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Impact of groundwater abstraction on physical habitat of brown trout (*Salmo trutta*) in a small Danish stream

M. Olsen, E. Boegh, S. Pedersen and M. F. Pedersen

ABSTRACT

The purpose of this study was to assess the impact of groundwater abstraction on stream discharge and physical habitat conditions for brown trout (*Salmo trutta*) in a small Danish stream. Stream discharge was simulated using a lumped hydrological model (NAM) and a scenario was set up for stream discharge reference conditions. Stream physical habitat conditions (WUA) were simulated for four life stages of trout using a hydraulic habitat model (RHYHABSIM). The impact of groundwater abstraction on WUA for trout was assessed by combined simulations from the NAM model and the RHYHABSIM model.

The model predicted that groundwater abstraction reduced median annual discharge by 37% and mean annual 90th percentile discharge by 82%. Summer discharge was relatively most affected by groundwater abstraction and WUA was therefore particularly affected by groundwater abstraction during summer. WUA for adult trout was mainly controlled by suitable water depths (>40 cm) even under conditions without abstraction. On an annual basis WUA for fry and juvenile trout was most affected by abstraction. Future modelling should consider improving simulation of low discharges and preferably not use general hydrological models.

Key words | brown trout (*Salmo trutta*), catchment hydrological modelling, groundwater abstraction, hydraulic habitat modelling, in-stream physical habitat conditions

M. Olsen (corresponding author)
E. Boegh
M. F. Pedersen
Department of Environmental, Social and Spatial Change,
Roskilde University,
PO Box 260,
DK-4000, Roskilde,
Denmark
Tel.: +45 4674 2593;
E-mail: *maol@ruc.dk*

S. Pedersen
National Institute of Aquatic Resources,
Technical University of Denmark,
Vejlsoevej 39, DK-8600
Silkeborg,
Denmark

INTRODUCTION

Stream discharge and discharge conditions are important to stream organisms since discharge determines size (stream width and depth) and suitability of the habitat. Furthermore, discharge influences the connectivity of the stream and thereby possibilities for migration in, and colonization of, the stream. Stream discharge is not the only parameter affecting biota, but many factors affecting stream biota are related to discharge or are influenced by discharge, e.g. water depth, water velocity, water temperature (Bain *et al.* 1988; Ward & Stanford 1989; Heggenes *et al.* 1991).

The majority of Danish streams are fed by groundwater (Henriksen *et al.* 2008) and abstraction of groundwater can therefore reduce stream discharge and thus affect in-stream physical habitat conditions for stream biota (Tallaksen & van Lanen 2004; McKay & King 2006; Dewson *et al.* 2007). The European Water Framework Directive (WFD) states that reduced flow from groundwater to surface water should not result in impaired (ecological) stream quality (EU 2000). In Denmark, 99% of the public water supply is based on groundwater abstraction, and groundwater abstraction is one of the main anthropogenic factors influencing discharge in Danish streams (Henriksen *et al.* 2008). Most streams in Denmark are small (average width <2.5 m) (Sand-Jensen *et al.* 2006). Since small streams generally have lower discharge than larger water courses they are relatively more vulnerable to reductions in stream flow, e.g. reduction of groundwater influx caused by groundwater abstraction (Orth & Leonard 1990).

Limits for minimum discharge in Danish streams have not been assessed to take account of flow requirements of

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stream biota, but rather of the ability to dilute wastewater emissions and excess water (Iversen *et al.* 1993). However, after a national inventory of the Danish freshwater resources (Henriksen *et al.* 2008), and during the implementation of the WFD, new methods for estimation of stream flow requirements and assessment of groundwater abstraction impact on stream biota have been in demand.

Several methods have been used for estimating in-stream flow requirements. These methods range from simple hydrological methods like the Tennant method (Tennant 1976) to more sophisticated habitat-rating methods like in-stream physical habitat modelling using hydraulic habitat models (Bovee *et al.* 1998). Physical habitat modelling, hereafter referred to as habitat modelling, has lately been proposed as a method for estimating flow requirements and assessing groundwater abstraction impact in relation to Danish streams (Refsgaard *et al.* 2002; Henriksen 2003). Habitat modelling includes setting up a hydraulic model of the stream in question, describing the relation between selected physical variables (often water depth, water velocity and substrate composition), stream discharge and habitat quality (Bovee *et al.* 1998). One or more in-stream related species, their life stages or activities are selected as indicators in the habitat modelling. Habitat Suitability Indices (HSI) then have to be developed for each of the physical variables that are included in the modelling. There are a few different ways of developing HSIs (Bovee *et al.* 1998), but most often they describe the indicator organisms' relative preference within a number of intervals or categories for each habitat variable. The hydraulic model of the stream is finally combined with the HSIs of each indicator to simulate the relationship between stream discharge and the combined physical habitat quality and quantity of the stream called the Weighted Usable Area (WUA) often expressed in $m^2 m^{-1}$ or %. The relationship is referred to as a WUA curve (Figure 1).

Habitat models are most often used to estimate discharge requirements, but when combined with observed or simulated discharge they can be used to predict the impact of groundwater abstraction on physical habitat conditions (Johnson *et al.* 1995; Strevens 1999; Dunbar *et al.* 2004). The impact of groundwater abstraction on Danish streams has been assessed on both national and local scales (Henriksen *et al.* 2008) and site-specific habitat models have been set up for a few streams (Lund 1996; Fjorback *et al.* 2002; Clausen *et al.* 2006; Thorn & Conallin 2006), but the two types of models have never been combined in Denmark.

