff et al., 1997). Taxonomic identity (e.g., macroinvertebrates, fish, and macrophytes) and type of response (abundance, diversity, demographic parameters, and ecological quality ratio) are often used to characterize ecological responses (Poff and Zimmerman, 2010). The links between flow regime alteration and ecological response developed in previous studies have shown different degrees of success and serviceability (Poff and Zimmerman, 2010; Belmar et al., 2013). Most of these studies reported relationships at specific stream segments or watershed scale and have often focused on only one taxonomic identity (Kennen et al., 2009; Stromberg et al., 2010; Falke et al., 2011; Domisch et al., 2017; Perkin et al., 2017).

Managing groundwater and surface water as an integrated resource is imperative to meet the growing water use for anthropogenic needs and increasing challenges in water resources management associated with water rights issues, ecological degradation and ongoing climate change. As integrated surface–subsurface hydrological models are capable of simulating water processes in an integrated and holistic fashion, provide spatially and temporally detailed description of the catchment-scale hydrological cycle, enable scenario analysis (Du et al., 2019), and may be coupled with other models (e.g. solute transport model) (Donn et al., 2012; Akbarpour and Niksokhan, 2018; Wei et al., 2018), they are essential and useful tools in integrated water resources management. The SWAT-MODFLOW developed by (Bailey et al., 2016) is such a surface-subsurface model. It has been applied to catchments of varying sizes worldwide, such as in the USA (Bailey et al., 2016; Gao et al., 2019; Wei and Bailey, 2019), Africa (Blin et al., 2017), Canada (Chunn et al., 2019), Denmark (Molina-Navarro et al., 2019), Iran (Semiromi and Koch, 2019), Japan (Sith et al., 2019), and India (Loukika et al., 2020), for water resources assessment and management.

Since groundwater aquifers contain about 30% of the global freshwaters (Shiklomanov, 1998), groundwater abstractions from aquifers are a prevalent activity all over the world. Abstractions are rapidly increasing worldwide as a result of escalating demands of water use for irrigation, household, industry, and recreation (Foster et al., 2013; Wada et al., 2014). However, groundwater abstraction can cause a decline of the groundwater table and thereby directly alter the flow regime of streams connected to the aquifer. Ample literature describing quantitative assessments of the effects of water withdrawals from streams on stream ecosystem has been published (Arroita et al., 2017; Benejam et al., 2010; Carolli et al., 2017; Pardo and Garcia, 2016), but only few studies have attempted to assess the effects of groundwater abstraction on stream ecosystems (Falke et al., 2011; Perkin et al., 2017), partly because it has been difficult to assess the effects of groundwater abstraction on flow regime.

The water consumption in Denmark comes almost entirely from groundwater abstractions (Jørgensen and Stockmarr, 2009). To provide a sufficient and persistent flow to support in-stream biota, Denmark has endeavored to regulate groundwater abstraction to a certain threshold level, mainly through a system of licenses. Nevertheless, there are still some areas where groundwater exploitation is above the sustainable yield and causes relatively severe streamflow depletion, which may impair the stream ecosystem (Henriksen et al., 2008). Therefore, quantitative assessment of the impact of pumping wells on streamflow and the ecosystems they support now and under potential abstraction and future climate scenarios is imperative for maintaining the integrity of stream ecosystems.

In this study, we took an integrated approach where we combined the SWAT-MODFLOW model with novel nationwide-scale flow-biota empirical models (Gräber et al., 2015) describing key biological taxonomic identities (fish, macroinvertebrates, and macrophytes) to quantitatively assess the effects of groundwater abstractions on stream ecology qualities. Results can therefore help guide management of water abstraction. We used a Danish, lowland, groundwater-dominated catchment, the Uggerby River catchment, as a case study and assessed to what extent the flow regime and key biota in stream segments of different sizes may be altered by the present level of groundwater abstraction and in a scenario with extreme groundwater abstraction.

2. Methods

2.1. Study area

The Uggerby River catchment, located in the northern-most part of Jutland (Fig. 1) in Denmark, drains an area of 357 km^2 and has an elevation ranging from −0.2 m to 108 m. The catchment is administratively covered by the Municipality of Hjørring, which has an area of 930 km^2. A SWAT-MODFLOW model for the Uggerby River catchment was set up with data for the period 2002 to 2015 (Liu et al., 2019). During this period, the annual mean temperature was 8 °C, July being the warmest month (17 °C average) and January the coldest (0.5 °C average). The average annual precipitation was approximately 933 mm with no pronounced seasonality. The dominant land use is agriculture (63%) and the dominant soil type is loamy sand (51%) (NERI, 2000).

There are 101 drinking water wells registered in the Uggerby River catchment investigated by Hjørring Municipality in 2009 (Fig. 1). The wastewater treatment plant in Sindal, located in subbasin 16 of the SWAT model delineation, is the only significant point source in the Uggerby River catchment. Based on the data available for the period 2007–2010, the average daily wastewater discharge to the stream is 2769 m^3, including a few minor sources. Like many catchments in Denmark, the Uggerby River is to a large extent groundwater-fed. Direct abstraction from surface water is prohibited and groundwater abstraction is only allowed with a permit license.

2.2. SWAT-MODFLOW model

SWAT-MODFLOW developed by Bailey et al. (2016) is a comprehensive coupled watershed model that combines the Soil and Water Assessment Tool (SWAT) (Neitsch et al., 2011), simulating the land surface and stream hydrologic processes, and MODFLOW-NWT (Niswonger et al., 2011), simulating the groundwater hydrologic processes and groundwater-surface water exchange. Since the model complex in the groundwater domain is fully distributed and accounts for two-way interactions between groundwater and surface waters, it enables a potentially better representation of hydrological dynamics relative to other hydrological models, such as the lumped semi-distributed SWAT model alone. The ability of SWAT-MODFLOW to evaluate the impacts of groundwater abstraction on streamflow or groundwater-surface water interactions has been tested in several studies (Guzman et al., 2015; Chunn et al., 2019; Molina-Navarro et al., 2019) and has been observed to produce more realistic results in terms of groundwater

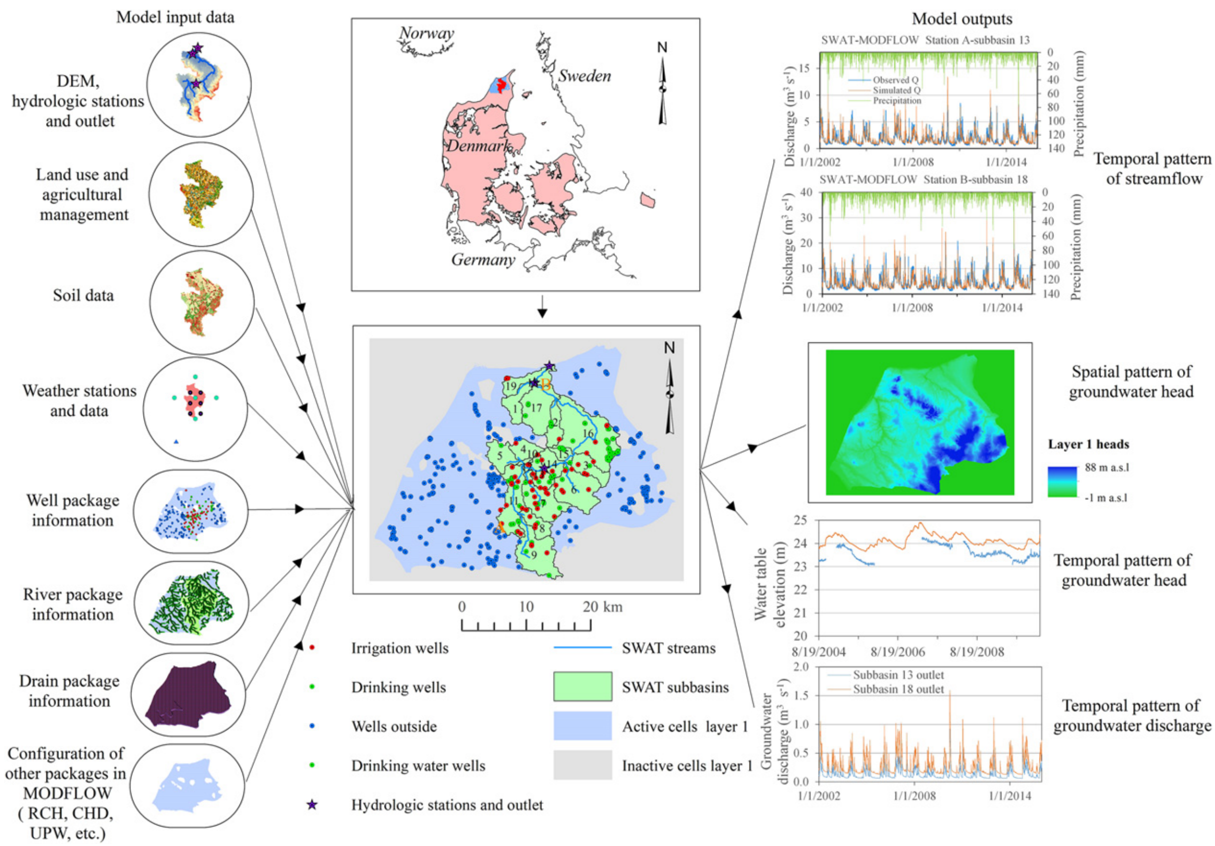

Fig. 1. Input and output data of the SWAT-MODFLOW model set-up for the Uggerby River catchment. Location of the catchment is also shown.

abstraction effects on streamflow than the widely used catchment model SWAT (Liu et al., 2019; Molina-Navarro et al., 2019).

