The impact of discharge change on physical instream habitats and its response to river morphology

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Abstract The impact of climate-induced discharge change on fish habitats, based on 1951–2008 time series, was investigated within the crystalline catchment of the Grosse Mühl River in Northern Austria. A significant trend change of air temperature, based on *Mann–Whitney* statistical testing, was recorded for spring 1989 ($P=98.9$ %) and summer 1990 ($P=99.9$ %). This led to a pronounced increase in summer low flow periods. Hydrodynamic-numerical (one-dimensional/two-dimensional) modelling was applied to simulate the changing habitat characteristics due to decreasing discharge in relation to various morphological patterns (riffle-pool/plane-bed reaches). Using bathymetric data, which were sampled on cross sectional measurements, we clearly determined that plane-bed reaches (featureless bed forms) are sensitive to climate-related, reduced discharge, whereas riffle-pool reaches continued to exhibit suitable physical fish habitats even under extreme low-flow conditions. The impact of the decreased summer discharge on instream habitats was strong for subadult and adult grayling which have been used as target fish species. In situ measurements in microhabitats (velocity/depth) revealed habitat suitabilities. These values were taken as biotic input for habitat evaluation on the micro scale. The findings clearly show that river morphology is a decisive parameter in terms of habitat preservation and restoration in the context of the future impacts of climate change (decreased discharge).

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1 Introduction

Many rivers have already been substantially altered by human activity (Hirsch et al. 1990). Channelization, flow regulation, or changes in land use, especially urbanization, significantly alter the water discharge, sediment transport, and morphology of rivers (Ashmore and Church 2001). One aspect is the short-term impact of anthropogenic measures (e.g. river training, dredging) or of artificial changes in discharge regime on instream habitats (e.g. residual flow). Mid- to long-term impacts, however, especially altered run-off, may cause less visible but possibly continuous variation of hydro-morphological channel characteristics. Changes in run-off due to changes in land use have been investigated on both the global (Karl 2003) and the catchment scale (Pauleit et al. 2003; Lørup et al. 1998; Nadakumar and Mein 1996). The most significant changes in flow regime, however, occur where snowfall is reduced due to higher temperatures, increasing winter discharge but decreasing spring flow (Arnell 1999). In general, flow regimes are likely to change substantially with increases in global temperature because weather patterns, precipitation and evapotranspiration would be altered (Poff et al. 1996; Mulholland et al. 1997). The effects of land-use change are expected to dominate in smaller basins, where a large proportion of the basin area may be affected, leading to substantial changes in runoff and erosion throughout. In larger drainage basins, land-use change is seldom widespread enough to affect the entire basin, and climatic effects will dominate (Ashmore and Church 2001).

The consequences of climate change on river morphology are mainly documented in relation to an increase in storm flow activity (more precipitation; Schumm 2005). This increases channel width, thus affecting fine gravel- and gravel- (riffle-pool morphology) reaches more than boulder- or bed rock river reaches (Ashmore and Church 2001). Even small changes in average climatic conditions may cause major change in the infrequent, but large flood events that most affect river morphology (Knox 1983, 1993). Such single floods can have significant effects on channels (Hauer and Habersack 2009). Wohl (2000) listed the impacts of catastrophic floods, which can cause a variety of riverbed- and floodplain changes: bed-/bank erosion, deposition within the channel, growth of bars and islands, floodplain accretion, channel lateral shift, and instream habitat change. With time, however, the channel can recover (Turner et al. 2001) and revert back to its pre-flood river morphology. Some morphological types (e.g. plane-bed channels with coarse material) exhibit slower recovery times (Ashmore and Church 2001).

A neglected but crucial aspect is the impact of discharge change (in terms of flow decrease) on instream habitats and its response to various morphological patterns. In analysing such interactions, two types of morphological bed forms (riffle-pool/plane-bed) are particularly important from the aquatic ecology perspective. Plane-bed and riffle-pool morphologies (Montgomery and Buffington 1997), which are found across various morphological patterns (straight, braided and meandering rivers), typically have a higher abundance of aquatic organisms than headwaters streams featuring step-pool and cascade channel reach morphology (Jungwirth et al. 2003). Thus, the European Commission focuses on those reaches when attempting to preserve or achieve the good ecological status related to the European Water Framework Directive (NGP 2010). Riffle-pool reaches are characterised by an undulating bed that defines a sequence of bars, pools and riffles (Leopold et al. 1964). Riffle-pool channels occur at moderate to low gradients, are generally unconfined and have well-developed floodplains (Montgomery and Buffington 1997). Habitat diversity on the meso-unit scale provides, beyond riffle and pool habitats, a variety of hydraulically significantly different habitat types including shallow water, backwater, run, and fast run units (Hauer et al. 2011a). Plane-bed rivers are the planar bed phases in sand-bed channels

(Simons et al. 1965) as well as the planar gravel and cobble bed form channel characteristics (Florsheim 1985; Lane and Carlson 1953). In terms of instream (meso-)habitats, plane-bed reaches exhibit mainly glide (run), riffle, and rapid hydro-morphological units (Montgomery and Buffington 1997).

For sediment transport a change in discharge involves a change in the concentrations of bed material load (Q_{bm}) and wash load (Q_W), depending on the extent to which sediment supply to the river is altered (Ashmore and Church 2001). Such changes in sediment supply are an additional conceivable, but less likely, outcome of climate change (e.g. increased sediment delivery due to melting of glaciers). More likely are the effects of land-use change (e.g. increased fine sediment supply due to agricultural land use and land drainage). Furthermore, less run-off as the result of a warmer climate may also reduce land cover, which increases rather than reduces the fine sediment supply (Knox 1983).