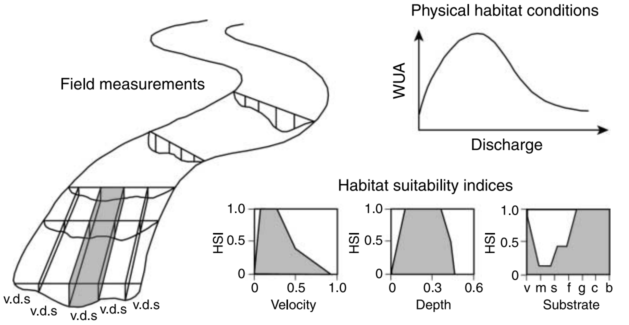

Figure 1 | Illustration of data requirements and techniques for physical habitat modelling. (1) In-stream physical hydraulic variables, e.g. stream profile, water depth (*d*), water velocity (*v*), substrate composition (*s*) are measured in selected transects. (2) Curves representing Habitat Suitability Indices (HSI) for selected indicators such as adult brown trout, juvenile brown trout and/or macroinvertebrates are established. (3) HSIs are applied to the in-stream physical hydraulic model to calculate the Weighted Usable Area (WUA) in response to stream discharge for the selected indicator (adapted from Clausen *et al.* (2006), by permission of the National Environmental Research Institute (NERI)).

The main objective of this study was therefore to assess the impact of groundwater abstraction on stream discharge and physical habitat conditions for brown trout (*Salmo trutta*) in a small Danish stream by combining a hydrological catchment model with an in-stream habitat model. Since the habitat requirements of brown trout, hereafter called trout, are well studied and often used in habitat modelling this species was selected as a suitable indicator.

STUDY AREA

Stream discharge is heavily affected by groundwater abstraction in the capital region on the island of Zealand where groundwater is abstracted for consumption in Copenhagen. This study was therefore conducted in the catchment of a small Danish stream in the capital region, Ledreborg stream, a contributor to the Langvad stream (Figure 2). The study section of the stream had an average width of 2 m and a mean annual discharge close to the outlet is $0.123\, m^3 s^{-1}$ (mean 1985–2005). The catchment covered $27.5\, km^2$ and the difference between the highest and lowest points in the catchment was 120 m over 10 km, which is quite steep in a Danish context.

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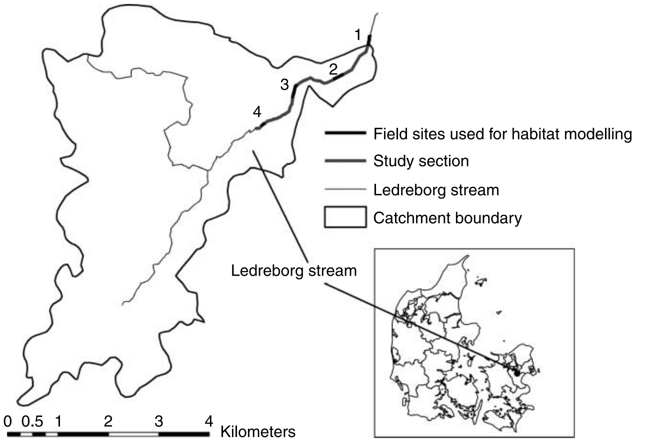

Figure 2 | Location of Ledreborg stream, the study section of the stream known to have trout and the field sites used for physical habitat modelling (1–4).

Groundwater abstraction in the Ledreborg catchment started around 1938 and reached a maximum abstraction rate of $5 \times 10^6 \mathrm{m}^3$ per year in 1982. At this time the groundwater table was lowered by 6–11 m. Over the 1990s groundwater abstraction was reduced considerably to $1.8 \times 10^6 \mathrm{m}^3$ per year. Consequently, the groundwater table rose 3–5 m in the same period.

Some reaches of the stream have a high biological quality according to the Danish Stream Fauna Index (DSFI) based on macroinvertebrates. The stream is considered to have a high potential as a brown trout spawning area; this is confirmed by brown trout stock assessments which have found late summer densities of brown trout fry most years between 20–50 per $100 \mathrm{m}^2$ on the best reach (Mikkelsen 1998, 2006). The main restriction on the biological quality of the stream both regarding DSFI and trout is thought to be groundwater abstraction and its impact on the summer discharge levels, since pollution and emissions from point sources was practically eliminated during the mid-1980s (Rasmussen 2005). The present study of the in-stream habitat conditions focused on the lower four kilometres of the stream known to accommodate both adult and juvenile trout. Here four reaches were selected (Figure 2).

MATERIAL AND METHODS

Field study of in-stream physical conditions

Physical hydraulic data to set up the habitat model RHYHABSIM (River HYdraulics and HABitat SIMulation) (Jowett 1989) was collected from four reaches in the stream (Figure 2) using a Habitat Mapping approach (Jowett 1989) where each reach was thoroughly mapped according to the relative cover of a number of habitat types; riffle, run and pool. Reaches had a length of 70–225 m. Because reaches were relatively homogeneous they were represented using two to five cross sections, with the most heterogeneous reaches having the most cross sections. Water depth and current velocity were measured at 30 cm intervals at each cross section to set up the RHYHABSIM model. Current velocities were measured at multiple points in each interval using an OTT10 propeller water current meter and discharge was calculated using the CALQ software (Clausen & Jensen 1994).