We used the SWAT-MODFLOW model set-up from Liu et al. (2019) as the basis for our study. It represents a SWAT model for the Uggerby River catchment, fully coupled with a MODFLOW-NWT model for the entire Hjørring Municipality. Although the MODFLOW model encompassed the entire municipality, only the portion covered by the Uggerby River catchment was coupled with the SWAT model, and the original functionality of MODFLOW was retained beyond the Uggerby River catchment.

In the SWAT set-up, the Uggerby River catchment was divided into 19 subbasins and discretized into 2620 individual Hydrological Response Units (HRUs) (Fig. 1). The daily streamflows of two hydrologically connected monitoring stations, located at the outlet of subbasin 13 (station A) and subbasin 18 (station B), were used for calibration (period: 2002–2008) and validation (period: 2009–2015) of the SWAT model. Generally, the model demonstrated satisfactory performance on the temporal pattern of streamflow simulation (Liu et al., 2019). Further details on the SWAT set-up can be found in (Liu et al., 2019).

The original MODFLOW model set-up for the entire Hjørring Municipality was configured as a steady-state MODFLOW-NWT model that serves as a basis for water resources management by the Hjørring municipality. Aquifers were conceptually represented by 5 hydrostratigraphic layers, the uppermost layer being unconfined and the other four confined. Each layer was discretized into grids having a cell-size of 100 m × 100 m. The first, third and fifth layers are dominated by sand with relatively high hydraulic conductivities, while the second and fourth layers are dominated by clay with low hydraulic conductivities (Liu et al., 2019). Seven of the 101 drinking water wells in the Uggerby River catchment were placed in the first layer, 91 in the third layer and 3 in the fifth layer. Both the river package and the drain package were employed in the model to simulate groundwater-surface water exchange. The model was calibrated using 1063 head observations during the period 1996–2010 at 1, 006 wells distributed at the first, third, and fifth layer by a combination of manual calibration and auto-calibration using the PEST software (http://www.pesthomepage.org/). For facilitating SWAT-MODFLOW coupling and its calibration, the specific aquifer hydraulic conductivities were reclassified and grouped into five groups, and the MODFLOW model was converted from steady state into transient state by assigning storage coefficients (specific storage, specific yield) to each MODFLOW grid cell.

SWAT and MODFLOW were combined using the coupling framework developed by (Bailey et al., 2016), but with further developments to enable the application of the Drain package and an auto-irrigation routine. Groundwater outflow simulated by the Drain package was fed to SWAT subbasin channels, and SWAT auto-irrigation depths dictated groundwater pumping using MODFLOW's Well package (Liu et al., 2019). The coupled SWAT-MODFLOW set-up was then calibrated through a PEST-based approach by calibrating SWAT and MODFLOW parameters simultaneously with both stream flow and groundwater levels as the objective observations. The calibrated SWAT-MODFLOW set-up demonstrated a good performance in hydrological simulation and provided more realistic outputs when assessing the impacts of groundwater abstraction for drinking water and irrigation on stream flow than the stand-alone SWAT. We demonstrated the main input and output data of the SWAT-MODFLOW set-up in Fig. 1. Further detail and discussions about the model set-up and outputs can be found in (Liu et al., 2019).

2.3. Groundwater abstraction scenarios

In order to evaluate the impacts of groundwater abstraction on streamflow and biota in streams of different sizes, three scenarios were set up and analyzed: 1) Baseline scenario, where all the wells in the calibrated SWAT-MODFLOW were maintained, reflecting the current state. 2) No drinking water wells scenario, where all the drinking water wells in the Uggerby River catchment were terminated. The wastewater point source was also terminated as we are simulating absence of people in the catchment; 3) Extreme abstraction scenario, where the pumping rates of all the drinking water wells in an upstream subbasin (subbasin 7) with an independent reach receiving no water from other subbasins (Fig. 1) were increased by a factor of 20 (Table 1). In the extreme abstraction scenario, we assumed that the extra water was due to the establishment of a new bottled water company and the bottled water was transported outside the catchment instead of being used locally and therefore not returned to the stream. In all the scenarios, the irrigation wells and their pumping rates remained unchanged.

2.4. The flow-biota empirical models

The EU Water Framework Directive (Todo and Sato, 2002) clearly states that the ecological status of European waters should be primarily assessed based on aquatic biota conditions and to what extent this differ from the human-unaffected state (the reference state). The description of aquatic biota conditions should account for both species composition and biomass. For streams, there are three main types of aquatic biota considered: fish, macrophytes and macroinvertebrates. In this context, the ecological quality ratios (EQR) associated with DFFSa (Danish Fish Index for Streams, in Danish-Dansk Fiskeindeks For Vandløb (DFFVa)), DSMI (Danish Stream Macrophytes Index, in Danish-Dansk Vandløbs Plante Indeks (DVPI)) and DSFI (Danish Stream Fauna Index, in Danish-Dansk Vandløbs Fauna Indeks (DVFI)) were proposed and developed to evaluate the ecological status of streams in Denmark. The ecological quality ratio (EQR) represents the relative deviation of the ecological status from the reference state normalized to a value between 0 (worst possible condition) and 1 (undisturbed reference condition).

To derive the $DSMI_{EQR}$ value of a stream site, the species composition and associated coverage ratios of the stream site determined, and a probability of the stream site belonging to each of the five state classes (bad (1), poor (2), moderate (3), good (4), bad (5)) is calculated first by using a classification model developed by Baattrup-Pedersen et al. (2013). Then the following equation is used to calculate the $DSMI_{EQR}$:

$$EQR = (5 \times P1 + 15 \times P2 + 25 \times P3 + 45 \times P4 + 55 \times P5)/50 \tag{1}$$

where P1 indicates the probability of belonging to state class 1, P2 indicates the probability of belonging to state class 2, and etc. More details about DSMI and the calculation of $DSMI_{EQR}$ could be found in (Baattrup-Pedersen et al., 2013; Søndergaard et al., 2013; Larsen and Baattrup-Pedersen, 2015).

DFFSa consists of 8 fish indicators, which are the prevalence or proportion of intolerant, lithophilic, rheophilic and omnivorous species (Table 2). Forty-five fish species were included in the DFFSa assessment, and 36 of them occur in Denmark. To calculate the $DFFSa_{EQR}$ of a stream site, the first step is to calculate the value of these 8 indicators. The second step is to evaluate the DFFSa type of the stream site, and categorize this into one of 5 different types based on the catchment area and slope of the stream. The third step is the calculation of an EQR for each of the 8 indicator. The reference values for the 8 indicators and for each of the 5 DFFSa type were given in Table 2. For indicators that generally decrease with increasing human impact (including the indicators regarding intolerant, lithophilic and rheophilic species), the EQR is calculated as: EQR = Measured Value / Reference Value. For indicators that generally increase with increasing human impact (the indicators regarding tolerant and omnivorous species), EQR is calculated as: EQR = (measured value − 100) / (Reference value − 100). The last step is done by first checking the EQR values; and values that are >1 set equal to 1, then the $DFFSa_{EQR}$ value is calculated as an average of the indicator values. The classification of fish species and more details about the DFFSa and $DFFSa_{EQR}$ can be found in (Kristensen et al., 2014).

The Danish Stream Fauna Index (DSFI) has been introduced as Denmark's national standard method for biological assessment of streams in Denmark since 1998. The index value (fauna class) is determined based on indicator taxa and the number of diversity groups, ranging from 1 (worst condition) to 7 (human-undisturbed condition). More information about DSFI can be found in (Skriver et al., 2000; Rasmussen et al., 2017), and the method converting DSFI values to continuous $DSFI_{EQR}$ values can be found in (Larsen et al., 2014).