Beyond altered river morphology and sediment transport, which directly affects instream habitat patterns, (climate-induced) discharge changes also impact stream temperature (due to higher air temperature). Fishes are homoeothermic, and processes that structure fish assemblages are therefore closely linked to water temperature (Varley 1967). Warming of rivers will no doubt affect fishes (especially salmonids) by exceeding temperature preferences and tolerances (Hari et al. 2006). Increased stream temperatures, however, are one of the primary (Mattula et al. 2007), but not the sole potential outcomes of a rapidly changing climate. Reduced snowpack, earlier spring runoff, reduced summer flows, increased floods, and drought will pose additional stressors for freshwater fish populations (Clark et al. 2001; Poff et al. 2002). Hydrologic variability in general can strongly affect fish assemblage structure (e.g. Bêche et al. 2009). In examining climate warming, Flebbe et al. (2006) found significant losses and increased population fragmentation, as fish retreated to remaining cooler waters in headwater stream reaches (Williams et al. 2009).

Most studies so far have investigated the many factors independently, for example the impact of (climate-induced) run-off change on river morphology and/or sediment load (e.g. Knox 1983), or the impact of discharge changes on aquatic ecology (e.g. response of fish) (Poff et al. 2002). A gap in our knowledge remains about how (climate-/land-use-induced) discharge changes impact instream aquatic habitats with regard to various morphological patterns (e.g. riffle-pool morphology vs. plane-bed river).

Thus, the paper investigates the linkage between possible discharge changes, river morphology and instream habitats with the following hypotheses: (i) significant changes in (summer) air temperature trends will trigger significant changes in discharge (which directly impact instream habitats) for the investigated study site and (ii) differences in habitat quantity (for selected target fish species) will occur for variable river morphology (riffle-pool vs. plane-bed reaches) if discharge changes.

2 Study reach

The Grosse (Gr.) Mühl River originates in the German part of the Bohemian mountains (1160 m.a.sl) (Fig. 1). The river drains an area of 559.9 km^2 over a length of 71 km and discharges into the Austrian Danube at Untermühl (Wagner and Trumler 1997). Applying the typology of Montgomery and Buffington (1997) the river morphology is classified, in most reaches, as a plane-bed river (no discrete bars, dominating substrate: cobbles, sand), whereby locally some meander or curved sections (e.g. Hinteranger) with riffle-pool morphology occur in former fine material deposits of the Tertiary (23.8–1.8 million years before present) (Gruber 1928). Most of the bed-forming material, however, is much older than
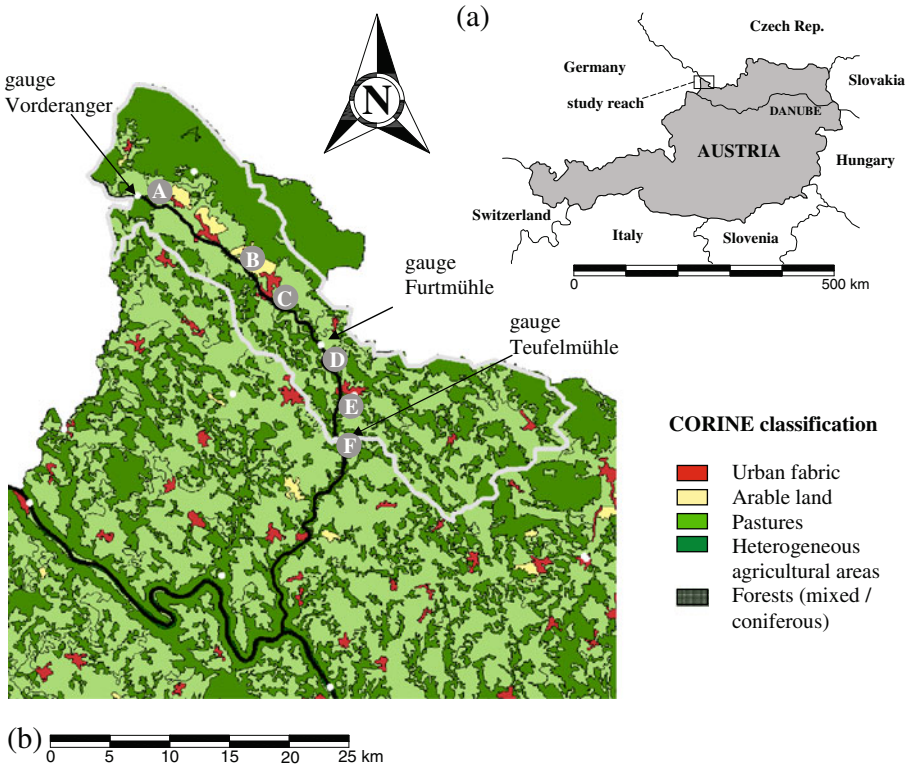
Fig. 1 **a** Große Mühl River catchment in Upper Austria close to the German and Czech Republic border. **b** Investigated river catchment with gauging stations (*n*=3) and reaches of detailed investigation highlighted (A–F) using the CORINE land use classification map

those deposited sediments. The basic geological features of the Gr. Mühl River catchment, as part of the Bohemian Massif, were formed about 300 million years ago in the Devonian and Permian. The longitudinal continuum of the river is partially disturbed by small hydropower plants which were historically used as mills (Bertlwieser 1999). Thus, the hydro-morphological classification of the 34.2-km-long investigated (Austrian) reach shows 24.9 % riffle-pool reaches, 53.6 % plane-bed sections, 14.8 % backwater effects (by weirs) and 6.7 % residual flow units (*n*=6) due to hydropower production.