All reaches were visited at least five times during the study period (May 2005–March 2006) to measure discharge (Q) and water surface height (h) in order to develop $Q - h$ relationships for each study reach. Measurements were done at high and low discharges to ensure a wide validity of the $Q - h$ relationship.

Hydrological modelling

Historical stream discharge was simulated using a lumped conceptual model, NAM from the MIKE 11 software, 2005 edition (DHI 2004). In addition to daily climate and discharge input, groundwater abstraction data was included in the simulation of historical daily discharge. Daily groundwater abstraction values were disaggregated from annual groundwater abstraction data. The model was set up using a split-sample method with a seven-year calibration period (1991–1997) and a five-year validation period (1998–2002). The model was calibrated using a standard water resources management approach with calibration of nine parameters to minimize overall water balance error and overall Root-Mean-Square Error (RMSE) on stream discharge using the automatic calibration in the MIKE 11 software. The model set-up's ability to simulate daily discharge was assessed by looking at differences between observed daily discharge (Q_{obs}) and simulated daily discharge (Q_{sim}) using the coefficient of determination (r^2), the Nash–Sutcliffe coefficient (R^2; Nash & Sutcliffe 1970) and a measure of the set-up's ability to simulate annual average runoff F_{Bal} (Henriksen *et al.* 2003). The performance

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Table 1 | Model performance indicators (R^2 and F_{Bal}) and criteria used to assess if the model set-up had an acceptable performance. R^2 values below zero indicate that the model does not contribute to explain data variability

Indicator	Perfect	Very good	Good	Poor	Very poor
R^2	1–0.85	0.85–0.65	0.65–0.5	0.5–0.2	0.2–0
F_{bal} (%)	<5	5–10	10–20	20–40	>40

indicators were evaluated using a set of criteria developed by Henriksen *et al.* (2003) (Table 1) to determine whether the model set-up had an acceptable performance or not.

Reference condition stream discharge was simulated by omitting groundwater abstraction from the validated model set-up after obtaining an acceptable model performance (good to perfect in Table 1).

Physical habitat modelling

In-stream physical habitat conditions were modelled using the RHYHABSIM model software (Jowett 1989). The stage–discharge relationship for the hydraulic model was derived through an empirical rating curve based on the best rating for a stage of zero flow, with r^2 values between 0.87 and 0.98 for the individual cross sections. The hydraulic data was combined with HSIs representing four different trout life stages (fry, juvenile, adult and spawners). HSIs representative of fry, juvenile and spawners (Figure 3) were based on expert opinion on Danish brown trout habitat preferences supported by the literature (Lund 1996) and HSIs representative of adult brown trout (Figure 3) were based on a field study of adult trout habitat preferences in a Danish stream (Pedersen *et al.* 2005). Only HSIs for depth and velocity were included in the habitat modelling since they were considered more applicable in this stream than HSIs for substrate. The same HSIs were used for all flows.

WUA curves were simulated for each of the trout life stages both for each of the single reaches and for the sum of the four reaches (whole stream). The curves were compared and evaluated in relation to two criteria:

(1) Maximum WUA value. A higher maximum WUA value indicates better potential physical habitat quality or larger area of habitat than low WUA values.
(2) Discharge level at which the maximum WUA is achieved. It is best if the maximum WUA is achieved at low discharge. In this case, WUA is less vulnerable to discharge reductions caused by excessive groundwater abstraction compared to a case where maximum WUA is achieved at high discharge.

Groundwater abstraction impact

Groundwater abstraction impact on stream discharge was assessed on annual, summer (1/6–30/9) and winter (1/11–28/2) discharge (1998–2002) by comparing discharge duration curves of simulated historical daily discharge with that of simulated reference condition daily discharge.

WUA duration curves where developed from WUA time series calculated according to Bovee *et al.* (1998). The WUA time series were calculated by combining time series of daily discharge, simulated historical and reference, with WUA

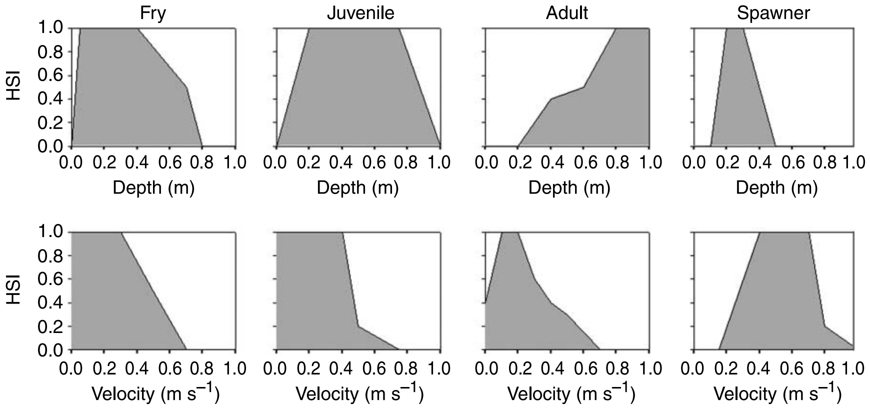

Figure 3 | Habitat Suitability Indices (HSIs) for depth and water velocity for four life stages of brown trout: fry, juvenile, adult and spawner. Fry, juvenile and spawner HSIs are based on expert opinion (Lund 1996) and adult HSIs are based on field study of habitat preferences (Pedersen *et al.* 2005).