The flow-biota empirical models refer to the empirical relationships between flow regime variables (FRVs, e.g. Q_{90}, the flow below the 90th percentile of the flow-duration curve) and the EQR of DFFSa, DSMI, and DSFI according to (Gräber et al., 2015). To develop the models, 165 NOVANA (National monitoring program for water bodies) stations in Danish streams were selected where both hydrological and biological data covering the period from 2004 to 2012 were available. At first, 72 FRVs and the EQR for at least one index were calculated for every station. The stream sinuosity was chosen to represent the physical condition of stream. Then an automated method based on "symbolic regression" suggested by Schmidt and Lipson (2009) was used to develop a number of models that could potentially predict the relationships between FRVs and EQRs. In this approach, the mathematical expressions were determined automatically with the best-functioning water flow variables, while minimizing the mean of the square deviation sum of the found models (with selected variables). The algorithm retains equations that model the experimental data better than others, leaving out solutions that do not seem promising (Schmidt and Lipson, 2009). From this set of equations, the model that has the minimum mean of the square deviation sum and which has the least model complexity can be identified. To determine whether some model coefficients (i.e., selected FRVs) could be removed to further simplify the model, each of the possible models from the symbolic regression program was further investigated for the significance of the effect of the model coefficients on biotic indicies using analysis of variance and plot functions in the statistical software package R (R Core Team, 2013). The ecological validity of the models was also evaluated by comparing results available in the scientific literature for the relationship between flow regime and biological response. Finally, the following three empirical models were derived for each biological index:

Table 1
Average annual abstraction (2002–2015) for each scenario in the areas from which the outlets of subbasin 7, 13, and 18 receive water and the corresponding annual stream flow change from the baseline scenario simulated in SWAT-MODFLOW set-up.

Scenarios		No drinking water wells	Baseline scenario	Extreme abstraction in subbasin 7
Annual abstraction (10^6 m^3 yr^{-1})	Subbasin 7	0	0.38	7.71 (0.38 + 7.33)
	Subbasins 4–5, 7–13	0	1.28	8.61 (1.28 + 7.33)
	The entire catchment excluding subbasin 19	0	3.96	11.29 (3.96 + 7.33)
Average annual stream flow decrease (−) or increase (+) (10^6 m^3 yr^{-1})	Subbasin 7 outlet	0.28 (3.1%)	9.1 (baseline)	−3.04 (−33.4%)
	Subbasin 13 outlet	0.97 (1.7%)	54.34 (baseline)	−5.16 (9.5%)
	Subbasin 18 outlet	1.25 (1%)	131.7 (baseline)	−5.78 (−4.4%)

Notes: Subbasin 7 outlet receives water from subbasin 7; Subbasin 13 outlet receives streamflow from subbasins 4–5, 7–13; Subbasin 18 outlet receives streamflow from the entire catchment excluding subbasin 19.

Table 2
Description of the 8 indicators included in DFFSa and associated reference values for the 5 DFFSa types based on the catchment area and slope of the stream.

Indicator	Descriptions	DFFSa types				
		1	2	3	4	5
INTOL_n%	Percentage (%) of individuals of intolerant species out of the total number of individuals	61	22	45	18	27
INTOL_sp_Nb	Number of intolerant species	3	n.a.	5	n.a.	5
LITH_ n %	Percentage (%) of individuals of lithophilic species out of the total number of individuals	96	52	93	33	65
LITH_ sp_Nb%	Percentage (%) of lithophilic species out of the total number of species	83	41	72	39	52
TOLE_ n %	Percentage (%) of individuals of tolerant species out of the total number of individuals	1	33	2	37	23
TOLE_sp_Nb %	Percentage (%) of tolerant species out of the total number of species	n.a.	18	14	18	14
RH_sp_Nb	Number of rheophilic species	n.a.	5	8	6	10
OMNI_n %	Proportion (%) of individuals of omnivorous species out of total number of individuals	3	37	4	53	38

Notes: "n.a" means that the indicator is not used for that type.

For DFFSa, the model with three FRVs was developed based on a dataset of 61 sites and with an R^2 of 0.53 ($p < 0.001$):

$$DFFSa_{EQR} = 0.811 * BFI + 0.058 * Sin + 0.050 * Fre_{25} - 0.319 - 0.0413 * Fre_{75} \quad (2)$$

where BFI is the baseflow index (baseflow volume divided by total flow volume), Sin is the class of sinuosity (Table 3), Fre_{25} is the average annual frequency of events with flows above the 25th percentile from the flow duration curve, and Fre_{75} is the average annual frequency of events with flows below the 75th percentile from the flow duration curve.

For DSMI, the model with three FRVs was developed based on a dataset of 91 sites and with an R^2 of 0.34 ($p < 0.001$):

$$DSMI_{EQR} = 0.546 + 0.020 * Fre_{25} - 0.019 * Dur_3 - 0.025 * Fre_{75} \quad (3)$$

where Dur_3 is the average annual duration (days) of flows 3 times the median flow. Fre_{25} and Fre_{75} are the same as in Eq. (1).

For DSFI, the model with two FRVs was developed based on a dataset from 122 stream sites in Denmark and with an R^2 of 0.44 ($p < 0.001$):

$$DSFI_{EQR} = 0.217 + 0.103 * Sin + 0.020 * Q_{90} * Fre_1 \quad (4)$$

where Q_{90} is the flow below the 90th percentile of the flow-duration curve, divided (standardized) by median flow (Q_{50}), and Fre_1 is the average annual frequency of events with flows above the median flow. Sin is the same as in Eq. (1).

Scripts for deriving the FRVs and biota indices (EQR values) were created and run through SAS 9.4 (www.sas.com/) with the SWAT-MODFLOW streamflow output file output.rch as the imported data.

3. Results

3.1. The impacts of groundwater abstractions on streamflow

Simulated average daily flow at the outlets of subbasin 7, 13, and 18 during the study period (2002–2015) was 0.29, 1.72, and 4.17 $m^3 s^{-1}$, respectively, representing a small, medium-sized, and relatively large stream in Denmark.

Table 3
Calculation of sinuosity classes based on class borders.

Class (Sin)	Description	Class borders
1	Straight/channelized	Sinuosity< 1.05
2	Slightly sinuous	1.05 < Sinuosity < 1.25
3	Sinuous	1.25 < Sinuosity < 1.50
4	Meandering	Sinuosity > 1.50

Notes: Sin is the class of sinuosity. The sinuosity of a stream was calculated from the stream length divided by linear distance within the subbasin. The stream length within each subbasin was available from main channel input file (.rte) of SWAT (Arnold et al., 2013). The linear distance of the stream within each subbasin was measured using QGIS.

The temporal patterns of streamflow in the three stream segments in the different scenarios were compared (Fig. 2). The streamflow difference between the scenario with no drinking water abstraction and the baseline scenario was almost always greater than or equal to 0, indicating a daily streamflow decrease caused by the current groundwater abstraction. The absolute difference was generally largest for subbasin 18, and the average differences were 0.009 $m^3 s^{-1}$ (subbasin 7), 0.031 $m^3 s^{-1}$ (subbasin 13), and 0.039 $m^3 s^{-1}$ (subbasin 18). The streamflow difference between the extreme abstraction scenario and the baseline scenario was almost always negative except for one day at the subbasin 13 outlet and two days at the subbasin 18 outlet, indicating a daily streamflow decrease due to an extreme abstraction situation. Again, the decrease was almost always largest at the subbasin 18 outlet and average values of decrease at the three subbasin outlets were 0.096 $m^3 s^{-1}$ (subbasin 7), 0.164 $m^3 s^{-1}$ (subbasin 13), and 0.183 $m^3 s^{-1}$ (subbasin 18). Average annual stream flow change from baseline scenario was also largest at the subbasin 18 outlet out of the three outlets for both the no drinking water wells scenario and the extreme abstraction scenario, but the stream flow change percentage at the subbasin 18 outlet was smallest compared with the baseline streamflow (Table 1).

3.2. The impacts of groundwater abstractions on groundwater discharge to streams

According to the water balance output of the SWAT-MODFLOW setup, groundwater discharge constitutes 75% of the streamflow in the baseline scenario, highlighting the benefit of assessing groundwater discharge change in groundwater abstraction scenarios.

The average daily groundwater discharge in all subbasins in the scenario with no drinking water abstraction was higher than in the baseline scenario with different extents, demonstrating the subbasin-level spatially varying impacts of the current level of drinking water abstraction on the groundwater discharge to streams (Fig. 3a, b). The average difference in the groundwater contribution to the streamflow was 327 $m^3 day^{-1}$ for the entire catchment, while the maximum difference was 1684 $m^3 day^{-1}$ in subbasin 16 and the minimum difference was approximately 0 $m^3 day^{-1}$ in subbasin 18 (Fig. 3b). Similarly, the average daily groundwater discharge in all subbasins in the baseline scenario was higher than in the extreme abstraction scenario, and again the differences varied among the individual subbasins of the catchment (Fig. 3a, c). The average difference was 842 $m^3 day^{-1}$ for the entire catchment, with a maximum difference of 8328 $m^3 day^{-1}$ in subbasin 7 and a minimum difference of 1 $m^3 day^{-1}$ in subbasin 18 (Fig. 3c).