Land use within the Gr. Mühl River catchment is dominated by forests (mixed and coniferous), followed by heterogeneous agricultural areas (according to CORINE classifi-cation) (Fig. 1b). Small settlements (classified as urban fabric) are located along the river with numbers of inhabitants <3,100. Comparing CORINE land-cover data of 1990 and 2000 revealed no quantitative change in classified units (e.g. no increase in agricultural areas). The mean annual temperature is about 5 to 6 °C with a January mean of −3 to −4 °C and mean summer temperatures (July) of 15 to 16 °C (Fuchs et al. 2003). However, the southern/south-western mountain sites exhibit somewhat above-average temperatures accompanied by higher precipitation rates. The annual precipitation rate for the investigated catchment is about 1,000 mm, with maximum outliers (2,000 mm) at the top of the mountainous ridge (Plöckenstein) (HAÖ 2007). The study reach is influenced by both the oceanic and conti-nental European climate, exhibiting variable conditions between different topographic units

(Haslinger 2009). Whereas the mountainous areas are mainly dominated by the oceanic climate (cool, wetting conditions with minor yearly deviations), the valley regions are more continentally influenced (higher amplitudes between summer and winter) due to discontinuous variations of the NAO (North Atlantic Oscillation)-index (Schönwiese 2008; Hurrel and Van Loon 1997). The flow regime of the Gr. Mühl River is defined as nivo-pluvial (Mader et al. 1996). Discharge characteristics are presented in Table 1 for the three gauging stations Q_Vorderanger (1966–2008), Q_Furtmühle (1951–2008), and Q_Teufelmühle (1951–2008), which are located at the upstream end (N:48°41′58″/E:13°50′35″, catchment size: 125.3 km^2), in the middle (N:48°36′13″/E:14°01′15″, catchment size: 256.4 km^2) and on the downstream end (N:48°32′33″/14°02′02″, catchment size: 435.5 km^2) of the investigated Gr. Mühl River section (entire reach 34.2 km) (Fig. 1b).

The fish region is classified as metarhithral (lower trout zone), with brown trout (*Salmo trutta ff.*), stone loach (*Barbatula barbatula*) and bullhead (*Cottus gobio*) as the main fish species. Less common and dominant, but still typical species are European grayling (*Thymallus thymallus*), European minnow (*Phoxinus phoxinus*), barbel (*Barbus barbus*), nase (*Chondrostoma nasus*) and pike (*Esox lucius*) (BAW 2009). Historically (notes of the monastery Schlägl; 1707 A.D.), however, grayling was documented as being the most abundant species (814 caught individuals) compared to other fish species such as brown trout (293 caught individuals) (Zick 2003).

For a detailed investigation of the impacts of possible discharge change on physical instream habitats, six different river sites were selected (Figs. 1, 2). Three of them are located in reaches containing riffle-pool morphology (Vorderanger (N:48°41′54″/E:13°51′06″), Damreith (N:48°36′06″/E:14°01′21″), Teufelmühle (N:48°32′40″/E:14°01′57″)), whereas three sites exhibit plane-bed characteristics (Bruckhäuser (N:48°39′18″/E:13°56′36″), Bruckmühle (N:48°37′42″/E:13°58′45″), Haslach (N:48°34′04″/E:14°02′07″)). All sites feature straight and meandering channel patterns (Muhar et al. 1998). Within this paper the specific reaches (*n*=6) are described by their local names (e.g. Vorderanger) and/or their short ID (A–F) (Fig. 1b).

3 Methods

3.1 Statistical testing of meteorological/hydrological data

Meteorological and hydrological data were analysed to determine those potential trend changes (e.g. decrease in discharge) on the sectional scale that might influence

Table 1 Hydrological data of the Gr. Mühl River. Gauging data are related to various time series (a) gauge Vorderanger (1966–2006), (b) gauge Furtmühle (1951–2006), (c) gauge Teufelmühle (1951–2006)
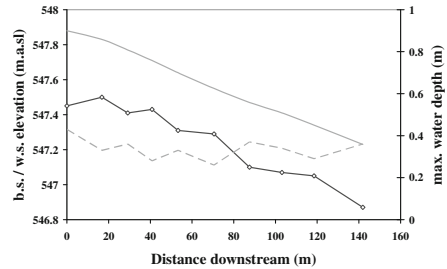
Gauge catchment area	Vorderanger (125.3 km^2)	Furtmühle (256.4 km^2)	Teufelmühle (435.5 km^2)
NNQ (m^3 s^{-1})	0.43	0.61	1.09
NQ (m^3 s^{-1})	0.96	1.47	2.34
MQ (m^3 s^{-1})	2.98	5.45	8.64
HQ (m^3 s^{-1})	33.0	47.8	71.3
HHQ (m^3 s^{-1})	65.9	94.9	155.0