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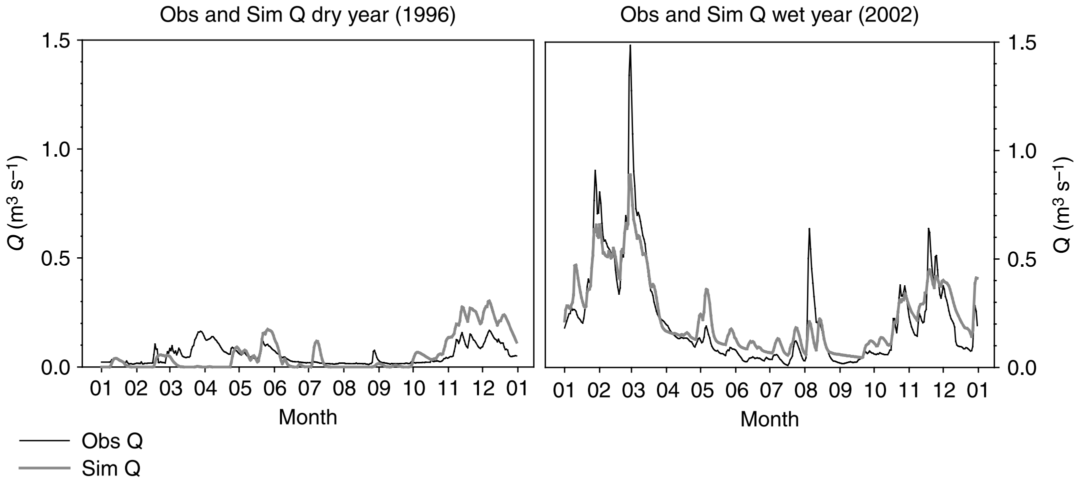

Figure 4 | Examples of observed (Obs) and simulated (Sim) mean daily discharge (*Q*) in Ledreborg stream in the dry year of 1996 (389 mm precipitation) and the wet year of 2002 (745 mm precipitation).

curves for each of the four brown trout life stages in an Excel spreadsheet (HABTS 2008) developed by the US Geological Survey (USGS). Groundwater abstraction impacts on physical habitat conditions were assessed by comparing WUA–duration curves for simulated historical and simulated reference condition discharge on an annual, summer and winter basis.

RESULTS

Simulations of historical stream discharge can be seen in Figure 4.

The NAM model set-up during the calibration period provided an acceptable simulation of daily discharge ($R^2 = 0.54$), while the simulation was better during the validation period ($R^2 = 0.79$) (Figure 4 and Table 2). The improved simulation of daily discharge in the validation period could be related to less extreme climatic conditions in this period. Visual comparison of observed and simulated daily discharges revealed that the model had problems simulating minimum and maximum discharges (in both the calibration and validation period; Figure 4). In particular the model had problems simulating daily discharge in periods with dry conditions (e.g. 1996 and 1997) compared to wet years (e.g. 2002) (Figure 4 and Table 2).

Table 2 | NAM modelling statistics from the calibration and validation period. Nash–Sutcliffe coefficient (R^2) for each year and the whole calibration period. F_{bal} denotes the error on the mean runoff for each year and the entire calibration period

Calibration period

Year	1991	1992	1993	1994	1995	1996	1997	Period
R^2	0.36	0.61	0.61	0.75	0.72	−1.44	−3.35	0.54
F_{bal}	−16	13	−3	16	27	−10	−112	−3

Validation period

Year	1998	1999	2000	2001	2002	Period
R^2	0.72	0.78	0.73	0.63	0.82	0.79
F_{bal}	−12	18	14	5	−9	4

Groundwater impact on stream discharge

Simulated discharge was higher when groundwater abstraction was not included in the simulation (under reference conditions) than under the simulated historical conditions (Figure 5).

On average, groundwater abstraction caused 37% reduction in median annual discharge and 82% reduction of the annual 90th percentile discharge (the discharge rate which is exceeded 90% of the time on an annual basis) (Table 3).

The model predicted that summer discharges were relatively most impacted by groundwater abstraction, e.g. summer median discharge was reduced by 66% compared to 20% reduction of winter median discharge. Absolute median discharge in summer was reduced by $0.045\,m^3\,s^{-1}$ compared to a $0.058\,m^3\,s^{-1}$ reduction during winter (Figure 6).

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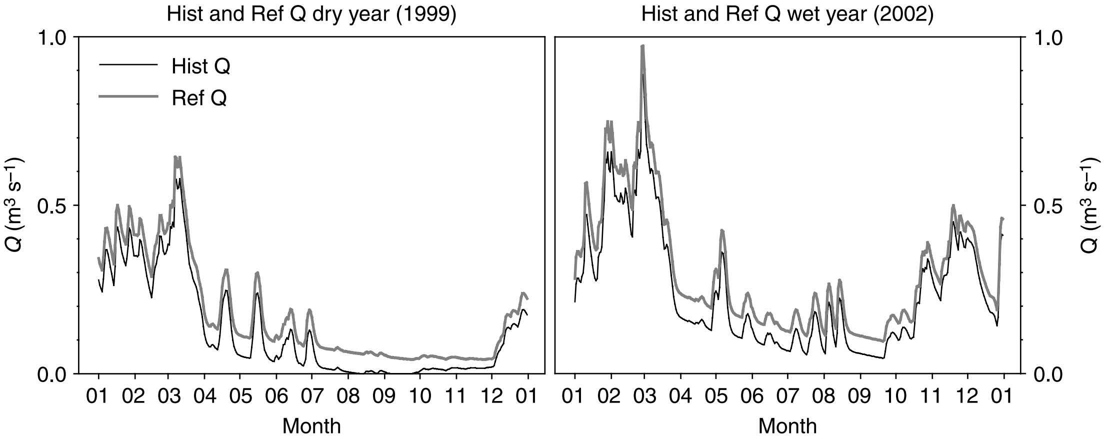

Figure 5 | Examples of simulated historical (Hist) and simulated reference condition (Ref) mean daily discharge (*Q*) in Ledreborg stream in the dry year of 1999 (484 mm precipitation) and the wet year of 2002 (745 mm precipitation).