3.3. The impacts of groundwater abstractions on FRVs

Six FRVs constitute the basis for the predictability in the three flow-biota empirical models. Four of them (Fre_1, Fre_{25}, BFI, Q_{90}) have positive effects on the biotic indices as they increase, while the other two (Fre_{75}, Dur_3) have negative effects on biotic indices, as indicated by the positive and negative operational signs (Fig. 4).

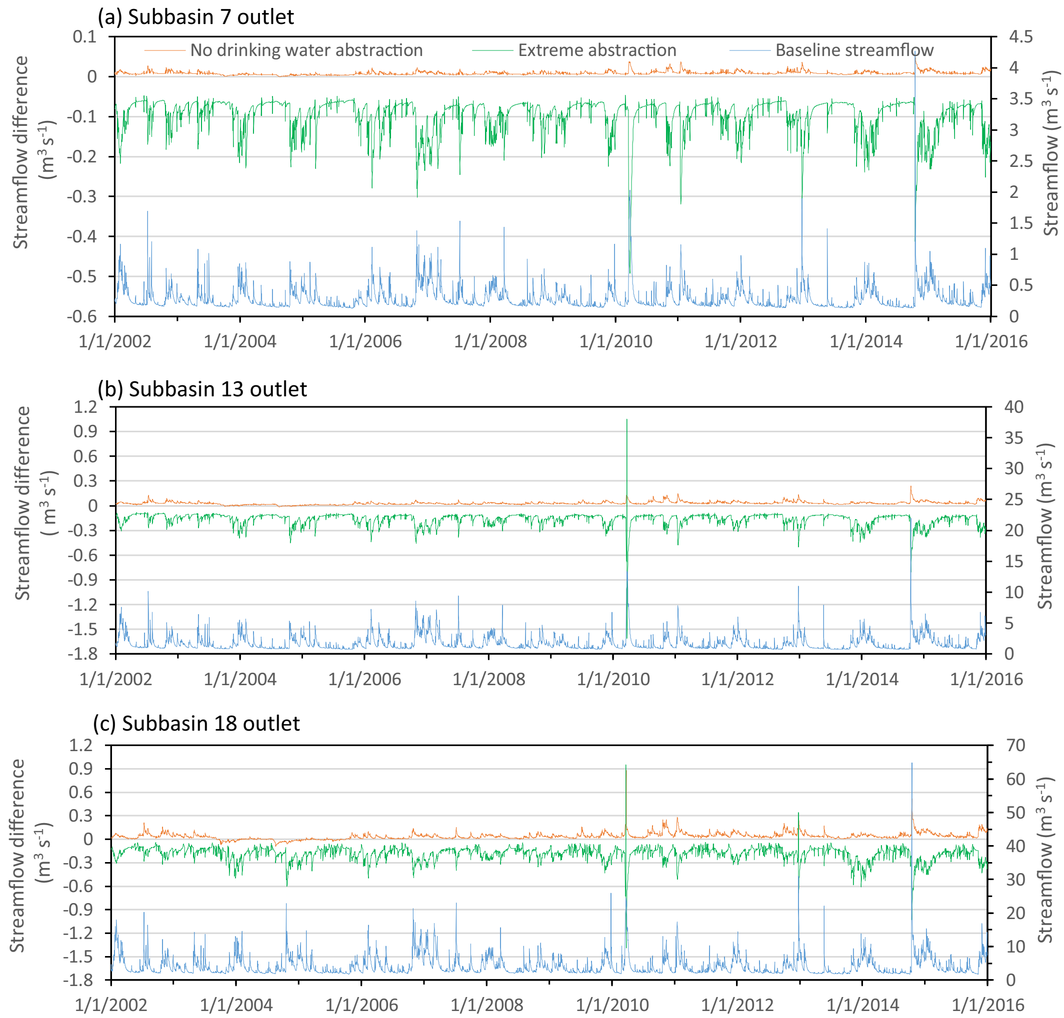

Fig. 2. Simulated daily streamflow in the baseline scenario and differences in daily streamflow between the baseline scenario and the model scenarios (no drinking water abstraction, extreme abstraction; in the latter the pumping rates of the drinking water wells at subbasin 7 were increased by 20) for the outlets of subbasin 7, subbasin 13 (station A), and subbasin 18 (station B) during the entire study period (2002–2015) based on SWAT-MODFLOW.

Compared with the scenario with no drinking water abstraction, BFI under the baseline scenario decreased by 0.4% at subbasin 7 outlet and 0.3% at subbasin 13 outlet, but no change was found at subbasin outlet 18. Similarly, compared with the baseline scenario, BFI in the extreme abstraction scenario decreased by 6.4%, 1.8%, and 0.4% at the outlets of subbasins 7, 13, 18, respectively. For the other FRVs, value differences between the scenario with no drinking water wells and baseline scenario were minimum. In contrast, the differences between the extreme abstraction scenario and the baseline scenario were more apparent, being largest for subbasin 7. Compared with the baseline scenario, at the subbasin 7 outlet, three of the four FRVs (Fre_{25}, BFI, Q_{90}) that play positive role on the biotic indices decreased by 10.5%, 6.4% and 10%, and the remaining one (Fre_1) increased by 11.3%. One of the two FRVs (Fre_{75}) that has a negative effect on the biotic indices increased by 11.3% and the other one (Dur_3) decreased by 5.1%.

3.4. The impacts of groundwater abstractions on stream biota

The biotic indices at the three subbasin outlets under the three different groundwater abstraction scenarios were compared (Fig. 5). No apparent difference of $DSFI_{EQR}$ values was observed at the three subbasin outlets. When comparing the baseline scenario with the scenario with no drinking water abstraction, the fish index $DFFSa_{EQR}$ decreased by 4.5%, 2.3% and 2.8%, and the macrophytes index $DSMI_{EQR}$ by 3.2%, 1.7% and 2.1% at the outlets of subbasin 7, 13 and 18, respectively, under the baseline scenario. Compared with the baseline scenario, the $DFFSa_{EQR}$ decreased by 23.5% and 3.8%, and the $DSMI_{EQR}$ by 11.2% and 0.4%, at the outlets of subbasin 7 and 13, respectively, in the extreme abstraction scenario, while the $DFFSa_{EQR}$ and $DSMI_{EQR}$ at subbasin 18 outlet increased by 5.9% and 4.9%.

4. Discussion

4.1. The impact of groundwater abstractions on hydrology, flow regime and stream biota

The current groundwater abstraction in the Uggerby River catchment has generally caused minor decreases in groundwater discharge and streamflow throughout the catchment. Consequently, the FRVs and the biotic indices for stream ecological quality have only shown modest changes. In contrast, the assumed extreme abstraction in subbasin 7, in which the abstraction rates increased 20-fold compared with the current abstraction, caused larger streamflow decrease at all three subbasin outlets, but only for subbasin 7 there was considerable impacts on the FRVs and the biotic indices despite the larger streamflow decreases in the outlets of subbasin 13 and 18. Besides subbasin 7, the outlets of subbasin 13 and subbasin 18 also receive water from other subbasins, so in subbasins 13 and 18 the impact of extreme abstraction in subbasin 7 is buffered

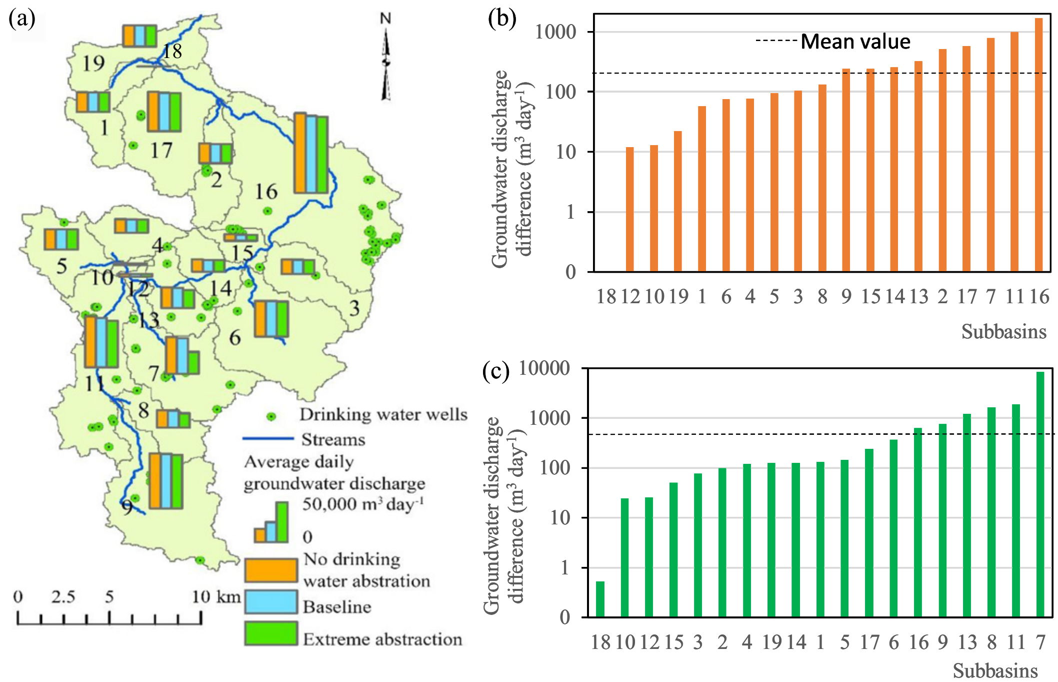

Fig. 3. Average daily groundwater discharge ($m^3\ day^{-1}$) in each subbasin from the aquifer to the stream network during the period 2002–2015 in different groundwater abstraction scenarios (no drinking water abstraction, baseline, extreme abstraction) simulated by the calibrated SWAT-MODFLOW model. (a): Groundwater discharge difference between the no drinking abstraction scenario and the baseline scenario in each subbasin; (b): groundwater discharge difference between the baseline scenario and the extreme abstraction scenario.

by the water contribution from the other subbasins in the catchment. This may reflect differences in the response by streams of different sizes, but it also highlights the importance of resolving these differences in a model set-up to advance today's water management and render groundwater abstraction permit confirmation according to such basin heterogeneities.