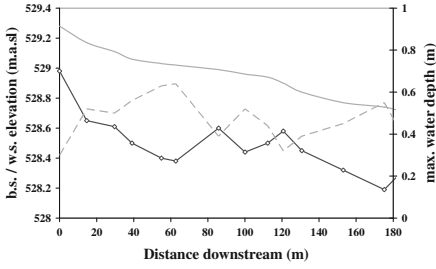*NNQ* lowest recorded flow, *NQ* mean low flow, *MQ* mean flow, *HQ* mean annual flood, *HHQ* highest recorded flood
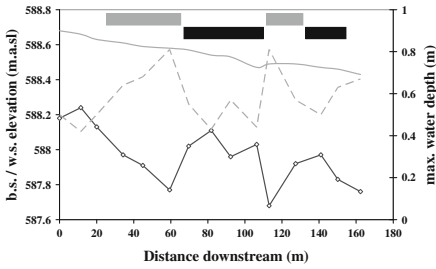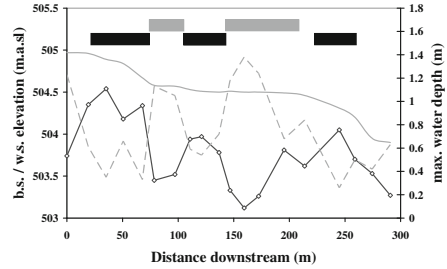
Fig. 2 Longitudinal profile plots of the modelling reaches (**a**) Vorderanger, (**b**) Bruckhäuser, (**c**) Bruckmühle, (**d**) Damreith, (**e**) Haslach and (**f**) Teufelmühle showing bed surface (*black solid line with white squares*), water surface for $MNQT_{July}$ (*grey solid line*) and maximum water depth $MNQT_{July}$ (*grey dashed line*; second y-axis); riffles are highlighted in *black* and pool sites in *grey bars*; b.s.=bed surface, w.s.=water surface, max.=maximum

physical instream habitats for selected target species. Time series (daily mean data) of air temperature (1948–2006; T_Kollerschlag: N:48°36′18″/E:13°50′30″) were taken, along with discharge data of three gauging stations. A break-point analysis (*Mann–Whitney*) was conducted to determine points in time with possible (significant) changes in parameter trends (discharge, temperature). This statistical test determines points within a continuous time series (on the x-axis) for which the probability (P) for trend changes is given (significant change $P > 95$ %). This analysis was carried out

with the software TESTEN (University of Karlsruhe 2009) using the following test statistic (Pettitt 1979):

$$U_{k,n} = \sum_{i=1}^{k} \sum_{j=k+1}^{n} sign(x_i - x_j) \qquad (1)$$

$$K_n = \max_{1 \leq k \leq n} |U_{k,n}| \qquad (2)$$

where: K_n=test statistics, $U_{k,n}$=sum of algebraic sign, n=entire period of time series, k=continuous time index;

The probable break-point is given for time step k, for which the test statistic K_n exhibits its maximum. The probability of the breakpoint is estimated according to Eq. 3:

$$P = \exp\left(\frac{-6 \cdot K_n^2}{n^3 + n^2}\right) \qquad (3)$$

Long-term trends in highly variable data may be identified by plotting cumulative departure from the mean. This method was used here to analyse time series data (discharge, temperature) if a sequence of above-average years appears as an upward trend or a sequence of below-average years appears as a downward trend. No changes in trends yield a flat plot showing a period of average conditions. Further statistical testing was conducted based on *Mann-Kendall*, highlighting if there is an increase (+) or a decrease (-) in mean for parameters (air temperature, discharge) in case of determined break-points. Beyond the catchment-scale hydrological analysis, hydrodynamic-numerical models helped to evaluate the hydro-morphological characteristics of the various study reaches (n=6) and/or provided the decisive parameters (depth-averaged velocity, water depth) for modelling instream habitats on the sectional scale. To derive geometric input data for the numerical models, a terrestrial survey (by total station Leica TC 805) of the study reaches (Fig. 1c) was conducted on 3/4 June 2009 (reach A, reach B) and additionally on 23/24/25 June 2009 (reach C, D, E, and F).

3.2 Terrain sampling and model description

Terrain data were detected by cross sectional measurements (n=84 in total). Additionally, points were sampled to generate high-quality Digital Terrain Models (DTMs), which were used as pre-processing data for numerical studies (e.g. Fig. 3a–b). The range of the average density of sampled terrain points was one point/12.5 m^2 (reach Vorderanger) up to one/point 27 m^2 (reach Teufelmühle). For hydrodynamic-numerical modelling, a one-dimensional and a two-dimensional modelling approach were selected. Resistance to flow in the form of roughness is a boundary condition in both the one- and two-dimensional hydrodynamic numerical models and had to be calibrated for the 6 sites. Bed roughness (sum of grain and form roughness) was assumed to be constant within each riffle-pool and/or plane-bed reach for the one- and two-dimensional modelling approach for various discharges. For one-dimensional modelling of each investigated reach (n=6), the unsteady flow model HEC-RAS® was used. The model was chosen because of its capabilities for sub-/supercritical modelling (USACE 2002) and for multifunctional parameter analysis for overbank- and main channel flow. In the 6 selected reaches (Fig. 3, Table 2) featuring riffle-pool and plane-
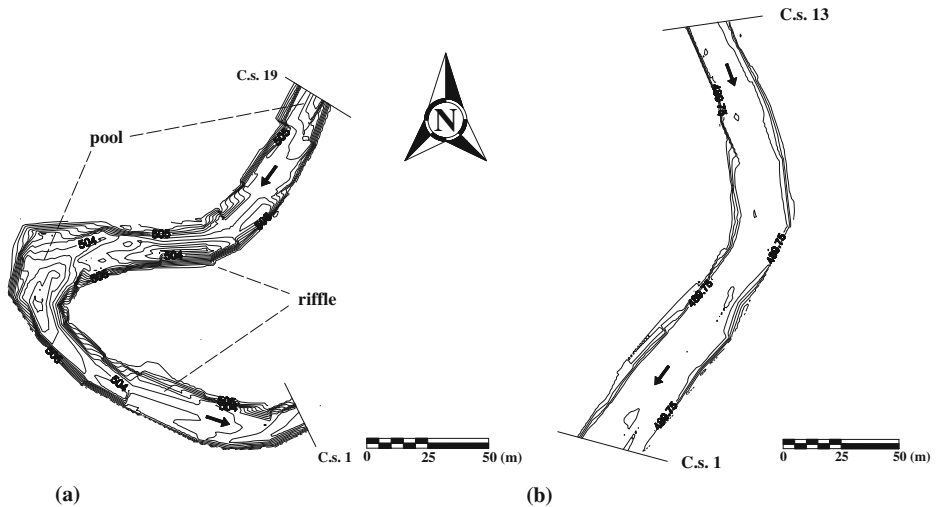
Fig. 3 Examples of Digital Terrain Models (DTMs) used for two-dimensional hydrodynamic-numerical habitat modelling highlighting riffle-pool mesounits; **a** reach C, Damreith, **b** reach E, Haslach; C.s.=cross section