Habitat modelling

The habitat model predicts that the potential physical habitat conditions (i.e. size of maximum WUA) on all reaches is highest for fry and juvenile, and lowest for spawners and adult trout (Figure 7).

The WUA curve for fry for "All reaches" peaks at $2.1\,\mathrm{m^2\,m^{-1}}$ (Figure 7A) compared to the WUA curve for adults which peaks at only $0.17\,\mathrm{m^2\,m^{-1}}$ (Figure 7C). This indicates that the potential physical habitat conditions are best for fry and worst for adult trout. When focusing on the second criteria, i.e. timing of WUA in relation to discharge, the WUA curve for fry "All reaches" peaks already at a discharge of $0.06\,\mathrm{m^3\,s^{-1}}$ (Figure 7A), while the WUA curve for spawners for "All reaches" peaks at $0.2\,\mathrm{m^3\,s^{-1}}$ (Figure 7D). This indicates that spawners are most vulnerable and fry least vulnerable to low discharge.

When comparing reaches, the model predicts that reach 1 has the highest potential physical habitat conditions (highest potential WUA) for fry and spawners compared to the other reaches (Figure 7A,D). Furthermore reach 1 has the second highest potential habitat for juvenile trout and at high flows (larger than $0.2\,\mathrm{m^3\,s^{-1}}$) it has the second highest potential for adult trout (Figure 7B,C). The model predicts that reach 2 has the highest potential physical habitat for juvenile and adult trout (Figure 7B,C). Potential physical habitat conditions are, in general, predicted to be lowest at reach 4 for all trout life stages (lowest maximum WUA). Only reach 2 has a lower maximum WUA for spawners than reach 4 (Figure 7D).

When comparing reach vulnerability to discharge reductions (i.e. criteria 2), the model predicts that reach 4 is least vulnerable to discharge reductions since the WUA curves peak at the lowest discharge compared to the other reaches for fry, juvenile and spawners (Figure 7A,B,D). Reach 2 is predicted to be most vulnerable to discharge reductions since WUA curves peak at the highest discharge compared to the other reaches for fry, juvenile and spawners (Figure 7A,B,D).

Table 3 | Simulated impact of groundwater abstraction expressed as relative change in median daily discharge ($\%\Delta Q_{\mathrm{med}}$) and relative change in annual 90th percentile discharge ($\%\Delta Q_{90}$)

	1998	1999	2000	2001	2002	Average
$\%\Delta Q_{\mathrm{med}}$	−28%	−52%	−31%	−47%	−25%	−37%
$\%\Delta Q_{90}$	−77%	−95%	−98%	−98%	−45%	−82%

Groundwater abstraction impact on physical habitat conditions for trout

Simulation of the groundwater abstraction impact on physical habitat conditions (WUA) for trout revealed that at some point groundwater abstraction reduced WUA for all indicators (Figure 8).

Adult trout during summer is an example of an indicator where WUA are reduced by groundwater abstraction (Figure 8G). The duration curve for the simulated reference condition WUA for adult trout is higher than the duration curve for the simulated historical WUA for more than 95% of

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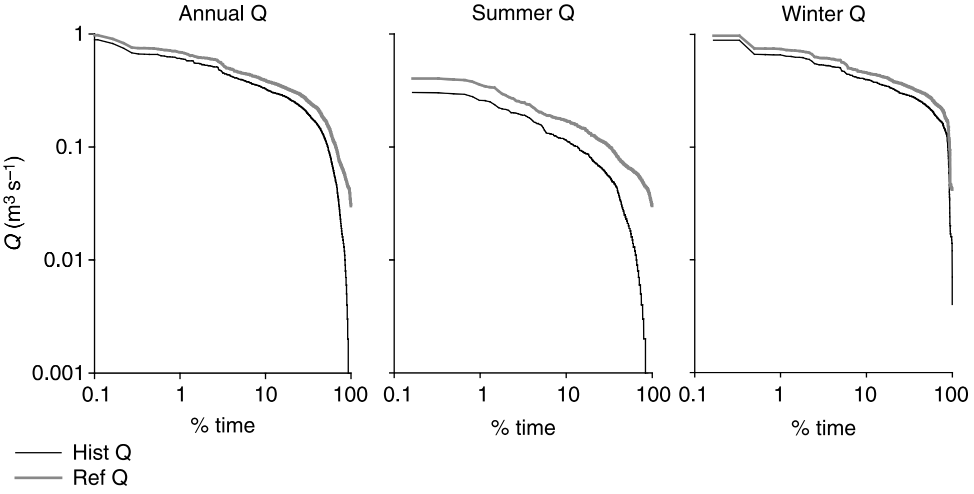

Figure 6 | Discharge duration curves of simulated historical (Hist) and simulated reference condition (Ref) mean daily discharge (*Q*) for annual, summer and winter period (1998–2002). The *Y* axis illustrates the relative time a certain discharge is equalled or exceeded.

the time during summer. For example, under summer reference conditions, WUA for adults exceeds $0.1\,\mathrm{m}^2\,\mathrm{m}^{-1}$ 77% of the time, but under the simulated historical conditions WUA only exceeds $0.1\,\mathrm{m}^2\,\mathrm{m}^{-1}$ 34% of the time (Figure 8G). The figure also reveals that groundwater abstraction has the largest impact on the most frequent and the lowest WUA values and less impact on the most infrequent and highest WUA values for adult trout during summer.