The $DFFSa_{EQR}$ is positively related to BFI and negatively related to Fre_{75}, reflecting a positive effect on the fish community of a stable discharge regime with rare occurrence of low flows (Poff and Zimmerman, 2010). Furthermore $DFFSa_{EQR}$ is positively related to Fre_{25}, suggesting that slight disturbances due to weak peak flows may improve the quality of the fish community. The relationship of $DSMI_{EQR}$ to the two coefficients Fre_{25} and Dur_3 confirms the hypothesis of a higher quality of the macrophyte community at intermediate disturbances and a lower quality at strong peak flows, as was also found by Riis et al. (2008) for Danish streams and rivers. Furthermore, the negative correlation with Fre_{75} may indicate that, due to the lack of disturbance at a high frequency of low flows, competitive species dominate the macrophyte community, resulting in lower diversity and hence lower $DSMI_{EQR}$. It has been reported that lotic macroinvertebrate species are lost and substituted by ubiquitous and lentic species when extreme low flow or stagnant conditions occur (Graeber et al., 2013; Hille et al., 2014). A Q_{90} value close to 0 means that the low flows are much more extreme (lower) than that if the Q_{90} is close to 1. Due to the positive correlation between Q_{90} and $DSFI_{EQR}$, $DSFI_{EQR}$ will be higher when the low flows are less extreme (Gräber et al., 2015). Fre_1 is the frequency of peak flows above the median flow. Such weak peak flows can positively affect lotic macroinvertebrate communities due to the removal of fine sediment (Dunbar et al., 2010; Pan et al., 2013) and the potentially increased habitat diversity (Poff et al., 2010).

Among the three biotic indices, the fish index was the most affected by groundwater abstractions. Groundwater abstractions affect streamflow mainly through reducing the baseflow, thereby lowering the BFI, which is highly dependent on the baseflow. All the flow-biota empirical models are based on multiple linear regressions. According to the coefficients related to each FRV, the BFI, of which the coefficient is 0.811 and much larger than the coefficients of the other FRVs, has the strongest influence on ecological state, making the fish index the most vulnerable index to groundwater abstractions. The impacts of groundwater abstraction on the other variables are more uncertain (can be either positive or negative) as their values are based on percentiles of the flow-duration curve. This may also explain why the biotic indices for the subbasin 18 outlet in the extreme groundwater abstraction scenario did not decrease but rather showed a small increase. According to the definitions, BFI, Fre_{75}, and Q_{90} are highly related to low flow on which groundwater abstractions have direct influence. In the flow-biota empirical relationship Eqs. (1) and (2), the values of Fre_{75} and BFI can have direct influence on ecological quality, and the impact of groundwater abstraction on streamflow ecology is thereby reflected in the fish and macrophyte indices (Fig. 5). In Eq. (3), the coefficient of Q_{90} for the effect on the macroinvertebrate index is only 0.02, which is the lowest among all the FRVs, and its effect is weakened due to its bundling with Fre1, which may increase with enhanced groundwater abstraction (Fig. 5). Hence, no obvious groundwater abstraction effects on macroinvertebrates were recorded when using this equation (Fig. 5).

4.2. Advantages of the approach

SWAT-MODFLOW is a useful tool for managing water resources in groundwater-affected catchments, especially when assessing the impacts of groundwater abstraction on streamflow (Liu et al., 2019; Molina-Navarro et al., 2019). A number of advantages of SWAT-MODFLOW over SWAT have been reported in earlier studies. The results from this study illustrate another advantage. In the widely used catchment model SWAT the subbasin aquifers are closed and independent from each other, meaning that pumping within one subbasin does not affect the groundwater hydrology in other subbasins

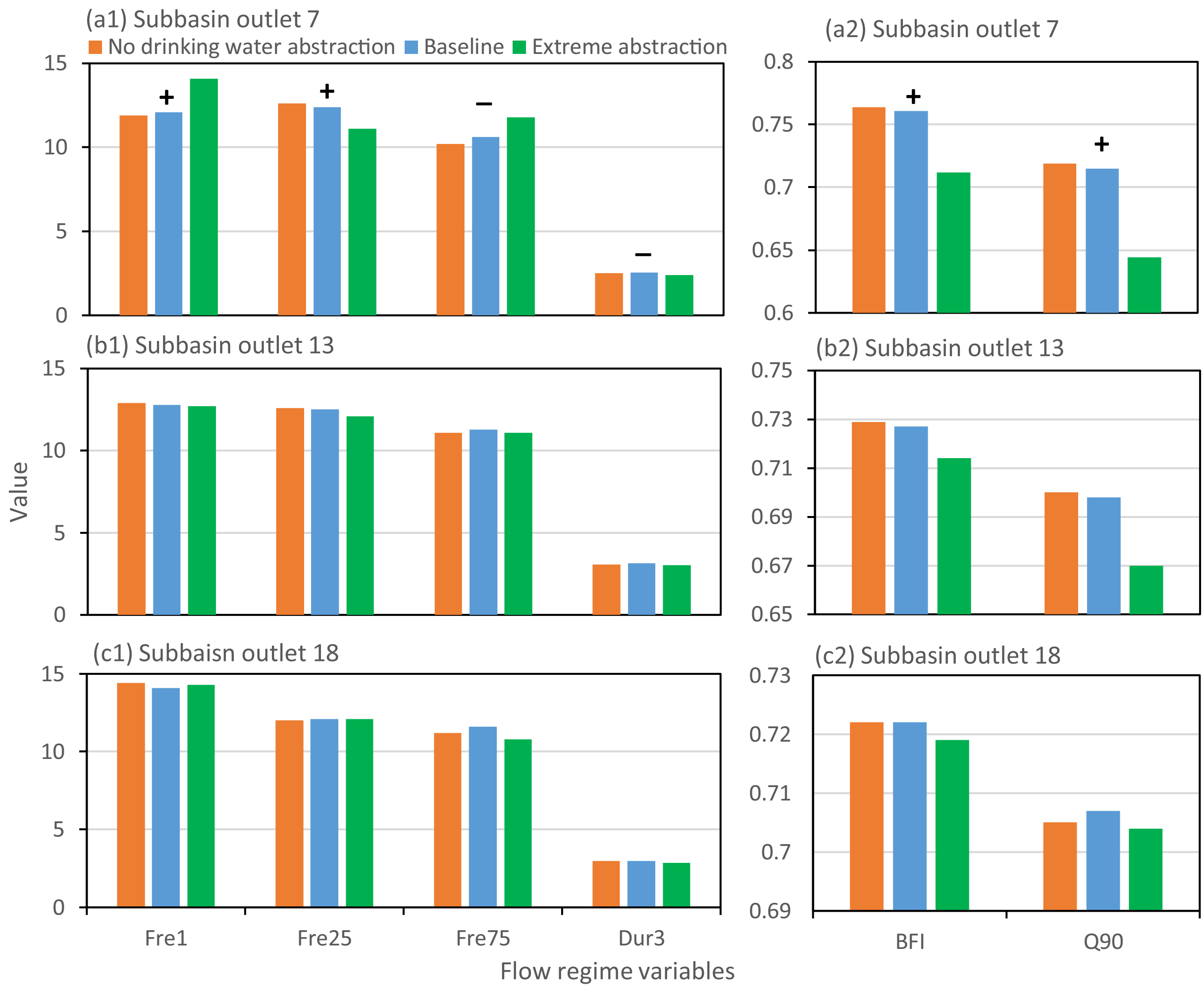

Fig. 4. Comparison of the FRVs for the streamflow at subbasin outlet 7, 13, and 18, respectively, during 2002–2015 between the three different scenarios (no drinking water abstraction, baseline, and extreme abstraction). "+" and "−"mean that the variable has a positive or negative effect on stream ecological quality state.

within the watershed. However, in the SWAT-MODFLOW model, realistic interaction of groundwater between subbasins can be simulated, and abstraction can therefore affect the groundwater hydrology in surrounding areas. Therefore, in the extreme abstraction scenario, the abstraction from wells in subbasin 7 not only decreased the groundwater discharge to the stream network but also in the discharge to other subbasins, allowing us to conclude that the streamflow changes in subbasin 13 and 18 were larger than in subbasin 7.