bed morphology, numerical modelling was based on a total of 84 cross sections (measured cross sections). The length of the 6 reaches varied between 141.9 m (reach B) and 290.8 m (reach D) (mean: 199.3 m/SE: 47.3 m). The number of cross sections varied from 10 to 19 in each investigated reach, depending on site length. Cross sections were spaced between 7.7 m and 26.7 m (average 15.4 m/SE: 4.6 m) with an average number of 16 sampled terrain points (range: 12–23), so that water surface slope changed only minimally between the cross sections. One-dimensional analysis was conducted to hydro-morphologically characterise the reaches based on the variance of width (m) and maximum depth (m). Both parameters reliably described habitat diversity (Jungwirth et al. 1993). The two-dimensional depth-averaged hydrodynamic-numerical model (Hydro_AS-2d; Nujic 1999) was applied as a pre-processing tool for numerical habitat modelling. It delivered information about depth-averaged velocity (ms^{-1}), water depth (m) and bottom shear stress (Nm^{-2}) on each mesh node.

Table 2 Hydrological characteristics (monthly average low flow) of the modelled reaches

	c.size (km^2)	MNQT_June ($m^3\ s^{-1}$)	MNQT_July ($m^3\ s^{-1}$)	MNQT_August ($m^3\ s^{-1}$)
reach_1 Vorderanger	125.3	1.41	1.32	1.19
reach_2 Bruckhäuser*	200.4	2.09	1.91	2.45
reach_3 Bruckmühle*	236.0	2.31	2.10	2.70
reach_4 Damreith	256.4	2.68	2.39	3.85
reach_5 Haslach*	394.3	3.61	3.32	4.10
reach_6 Teufelmühle	453.5	4.08	3.85	3.49

c.size catchment size; *=MNQT (mean monthly low flow) calculated according to Wundt (1950)

3.3 Hydrological analysis

Hydrological input data for numerical modelling, characterising those discharge scenarios which are decisive for instream habitats, were determined according to the gauge statistics (using the time period 1951–2006 for Q_Furtmühle and Q_Teufelmühle and/or 1966–2006 for Q_Vorderanger). Mean flow (Q_M) and low flow (Q_L) were modelled for the reaches; summer discharge characteristics (June, July and August) were described by the MNQT (statistically mean monthly low flow). As only three modelling sites are located close to gauging stations (reaches A, D, E), hydrological data (Q_M, MNQT, and Q_L) had to be interpolated for the remaining reaches ($n=3$) according to Wundt (1950), whereas A_E was used as the scaling factor; (Eq. 4).

$$Q = 13.8 \cdot f \cdot A_E^{0.6} \tag{4}$$

where: Q=discharge ($m^3\ s^{-1}$), f=run-off coefficient ($m*10^{-6}\ s^{-1}$), A_E=catchment size at the point of interest (km^2);

Thus, based on five flow simulations for each reach (Q_M, $MNQT_{June}$, $MNQT_{July}$, $MNQT_{August}$, and Q_L), 30 one-dimensional and 30 two-dimensional model runs were performed; these were extended (for habitat sensitivity testing) by 8 additional two-dimensional simulations for each section ($n=48$).

3.4 Hydrodynamic-numerical modelling

Overall, 78 two-dimensional model runs were conducted using the Hydro_AS-2d software, developed by Nujic (1999). Hydro_AS-2d calculates the hydraulic conditions on a linear grid by a finite volume approach and uses the Surface Modelling System (SMS) model as a pre- and post-processing tool. The convective flow of the two-dimensional model is based on the Upwind-scheme by Pironneau (1989) and the discretisation of time is done by an explicit Runge Kutta method in second order. The simulations were performed with the parabolic eddy viscosity model and a constant turbulent viscosity coefficient of 0.6; computation time was set as 20,000 to achieve steady state conditions for the modelling discharges (Q_M, $MNQT_x$, Q_L plus eight discrete discharges between Q_L and Q_M) in the various reaches; depth criteria were set to 0.01 m for wetting/drying computations.

3.5 Habitat modelling

For habitat modelling, habitat suitability with regard to water depth (m) and flow velocity (ms^{-1}) were derived for the selected target species (sub-adult/adult grayling). Those suitability curves were defined on expert judgement (based on existing literature for summer habitat use; e.g. Vehanen et al. 2003) and were further amended by measured abiotic habitat characteristics at the Gr. Mühl River. Thus, habitat characteristic for subadult/adult grayling was determined visually (from banks and by underwater video camera) in the field (June/July, 2009), accompanied by measurement of water depth (m), mean flow velocity (ms^{-1}) and nose velocity (ms^{-1}) at the recorded micro-habitats. Visibility from banks and partially bridges was good due to low suspended load concentration during summer low flows. On the one hand water depth of nose position was estimated due to fish position related to bed surface on the other hand fish length (grouped into 5 cm classes) was estimated due to comparison fish length with bed surface material (grain size determined during velocity measurements). In general so-called suitability curves indicate the suitability of habitats