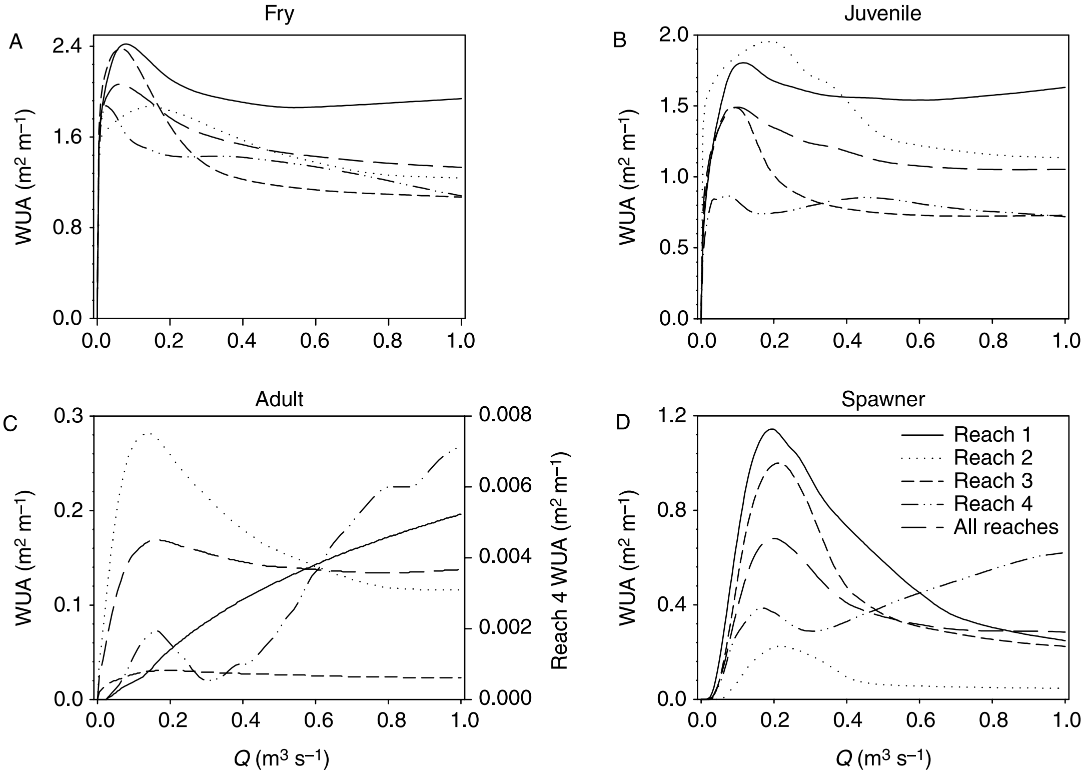

Figure 7 | Relationship between discharge (*Q*) and Weighted Usable Area (WUA) for fry, juvenile, adult and spawning trout on each for the four reaches (1–4). The combined WUA for "All reaches" is also shown. Notice the scale for adult on reach 4 is separate from the other reaches for adult.

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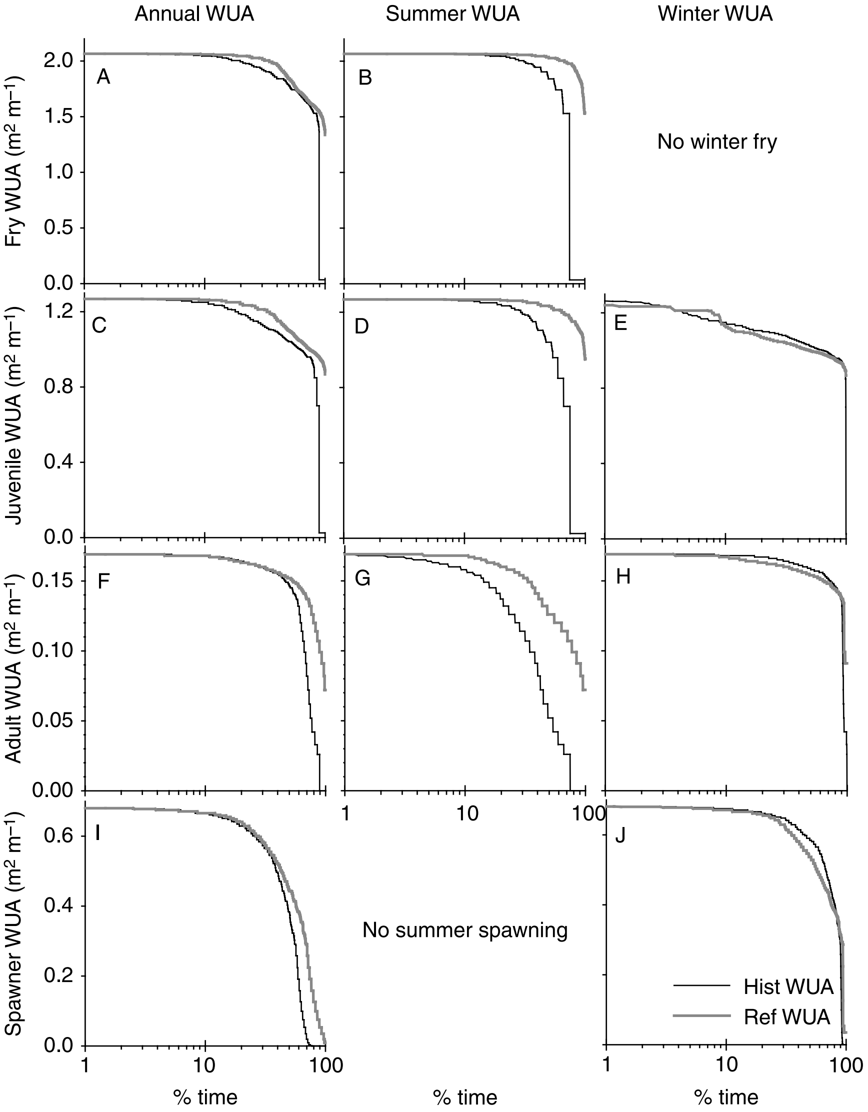