The flow-biota empirical models applied in this study are easy to employ and applicable in many lowland, temperate stream systems. Firstly, they are formulated as equations based on multiple easily understandable linear regressions, and the ecological quality ratio is a comprehensive coefficient that considers both species composition and biomass. Secondly, the determination coefficients of the models are fairly good (Gräber et al., 2015). Thirdly, they were developed based on samples and stream locations from numerous sites spread across Denmark and include three key taxonomical groups (fish, macrophytes, and macroinvertebrates). In contrast, most of previous flow alteration-ecology response studies report relationships for only specific stream segments, catchments or regions (Crossman et al., 2011; Belmar et al., 2013; Stein et al., 2017; Stein et al., 2018). They do not include formulated equations (Kennen et al., 2009; Stromberg et al., 2010; Meador and Carlisle, 2012; Buchanan et al., 2013; Domisch et al., 2017) and are often focused on only one taxonomic identity (Kennen et al., 2009; Stromberg et al., 2010; Falke et al., 2011; Domisch et al., 2017; Perkin et al., 2017; Ruhi et al., 2018).

The combination of SWAT-MODFLOW and the flow-biota empirical models enables scenario studies for quantitative assessment of the impacts of groundwater abstraction on ecological quality, not only for stream segments with observed streamflow but also for segments without observations. With simulated long-term streamflow data and the flow-biota empirical models, the ecological quality indices and their alteration due to groundwater abstraction at all the subbasin outlets can be derived. This study provides a methodology for doing so.

4.3. Limitations and future research

The patterns of daily streamflow differences among scenarios were generally as expected, but, surprisingly, the streamflow difference between the extreme abstraction scenario and the baseline scenario was positive at the outlets of subbasin 13 and 18 on 23th March, 2010, and at the subbasin 18 outlet on 24th December, 2012, being 1.05, 0.95 and 0.34 $m^3 s^{-1}$, respectively (Fig. 2). This cannot readily be explained. However, in tests of how these" outliers" affected our general results and conclusions, in which these two dates were omitted from the calculation of biotic indices, we found that the impacts on the FRVs and biotic indices were insignificant.

The flow-biota empirical models were developed based on the stream sites where both the biological data and long-term

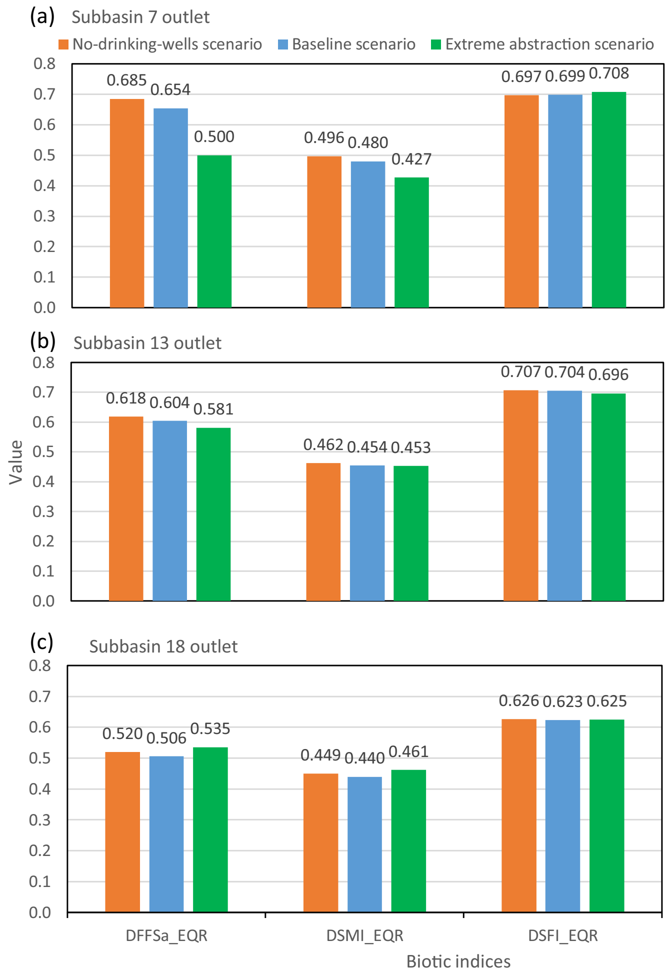

Fig. 5. Comparison of the biotic indices (DFFSa: fish index; DSMI: macrophyte index; and DSFI: macroinvertebrate index) at subbasin outlet 7, 13, and 18, respectively, during 2002–2015 between the three different scenarios (no drinking water abstraction, baseline, and extreme abstraction).

hydrological data are available. Generally, these hydrological stations in Danish stream segments are established in the middle and downstream receiving waters, i.e. not smaller headwater streams, and the equations therefore mainly represent relatively large streams. This implies that the equations may not adequately represent the small headwater streams that presumably are particularly sensitive to changes in groundwater discharge. If empirical flow-biota models for small streams become available, then the overall predictions of the coupled model complex would become even more reliable. In addition, the flow-biota models account for the impacts of flow regime changes on biotic indices, however, uncertainties can be caused by other factors not accounted for (e.g. nutrient concentrations, temperature and biota interactions) that also affect the biotic response. Therefore, further development of the models would ideally involve research on how other factors may influence the biotic indices.

We used the objective function NSE and squared weighted residuals as the objective function to calibrate the SWAT-MODFLOW against the observed streamflow and groundwater head, and also used P_{bias}, NSE and R^2 to further evaluate the SWAT-MODFLOW hydrological simulation. Results demonstrated a good performance (Liu et al., 2019). However, it was found that simulations even with good hydrological statistics (NSE, KGE) could still perform badly in representing ecologically relevant streamflow characteristics (Kiesel et al., 2017; Pool et al., 2017). We therefore also calculated the values of FRVs in the flow-regime models based on observed streamflow at both subbasin 13 and 18, and then compared them with the values achieved when based on the simulated streamflow of baseline. We used the efficiency of individual FRV I_{single} and the efficiency of all FRVs I_{multi} (see Appendix A for the exact equations) used in (Pool et al., 2017) to indicate the SWAT-MODFLOW performance in depicting the FRVs as shown in Appendix A. In future research, using an objective function representing the performance in depicting the FRVs (e.g. I_{multi}) to calibrate the SWAT-MODFLOW needs to be explored.

All the scenario analysis and hydrological impact assessments in this study were based on the “best” parameter combination achieved through calibration. We deem this method as satisfactory for the purpose of this study. However, in practical water resources management, uncertainties of hydrological simulations by models should also ideally be considered, e.g. using parameter ensembles or even multi-model ensembles.

Case studies provide a critical bridge between the science of flow-ecology and real-world implementation of best management practices (Stein et al., 2017). Our study is an example of how to quantitatively assess the effects of groundwater abstractions on stream biota through scenario simulations, which could have potential implications for groundwater abstraction management decisions. Broader application of the approach to other catchments could help foster science-informed groundwater management in Denmark or other countries (if similar flow-biota empirical models in those countries are developed).

5. Summary and conclusions

We jointly applied the SWAT-MODFLOW model and the flow-biota empirical model to a Danish groundwater-dominated catchment, the Uggerby River catchment, to quantitatively assess the effects of groundwater abstractions on flow regime and stream biota.

Effects were analyzed at three subbasin outlets representing stream segments of different sizes. The current groundwater abstraction level had slight impacts on the flow regime and stream biota for all three stream segments. The extreme abstraction scenario had significant impacts on the small stream but only slight impacts on the larger streams. Among the three biotic indices, the fish index was most severely affected by groundwater abstractions, followed by the macrophyte index, while no apparent impact of groundwater abstractions was found on the macroinvertebrate index.