based on a single parameter. They are computed from empirical frequency distributions, which are standardised based on the most strongly occupied class (Bovee and Cochnauer 1977; Bozek and Rahel 1992). The class with the largest frequency (highest suitability) receives a suitability index (SI) value of 1. All further classes are weighted based on this. The unused classes have a SI of 0. For determining water depth at the documented micro-habitats of subadult/adult grayling, a depth stick was used (200 cm entire length/1 cm interval). The P.-EMS (Delft Hydraulics 2006) was applied to measure flow velocities (nose velocity/depth-averaged) in a 2D-plane. Data were transported to data-acquisition equipment (LabVIEW®). The P.-EMS measures flow velocity within a range of 0–2.5 ms^{-1} (optional 0–5.0 ms^{-1}) bi-axially in a four quadrant range. We calculated the entire habitat suitability of available instream habitats for grayling within the reaches by multiplying discrete suitability indices (velocity/depth) according to the PHABSIM approach (Gard 2005; Williams 1996; Gibbins et al. 2002). Further spatial quantification involved using the Weighted Usable Area (WUA) method (Bovee 1986) (Eq. 5).

$$WUA = \sum_{i=1}^{n} HSI_i \cdot A_i \qquad (5)$$

where: n=total number of grid cells (–), HSI$_i$=habitat suitability index (–), A$_i$=area of single grid cells (m^2);

Parameter sensitivity to discharge change was determined by calculating WUAs by 1) a combined analysis of velocity/depth suitability, and 2) a discrete water depth analysis (only depth suitability used). Comparative between-reach habitat modelling results involved deriving a specific Habitat Suitability (–) due to the variability in study reach length (Eq. 6).

$$spec \cdot HSI_i = \frac{WUA_i}{A_i} \qquad (6)$$

where: spec. HSI$_i$=specific Habitat Suitability for discharge i (–), WUA$_i$=weighted useable area for discharge i (m^2), A$_i$=wetted Area for discharge i (m^2);

4 Results

4.1 Statistical testing of meteorological/hydrological data

Long-term recorded data (temperature/discharge) were statistically tested to determine possible trend changes. Two different time resolutions of the hydrological year (seasons and entire year) were considered. Initially, in a first statistical (*Mann–Whitney*) step, meteorological seasons (spring, summer, autumn, winter) were merged (Table 3). Air temperature time series in spring (March, April, May) exhibited a significant change in trend (increase) for 1989 (*P*=98.9 %). This was similar to the summer series, which highlighted the year 1990 as a breakpoint for significant temperature increase (*P*= 99.9 %). No significant temperature increase was found for the autumn series. This contrasts to the winter data (December, January, February), which exhibited a significant temperature break-point for 1971 (*P*=98.3 %). Seasonal discharge at the three gauging stations showed three discrete dates of trend changes (Table 3). In the spring analysis, 1999 was breakpoint (statistically not significant: *P*=59.1 %–89.8 %) for increasing discharge. Summer discharge decreased (partially significant) in the early 1980s (*P*=86.9 %–99.9 %), with a decreased for mean summer discharge for Q_Vorderanger from 2.53 m^3 s^{-1} (period 1966–1982) to

Table 3 Determination of statistically significant changes in trends (*P*>95 %) using *Mann-Whitney* testing for break-points and/or changes in trends (*P*>95 %) for the annual number of days below MNQT; significant changes in bold

	T_Kollerschlag[a]		Q_Vorderanger[b]		Q_Furtmühle[c]		Q_Teufelmühle[c]	
	year	P (%)	year	P (%)	year	P (%)	year	P (%)
Seasons								
Spring	**1989**	**98.9 (+)**	1999	89.8 (+)	1999	71.6 (+)	1999	59.1 (+)
Summer	**1990**	**99.9 (+)**	1983	86.9 (–)	**1982**	**98.8 (–)**	**1981**	**99.9 (–)**
Autumn	1999	66.8 (+)	—	—	—	—	—	—
Winter	**1971**	**98.3 (+)**	1974	73.4 (+)	**1974**	**97.3 (+)**	**1974**	**96.6 (+)**
			1980[d]	41.3			1996[d]	41.4[d]
Year	**1988**	**99.7 (+)**	2006	65.4 (+)	—	—	1982	44.2 (–)
Months								
June			**1989**	**98.6 (+)**	1989	99.2 (+)	1989	85.1 (+)
July			1989	94.1 (+)	1989	98.0 (+)	1981	93.4 (+)
August			**1990**	**98.7 (+)**	1990	98.6 (+)	1981	91.6 (+)
Seasons								
Summer			**1990**	**98.7 (+)**	1990	99.4 (+)	1981	90.7 (+)

[a] temperature monitoring (°C) 1948–2006

[b] recorded discharges (1966–2008)

[c] recorded discharges (1951–2008)

[d] second break-point calculated

(+/–)=increase/decrease in means following the breakpoint;

2.14 m^3 s^{-1} (period 1983–2008). Gauge Furtmühle exhibited a decrease in mean summer discharge from 4.8 m^3 s^{-1} (period 1951–1981) to 3.5 m^3 s^{-1} (period 1982–2008) as well as Q_Teufelmühle with a decrease from 8.1 m^3 s^{-1} (period 1951–1980) to 5.5 m^3 s^{-1} (period 1981–2008). Additionally the winter discharge series showed (significant) trend changes in 1974, increase in discharge, with a possible second break−point in 1980 (gauge Vorderanger) and 1996 (gauge Teufelmühle). No trend change occurred for autumn discharge (*n*=3). Seasonal comparisons between temperature and discharge change, however, were not correlated according to points in time of the trend change. Thus, the mean annual data contained no signal of trend change in discharge that could be related to a signal in temperature trend (Table 3).