Figure 8 | Duration curves of simulated historical (Hist) and reference (Ref) physical habitat conditions expressed as Weighted Usable Area (WUA) for brown trout life stages (fry, juvenile, adult, spawner) under annual, summer and winter conditions (1998–2002). The *Y* axis illustrates the relative time a certain discharge is equalled or exceeded. In Ledreborg stream, brown trout have fry size (0–7 cm) during summer and only spawn during winter.

In general, physical habitat conditions for trout life stages are negatively affected by groundwater abstraction on an annual basis and during summer where reference conditions are better than historical conditions (Figure 8A–D,F,G,I). During winter the impact from groundwater abstraction is less obvious since reference habitat conditions and historical habitat conditions are more or less the same (Figure 8E,H,J). Summer habitat conditions are most affected by groundwater abstraction since the difference between reference conditions and historical conditions are largest during summer (Figure 8B,D,G). Spawning trout seems to be least impacted by groundwater abstraction since they are not present in the Ledreborg stream during summer and the impact from groundwater abstraction is predicted to be positive during winter (Figure 8J).

Juvenile trout and fry are predicted to be affected for the longest time on an annual basis and groundwater abstraction is predicted to have the relatively largest impact on median WUA on an annual basis for juveniles and fry

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Table 4 | Impact of groundwater abstraction on annual and summer habitat conditions for four life stages of trout. Temporal impact illustrates the relative time habitat conditions are negatively impacted by groundwater abstraction. Reduction of median WUA illustrates the relative reduction of median WUA

	Impact on annual conditions		Impact on summer conditions	
	Temporal impact	Reduction of median WUA	Temporal impact	Reduction of median WUA
Fry	92%	3%	85%	10%
Juvenile	96%	5%	92%	15%
Adult	47%	0%	95%	62%
Spawner	73%	14%	–	–

compared to adult trout (Table 4). Habitat conditions for adult trout are predicted to be more affected by groundwater abstraction during summer compared to habitat conditions of juveniles, which again is more affected than habitat conditions for fry (Table 4).

DISCUSSION

Assessment of groundwater abstraction impact on ecological conditions in streams and assessment ecological acceptable stream flows has received a great deal of attention, especially in Denmark after implementation of the European Water Framework Directive (WFD) (Refsgaard *et al.* 2002). The traditional Danish approach for assessing minimum acceptable flow is based on a maximum reduction of the median minimum discharge (Miljoestyrelsen 1979; Henriksen & Sonnenborg 2003) which gives no indication of how influenced the habitat conditions are after a change in hydrological conditions, e.g. increased groundwater abstraction, climate changes or damming. By using the approach presented in this study where hydrological models are combined with physical habitat models it is possible to quantify the impact on habitat conditions in relation to any indicator, be it fish, macro-invertebrates or macrophytes.

Impact on discharge

Groundwater abstraction reduces both discharge and the physical habitat conditions (WUA) in streams within the catchment where abstraction is taking place (Johnson *et al.* 1995; Strevens 1999). The impact of groundwater abstraction in Ledreborg stream is relatively high (37% reduction of median daily discharge and 82% reduction of 90th percentile) but comparable to the impact on many small streams in sandy-loam catchments in Denmark where groundwater abstraction is taking place (Henriksen & Sonnenborg 2003; Troldborg & Henriksen 2006). In general, the groundwater abstraction had a negative impact on stream discharge with the largest relative impact on summer flows and the largest absolute impact on winter flows. The same pattern has also been found for other Danish catchments with the same characteristics (Christensen 1993; Troldborg & Henriksen 2006). The largest relative effect on summer flow from groundwater abstraction is related to the fact that summer discharges in general are low and mainly consists of flow from the groundwater in these sandy-loam based catchments (Troldborg & Henriksen 2006).

Impact on physical habitat conditions

We expected physical habitat conditions for all life stages of trout to be negatively influenced by groundwater abstraction. However, even if groundwater abstraction had the greatest absolute impact on winter discharges, simulations predicted a neutral or slightly positive impact from groundwater abstraction on winter habitat conditions for trout. In contrast, summer habitat conditions were particularly negatively affected by groundwater abstraction. This finding supports the general idea that low flows caused by natural causes or groundwater abstraction has the largest impact on brown trout habitat conditions and populations during summer (Johnson *et al.* 1995; Elliott *et al.* 1997; Strevens 1999).