We conclude that the novel approach of combining the SWAT-MODFLOW model with comprehensive flow-biota empirical models to quantitatively assess the effects of groundwater abstraction on stream biota is useful for developing water planning and regulation in Denmark and elsewhere. However, there is a need for developing more sufficient biotic models that also represent small headwater streams, which due to low flows can be significantly impacted by nearby groundwater abstraction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. The SWAT-MODFLOW performance in depicting the FRVs used in the empirical flow-biota models

Subbasin	Performance metrics	Definition of the performance metrics	Q_{90}	Fre_{75}	Fre_1	Dur_3	Fre_{25}	BFI
13	I_{obs}	I_{obs} is the value of individual FRV calculated based on observed flow.	0.54	7.57	9.71	4.59	11.14	0.68
	I_{sims}	I_{sims} is the value of individual FRV calculated based on simulated flow.	0.70	11.29	12.79	3.14	12.50	0.73
18	I_{obs}	–	0.57	10.43	12.07	4.00	12.14	0.67
	I_{sims}	–	0.71	11.64	14.14	2.99	12.07	0.72
13	I_{single}	I_{single} is the efficiency for individual FRV. $I_{single} = 1 - \|I_{obs} - I_{sim}\|/I_{obs}$.	0.72	0.51	0.68	0.68	0.88	0.94
18	I_{single}		0.76	0.88	0.83	0.75	0.99	0.92
13	I_{multi}	I_{multi} is the efficiency for all FRVs. $I_{multi} = 1/n\ (I_{single1} + \ldots + I_{single\_n})$	0.74					
18	I_{multi}		0.88					

Notes: The optimal value of I_{multi} and I_{single} is 1 (Pool et al., 2017). The closer to 1 the value of I_{multi} or I_{single} *is*, the better the model performs in depicting the FRV.

References

Akbarpour, S., Niksokhan, M.H., 2018. Investigating effects of climate change, urbanization, and sea level changes on groundwater resources in a coastal aquifer: an integrated assessment. Environ. Monit. Assess. 190 (579). https://doi.org/10.1007/s10661-018-6953-3.

Arnold, J., Kiniry, J., Srinivasan, R., Williams, J., Haney, E., Neitsch, S., 2013. SWAT 2012 Input/Output Documentation. Texas Water Resources Institute.

Arroita, M., Flores, L., Larranaga, A., Martinez, A., Martinez-Santos, M., Pereda, O., Ruiz-Romera, E., Solagaistua, L., Elosegi, A., 2017. Water abstraction impacts stream ecosystem functioning via wetted-channel contraction. Freshw. Biol. 62, 243–257. https://doi.org/10.1111/fwb.12864.

Baattrup-Pedersen, A., Larsen, S.E., Riis, T., 2013. From expert judgement to supervised classification: a new approach to assess ecological status in lowland streams. Sci. Total Environ. 447, 116–122. https://doi.org/10.1016/j.scitotenv.2012.12.062.

Bailey, R.T., Wible, T.C., Arabi, M., Records, R.M., Ditty, J., 2016. Assessing regional-scale spatio-temporal patterns of groundwater-surface water interactions using a coupled SWAT-MODFLOW model. Hydrol. Process. 30, 4420–4433. https://doi.org/10.1002/hyp.10933.

Belmar, O., Bruno, D., Martínez-Capel, F., Barquín, J., Velasco, J., 2013. Effects of flow regime alteration on fluvial habitats and riparian quality in a semiarid Mediterranean basin. Ecol. Indic. 30, 52–64.

Benejam, L., Angermeier, P.L., Munne, A., GARCÍA-BERTHOU, E., 2010. Assessing effects of water abstraction on fish assemblages in Mediterranean streams. Freshw. Biol. 55, 628–642.

Blin, N., Hausner, M.B., Suarez, F.I., 2017. Evaluating groundwater recharge variations under climate change in an endorheic basin of the Andean plateau. AGU Fall Meeting Abstracts.

Buchanan, C., Moltz, H.L.N., Haywood, H.C., Palmer, J.B., Griggs, A.N., 2013. A test of the ecological limits of hydrologic alteration (ELOHA) method for determining environmental flows in the Potomac River basin, U.S.A. 58, 2632–2647. https://doi.org/10.1111/fwb.12240.

Bunn, S.E., Arthington, A.H., 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. Environ. Manag. 30, 492–507.

Carlisle, D.M., Wolock, D.M., Meador, M.R., 2011. Alteration of streamflow magnitudes and potential ecological consequences: a multiregional assessment. Front. Ecol. Environ. 9, 264–270.

Carolli, M., Geneletti, D., Zolezzi, G., 2017. Assessing the impacts of water abstractions on river ecosystem services: an eco-hydraulic modelling approach. Environ Impact Asses 63, 136–146. https://doi.org/10.1016/j.eiar.2016.12.005.

Chunn, D., Faramarzi, M., Smerdon, B., Alessi, D., 2019. Application of an integrated SWAT–MODFLOW model to evaluate potential impacts of climate change and water withdrawals on groundwater–surface water interactions in West-Central Alberta. Water 11. https://doi.org/10.3390/w11010110.

Crossman, J., Bradley, C., Boomer, I., Milner, A., 2011. Water flow dynamics of groundwater-fed streams and their ecological significance in a glacierized catchment. Arct. Antarct. Alp. Res. 43, 364–379.

Domisch, S., Portmann, F.T., Kuemmerlen, M., O'Hara, R.B., Johnson, R.K., Davy-Bowker, J., Baekken, T., Zamora-Muñoz, C., Sáinz-Bariáin, M., Bonada, N., Haase, P., Döll, P., Jähnig, S.C., 2017. Using streamflow observations to estimate the impact of hydrological regimes and anthropogenic water use on European stream macroinvertebrate occurrences. Ecohydrology 10, e1895. https://doi.org/10.1002/eco.1895.

Donn, M.J., Barron, O.V., Barr, A.D., 2012. Identification of phosphorus export from low-runoff yielding areas using combined application of high frequency water quality data and MODHMS modelling. Sci. Total Environ. 426, 264–271. https://doi.org/10.1016/j.scitotenv.2012.03.021.

Du, M., Fouché, O., Zavattero, E., Ma, Q., Delestre, O., Gourbesville, P., 2019. Water planning in a mixed land use Mediterranean area: point-source abstraction and pollution scenarios by a numerical model of varying stream-aquifer regime. Environ. Sci. Pollut. Res. 26, 2145–2166. https://doi.org/10.1007/s11356-018-1437-0.

Dunbar, M.J., Pedersen, M.L., Cadman, D., Extence, C., Waddingham, J., Chadd, R., Larsen, S.E., 2010. River discharge and local-scale physical habitat influence macroinvertebrate LIFE scores. Freshw. Biol. 55, 226–242.

Falke, J.A., Fausch, K.D., Magelky, R., Aldred, A., Durnford, D.S., Riley, L.K., Oad, R., 2011. The role of groundwater pumping and drought in shaping ecological futures for stream fishes in a dryland river basin of the western Great Plains, USA. Ecohydrology 4, 682–697.

Foster, S., Chilton, J., Nijsten, G.-J., Richts, A., 2013. Groundwater—a global focus on the 'local resource'. Curr. Opin. Environ. Sustain. 5, 685–695. https://doi.org/10.1016/j.cosust.2013.10.010.

Gao, F., Feng, G., Han, M., Dash, P., Jenkins, J., Liu, C., 2019. Assessment of surface water resources in the big sunflower river watershed using coupled SWAT–MODFLOW model. Water 11, 528.

Gräber, D., Wiberg-Larsen, P., Bøgestrand, J., Baattrup-Pedersen, A., 2015. Vurdering af effekten af vandindvinding på vandløbs økologiske tilstand. DCE-Nationalt Center for Miljø og Energi, Aarhus Universitet, Roskilde, p. 29.

Graeber, D., Pusch, M.T., Lorenz, S., Brauns, M., 2013. Cascading effects of flow reduction on the benthic invertebrate community in a lowland river. Hydrobiologia 717, 147–159.

Guzman, J.A., Moriasi, D.N., Gowda, P.H., Steiner, J.L., Starks, P.J., Arnold, J.G., Srinivasan, R., 2015. A model integration framework for linking SWAT and MODFLOW. Environ. Model Softw. 73, 103–116. https://doi.org/10.1016/j.envsoft.2015.08.011.

Henriksen, H.J., Troldborg, L., Højberg, A.L., Refsgaard, J.C., 2008. Assessment of exploitable groundwater resources of Denmark by use of ensemble resource indicators and a numerical groundwater–surface water model. J. Hydrol. 348, 224–240.

Hille, S., Kristensen, E.A., Graeber, D., Riis, T., Jørgensen, N.K., Baattrup-Pedersen, A., 2014. Fast reaction of macroinvertebrate communities to stagnation and drought in streams with contrasting nutrient availability. Freshw. Sci. 33, 847–859.

Jørgensen, L.F., Stockmarr, J., 2009. Groundwater monitoring in Denmark: characteristics, perspectives and comparison with other countries. Hydrogeol. J. 17, 827–842. https://doi.org/10.1007/s10040-008-0398-7.

Kennen, J.G., Riva-Murray, K., Beaulieu, K.M., 2009. Determining Hydrologic Factors That Influence Stream Macroinvertebrate Assemblages in the Northeastern US. n/a-n/a. https://doi.org/10.1002/eco.99.