The focus of this study, however, is on (summer) low-flow periods that might limit the physical instream habitat. Therefore, the cumulative deviation of the mean is additionally presented for summer air temperature data (Fig. 4a). The values (T_Kollerschlag, Fig. 4a) clearly indicate three time periods with different air temperature developments; one period with temperature below average (until 1980), the second between 1980 and 1990 (temperatures around the mean) and a third period with an increase in average summer temperature from 1990 on (mean before 1990: 15.6 °C; mean after 1990: 17.0 °C). In order to show possible impacts of temperature change on discharge the cumulative deviation of the mean summer discharge is also depicted for the three gauging stations (Fig. 4b–d). Trend changes (for reduced discharge) are evident in the early 1980s, however, with distinctly reduced discharge from 1990 on (Fig. 4b–d). This pronounced decrease (since 1990), in the graphical analysis supports our first hypothesis that changes in temperature trends trigger discharge
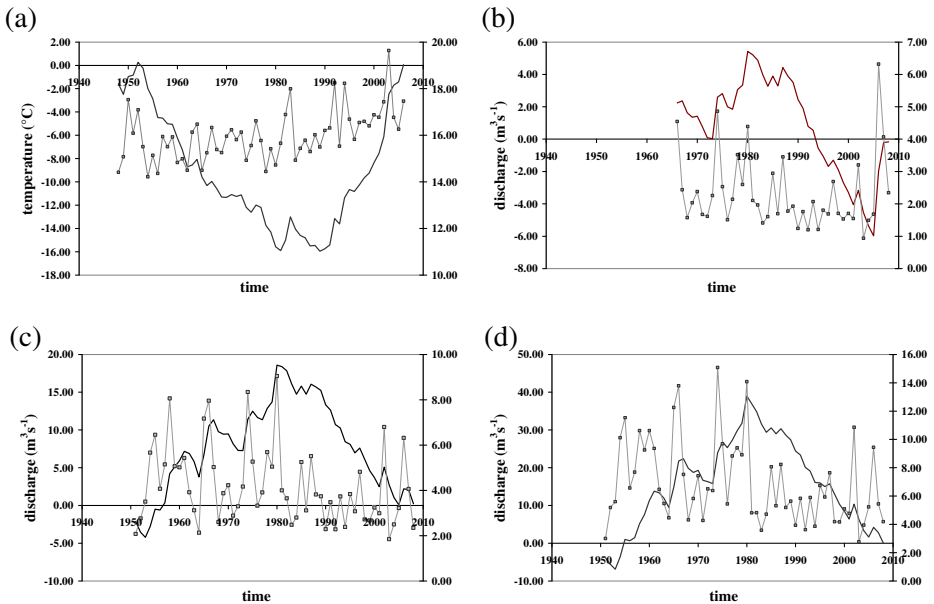
Fig. 4 Cumulative deviation from the mean (*black solid line*) and recorded data (*grey solid line*) for (**a**) summer temperature, (**b**) summer discharge (*gauge Vorderanger*), (**c**) summer discharge (*gauge Furtmühle*) and (**d**) summer discharge (*gauge Teufelmühle*)

changes. This was further tested based on the cumulative deviation of the mean for the annual number of days below MNQT (June, July, August) for the three gauging stations (Q_Vorderanger, Q_Furtmühle, Q_Teufelmühle), representing the occurrence of low flow periods (Fig. 7a–c). The frequency of those periods increased in the early 1990s for the entire set of gauging stations ($n=3$), corresponding with higher air temperatures (Fig. 4a, Table 3). Break-point testing (*Mann–Whitney*) exhibited an (mostly significant) increase in annual days below MNQT for the June, July and August data of Q_Vorderanger and Q_Furtmühle during the years of 1989 and 1990 (94.1 %<P<99.2 %), leading to a significant increase in summer low flow periods since 1990 ($P=98.7$ % Q_Vorderanger; $P=99.4$ % Q_Furtmühle). Moreover, regression analysis in Fig. 5 for the cumulative deviation of the mean for summer air temperature and mean summer discharge emphasised this correlation by $R^2=0.75$ (Q_Vorderanger), $R^2=0.88$ (Q_Furtmühle), and $R^2=0.87$ (Q_Teufelmühle). Thus, in a summarized view, the impact of an increased air temperature features not a correlation to the point in time of trend change for mean (seasonal, annual) discharge data. However, the signal of increased (summer) temperature was related to thresholds in discharge which causes an increase in low flow (drought) periods since 1990 (given by the number of days below MNQT) (Figs. 4, and 7, Table 3). Exceptions are July and August data at Teufelmühle (downstream of the major tributary Steinerne Mühl River): there, the increased frequency of annual days below MNQT first began in 1981 (Table 3) leading to a non-significant break-point ($P=90.7$ %) for the entire summer data for gauging station Teufelmühle.