During summer, adult trout were predicted to be affected the most and fry the least by groundwater abstraction (Table 4). This finding contrasts with the findings of other studies where fry and juveniles were

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assessed to be most affected by groundwater abstraction (Johnson *et al.* 1995; Strevens 1999) or summer low flows (Elliott *et al.* 1997). The reason for this difference could be related to the fact that we are considering summer conditions in combination with the general poor habitat conditions for adult trout in small streams, compared to that of other life stages, even if discharge levels reached simulated reference conditions. Water depth is considered to be an important physical variable for trout habitat selection (Heggenes 1988; Heggenes *et al.* 1991; Crisp 1996; Armstrong *et al.* 2003) and lack of habitats with suitable water depths (>40 cm) seems to be the main reason for the low WUA for adult trout in Ledreborg stream (Rasmussen 2005). Although habitat conditions for adult trout are generally unfavourable in small streams, it is a useful indicator for the physical conditions in the deeper parts of the streams which is an essential part of the ideal stream and an important refuge for brown trout under low flow conditions (Elliott 2000).

The habitat model simulated the best physical habitat conditions for fry and juvenile trout, which is consistent with the notion that small streams like the Ledreborg stream often have reaches that are considered suitable as spawning and nursery areas for trout and the stream therefore has a management target as "Potential salmonid spawning and nursery area". This suggests that stream management targets and simulated physical habitat conditions correspond to each other, which is positive if habitat modelling is going to be implemented in Danish stream management.

On an annual basis physical habitat conditions for fry and juvenile trout were more affected by groundwater abstraction than habitat conditions for adult and spawning trout, which is similar to that found in other studies (Johnson *et al.* 1995; Strevens 1999). So, although size and type of water course has proven to affect trout habitat selection (Heggenes 1988) and the Ledreborg stream is much smaller (average width 2 m) than water courses in most other studies (e.g. 7.4 m for River Piddle (Strevens 1999)), it still seems like the young life stages are most vulnerable to groundwater abstraction on an annual basis. But the largest reductions of median physical habitat conditions for the young life stages appeared during summer where water levels were most reduced. The shape of the WUA curves for fry and juvenile trout means that even a small change in the lowest discharge can have a large impact on physical habitat conditions (Figure 7A,B). Therefore the young life stages are more vulnerable to additional reduction in discharge, e.g. caused by extended dry periods during summer. Although summer physical habitat conditions for fry and juvenile trout are less affected by groundwater abstraction than adult physical habitat conditions we still suggest they are used as indicators of groundwater abstraction impact, since spawning and nursery areas are the most important habitats in this type of stream in relation to the management target and these life stages are important for the future population (Elliott *et al.* 1997).

The simulated negative impact of groundwater abstraction on habitat conditions for trout match the general finding that flow reductions have a negative impact on stream biota, e.g. reduced invertebrate diversity (McKay & King 2006; Dewson *et al.* 2007).

Critical low discharges

This study revealed that lowest discharges are most impacted by groundwater abstraction and that the lowest discharges are also critical in relation to trout habitat conditions, especially during summer. This study also revealed that low discharges were poorly simulated by the hydrological model, which is also a problem in other hydrological models (Troldborg & Henriksen 2006; Olsen *et al.* 2008). Since small changes in the lowest discharges can have a severe effect on habitat conditions for stream biota simulations of low discharges should be improved if hydrological models are to be combined with habitat models in this kind of impact assessment of groundwater abstraction on stream biota.

Different conditions on different reaches

Simulation of the habitat conditions at different reaches clearly shows that there is a large difference in habitat conditions and the response to changes in discharge is also very different in the different reaches. This finding stresses the importance of selecting representative or critical reaches of the stream under habitat modelling (Bovee *et al.* 1998). Comparison of the selected reaches in this study

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shows that not all reaches are equally susceptible to reduction in discharge and not all reaches are equally suitable for the different life stages. It is therefore important to do initial surveys or to have prior knowledge of the stream in order to conduct meaningful habitat modelling, where the different types of habitats and responses to changes in discharge are included. Use of an objective method for selecting reaches and assessing the response in the reaches to changes in discharge would be valuable in a management context.

CONCLUSIONS

By combining a catchment hydrological model and an in-stream habitat model it was possible to assess if groundwater abstraction resulted in reduced physical habitat conditions in a small Danish stream, and what indicators and reaches in the stream were most affected. This study revealed that, although groundwater abstraction had the largest actual impact on winter discharges, the largest impact on physical habitat conditions for trout was during summer, where discharges are relatively most affected by groundwater abstraction. Groundwater abstraction had the greatest impact on simulated summer physical habitat conditions for adult trout in this small stream, but habitat conditions for adults were, in general, limited by suitable water depths even under reference condition discharge, i.e. without groundwater abstraction. This indicates that this stream type in general has a low suitability as a habitat for adult trout, and adult fish are, in general, poor indicators of habitat conditions in this type of stream. Physical habitat simulations revealed that the stream was most suited as a habitat for fry and juvenile trout, which is consistent with the general notion of this stream type and the management target of the stream as a spawning and rearing area for trout. Groundwater abstraction would make summer habitat conditions for fry and juvenile trout much more vulnerable to natural reductions in discharge. But a small increase in summer discharge could increase habitat conditions for fry and juvenile to nearly optimal levels. Finally we suggest that low flow simulations should be improved if hydrological models and in-stream habitat models are to be used to assess groundwater abstraction impact on stream biota.

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