Kiesel, J., Guse, B., Pfannerstill, M., Kakouei, K., Jähnig, S.C., Fohrer, N., 2017. Improving hydrological model optimization for riverine species. Ecol. Indic. 80, 376–385. https://doi.org/10.1016/j.ecolind.2017.04.032.

Kristensen, E.A., Jepsen, N., Nielsen, J., Pedersen, S., Koed, A., 2014. Dansk fiskeindeks for vandløb (DFFV).

Larsen, S.E., Baattrup-Pedersen, A., 2015. Matematisk beskrivelse af Dansk Vandløbsplante Indeks.

Larsen, S.E., Friberg, N., Wiberg-Larsen, P., Skriver, J., Larsen, L., 2014. Konvertering af DVFI faunaklasser til EQR-værdier (Økologisk Kvalitets Ratio). Vand og Jord 1, 12–16.

Liu, W., Park, S., Bailey, R.T., Molina-Navarro, E., Andersen, H.E., Thodsen, H., Nielsen, A., Jeppesen, E., Jensen, J.S., Jensen, J.B., Trolle, D., 2019. Comparing SWAT with SWAT-MODFLOW hydrological simulations when assessing the impacts of groundwater abstractions for irrigation and drinking water. Hydrol. Earth Syst. Sci. Discuss. 2019, 1–51. https://doi.org/10.5194/hess-2019-232.

Loukika, K., Reddy, K.V., Rao, K.D., Singh, A., 2020. Estimation of groundwater recharge rate using SWAT MODFLOW model. Applications of Geomatics in Civil Engineering. Springer, pp. 143–154.

Meador, M.R., Carlisle, D.M., 2012. Relations between altered streamflow variability and fish assemblages in Eastern USA streams. 28, 1359–1368. https://doi.org/10.1002/rra.1534.

Molina-Navarro, E., Bailey, R.T., Andersen, H.E., Thodsen, H., Nielsen, A., Park, S., Jensen, J.S., Jensen, J.B., Trolle, D., 2019. Comparison of abstraction scenarios simulated by SWAT and SWAT-MODFLOW. Hydrol. Sci. J. 64 (4), 434–454.

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute.

NERI, 2000. Metadata for the Area Information System. (in Danish: Metadata for Arealinformation Systemet). Danish National Environmental Research Institute, Roskilde.

Niswonger, R.G., Panday, S., Ibaraki, M., 2011. MODFLOW-NWT, a Newton formulation for MODFLOW-2005. US Geological Survey Techniques and Methods 6, p. 44.
Pan, B., Wang, Z., Li, Z., Yu, G., Xu, M., Zhao, N., Brierley, G., 2013. An exploratory analysis of benthic macroinvertebrates as indicators of the ecological status of the Upper Yellow and Yangtze Rivers. J. Geogr. Sci. 23, 871–882.
Pardo, I., Garcia, L., 2016. Water abstraction in small lowland streams: unforeseen hypoxia and anoxia effects. Sci. Total Environ. 568, 226–235. https://doi.org/10.1016/j.scitotenv.2016.05.218.
Perkin, J.S., Gido, K.B., Falke, J.A., Fausch, K.D., Crockett, H., Johnson, E.R., Sanderson, J., 2017. Groundwater declines are linked to changes in Great Plains stream fish assemblages. Proc. Natl. Acad. Sci. 114, 7373–7378.
Petts, G.E., 2018. Perspectives for ecological management of regulated rivers. Alternatives in Regulated River Management. CRC press, pp. 13–34.
Poff, N.L., Zimmerman, J.K., 2010. Ecological responses to altered flow regimes: a literature review to inform the science and management of environmental flows. Freshw. Biol. 55, 194–205.
Poff, N.L., Allan, J.D., Bain, M.B., Karr, J.R., Prestegaard, K.L., Richter, B.D., Sparks, R.E., Stromberg, J.C., 1997. The natural flow regime. BioScience 47, 769–784. https://doi.org/10.2307/1313099.
Poff, N.L., Richter, B.D., Arthington, A.H., Bunn, S.E., Naiman, R.J., Kendy, E., Acreman, M., Apse, C., Bledsoe, B.P., Freeman, M.C., Henriksen, J., Jacobson, R.B., Kennen, J.G., Merritt, D.M., Oâ Keeffe, J.H., Olden, J.D., Rogers, K., Tharme, R.E., Warner, A., 2010. The ecological limits of hydrologic alteration (ELOHA): a new framework for developing regional environmental flow standards. 55, 147–170. https://doi.org/10.1111/j.1365-2427.2009.02204.x.
Pool, S., Vis, M.J., Knight, R.R., Seibert, J., 2017. Streamflow characteristics from modeled runoff time series importance of calibration criteria selection. Hydrol. Earth Syst. Sci. 21, 5443–5457.
R Core Team, 2013. R: A language and environment for statistical computing. R Foundation for statistical Computing, Vienna, Austria.
Rasmussen, M.L., Wiberg-Larsen, P., Jacobsen, D., 2017. A long-term improvement in Danish stream fauna: analyses of temporal dynamics and community alignment of a biotic index. Ecol. Indic. 81, 47–53.
Riis, T., Suren, A.M., Clausen, B., SAND-JENSEN, K., 2008. Vegetation and flow regime in lowland streams. Freshw. Biol. 53, 1531–1543.
Ruhi, A., Dong, X., McDaniel, C.H., Batzer, D.P., Sabo, J.L., 2018. Detrimental effects of a novel flow regime on the functional trajectory of an aquatic invertebrate metacommunity. Glob. Chang. Biol. 24, 3749–3765.
Schmidt, M., Lipson, H., 2009. Distilling free-form natural laws from experimental data. Science 324, 81–85.
Semiromi, M.T., Koch, M., 2019. Analysis of spatio-temporal variability of surface–groundwater interactions in the Gharehsoo river basin, Iran, using a coupled SWAT-MODFLOW model. Environ. Earth Sci. 78 (201).
Shiklomanov, I.A., 1998. World Water Resources: A New Appraisal and Assessment for the 21st Century: A Summary of the Monograph World Water Resources. Unesco.
Sith, R., Watanabe, A., Nakamura, T., Yamamoto, T., Nadaoka, K., 2019. Assessment of water quality and evaluation of best management practices in a small agricultural watershed adjacent to Coral Reef area in Japan. Agric. Water Manag. 213, 659–673. https://doi.org/10.1016/j.agwat.2018.11.014.
Skriver, J., Friberg, N., Kirkegaard, J., 2000. Biological assessment of running waters in Denmark: introduction of the Danish Stream Fauna Index (DSFI). Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen 27, 1822–1830.
Søndergaard, M., Lauridsen, T., Kristensen, E., Baattrup-Pedersen, A., Wiberg-Larsen, P., Bjerring, R., Friberg, N., 2013. Biologiske indikatorer til vurdering af økologisk kvalitet i danske søer og vandløb. Aarhus Universitet, DCE–Nationalt Center for Miljø og Energi 78 s, Videnskabelig rapport fra DCE-Nationalt Center for Miljø og Energi.
Stein, E.D., Sengupta, A., Mazor, R.D., McCune, K., Bledsoe, B.P., Adams, S., 2017. Application of regional flow-ecology relationships to inform watershed management decisions: application of the ELOHA framework in the San Diego River watershed, California, USA. Ecohydrology 10. https://doi.org/10.1002/eco.1869.
Stein, E.D., Taylor, J., Sengupta, A., Yarnell, S.M., 2018. Evaluating the Effect of Changes in Flow and Water Temperature on Stream Habitats and Communities in the Los Angeles/Ventura Region.
Stromberg, J., Lite, S., Dixon, M., 2010. Effects of stream flow patterns on riparian vegetation of a semiarid river: implications for a changing climate. River Res. Appl. 26, 712–729.
Todo, K., Sato, K., 2002. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy. Environmental Research Quarterly, pp. 66–106.
Tonkin, J.D., Merritt, D.M., Olden, J.D., Reynolds, L.V., Lytle, D.A., 2018. Flow regime alteration degrades ecological networks in riparian ecosystems. Nat. Ecol. Evol. 2, 86.
Wada, Y., Wisser, D., Bierkens, M.F.P., 2014. Global modeling of withdrawal, allocation and consumptive use of surface water and groundwater resources. Earth Syst. Dynam. 5, 15–40. https://doi.org/10.5194/esd-5-15-2014.
Wei, X., Bailey, R.T., 2019. Assessment of system responses in intensively irrigated stream–aquifer systems using SWAT-MODFLOW. Water 11, 1576.
Wei, X., Bailey, R.T., Records, R.M., Wible, T.C., Arabi, M., 2018. Comprehensive simulation of nitrate transport in coupled surface-subsurface hydrologic systems using the linked SWAT-MODFLOW-RT3D model. Environ. Model Softw. https://doi.org/10.1016/j.envsoft.2018.06.012.