4.2 Hydrodynamic-numerical modelling

To link catchment-scale changes in discharge with possible impacts on instream habitats on the sectional scale, hydrodynamic-numerical modelling (1D/2D) was applied to the three
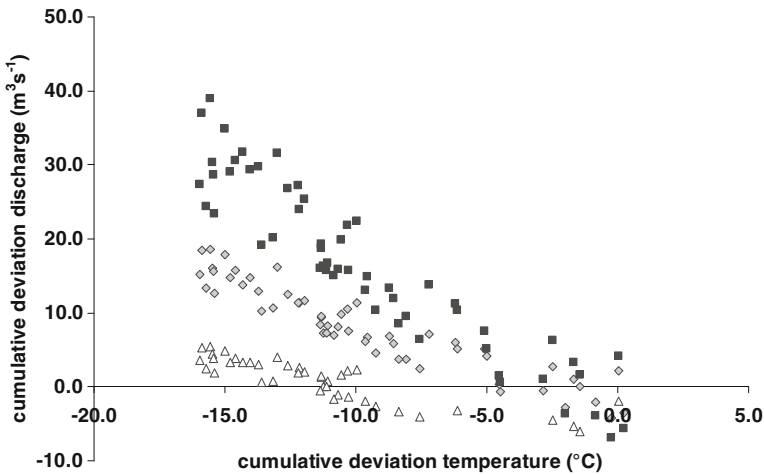
Fig. 5 Correlation analysis of annual deviation of the mean for summer air temperature (y-axis) and summer discharge (x-axis); *white triangles*=Q_Vorderanger, *grey square*=Q_Furtmühle, *black square*=Q_Teufelmühle

selected riffle-pool (reaches A, D, F) and three typical plane-bed sections (reaches B, C, E) of the Gr. Mühl River. The calibration process for low flow conditions (1.42–3.13 m^3 s^{-1}) yielded good agreement between the measured and calculated water surface elevations: most of the water surface differences were below +/-4 cm and exhibiting maximum outliers of 8 cm. The calibrated roughness for 6 sections ranged from n=0.053 to n=0.042 for the one-dimensional and n=0.048 to n=0.038 for the two-dimensional model. At first, one-dimensional numerical modelling allowed cross-section-based results of width- and maximum flow depth variance. Reach A (Vorderanger; average bed slope 0.002), containing riffle-pool morphology, had a width variance of 2.35 m^2 and a depth variance of 0.12 m^2 at low flow (Q_L). Modelling results are similar to Q_M (Table 4). The second riffle-pool section of reach D was modelled as having 5.04 m^2 width variance for Q_L, slightly decreasing for mean flow (Table 4). The third investigated reach, containing riffle-pool morphology, showed distinct deviation between variance in width for low flow and mean flow. That deviation was less obvious for the variance in depth (Table 4). Plane-bed reaches, however, exhibited less variability in depth and width variance. Reach B (Bruckhäuser) featured low variance in depth for both, low- and mean flow, as well as low variance in depth too. Similar

Table 4 Hydro-morphological characteristics of the investigated river reaches (n=6) based on one-dimensional hydrodynamic-numerical modelling

|	Q_L	Q_M	Q_L	Q_M	Q_L	Q_M
	Vorderanger		Bruckhäuser		Bruckmühle	
var_width (m^2)	2.35	2.38	0.41	0.62	1.09	0.04
var_depth (m^2)	0.12	0.12	0.03	0.05	0.04	0.09
	Damreith		Haslach		Teufelmühle	
var_width (m^2)	5.04	4.76	2.40	3.78	4.16	2.58
var_depth (m^2)	0.32	0.35	0.09	0.06	0.14	0.19

var_width variance in width, *var_depth* variance in depth, Q_L mean annual low flow, Q_M mean flow

results were modelled (based on the one-dimensional approach) for reach C, featuring a low depth variability (Q_L=0.04 m^2/Q_M=0.09 m^2) and a low variability in maximum cross sectional width (Table 4). Only reach E showed a higher variance in width similar to riffle-pool sites (Table 4), whereas the featureless characteristics (e.g. lack of discrete bars) of the plane-bed reach exhibited a low depth variance for both Q_L (0.09 m^2) and Q_M (0.06 m^2). Moreover, two-dimensional hydrodynamic-numerical modelling (Hydro_AS-2d) was conducted to derive basic abiotic parameters (depth-averaged velocity/depth) for habitat modelling. Beyond such abiotic input, fundamental ecological knowledge of target fish species is necessary to model instream habitats. According to the PHABSIM approach, biotic input must be delivered in form of suitability (SI) curves.

4.3 Habitat modelling

Habitat suitability (velocity/depth) for subadult/adult grayling was determined based on existing instream habitat studies and were supplemented by measured on-site habitat characteristics. Grayling habitats at the Gr. Mühl River were appointed visually in the field (June/July, 2009), accompanied by measurement of water depth (m), mean flow velocity (ms^{-1}) and nose velocity (ms^{-1}) at the recorded micro-habitats. A total of 18 grayling habitats were observed and analysed. Abiotic characteristics are presented in Fig. 6. Water depth ranged from 0.33 m to 0.95 m (mean: 0.67 m), exhibiting a deviation of 0.39 m with the 25 % and 75 % quantile (n=18). Mean flow velocities had a broader range (−0.05–0.8 ms^{-1}) than the nose velocity delineation (0.12–0.60 ms^{-1}). Within the 25 % and 75 % quantile range, however, the mean flow velocities were classified similar to the recorded nose velocities (n= 18) (Fig. 6). The outlier within the mean velocities (−0.05 ms^{-1}) occurred because one subadult (male, approx. 25 cm) selected a habitat position directly behind a boulder which created secondary currents along the vertical velocity profile. However, the average mean velocity (0.38 ms^{-1}) and average nose velocity (0.36 ms^{-1}) deviated only minimally. The information from the few micro-habitat samples (n=18) was amended by information of habitat use (flow velocity, water depth) based on literature data (Nykänen et al. 2001; Vehanen et al. 2003; Nykänen et al. 2004) to determine grayling suitability curves. These curves were used as biotic input to evaluate the sensitivity of discharge change in relation to

Fig. 6 Measured abiotic characteristics (water depth, mean velocity, nose velocity) of subadult/adult grayling microhabitats (n= 18) at the Gr. Mühl River during summer; box plot graphics show median, 10th, 25th, 75th and 90th percentile
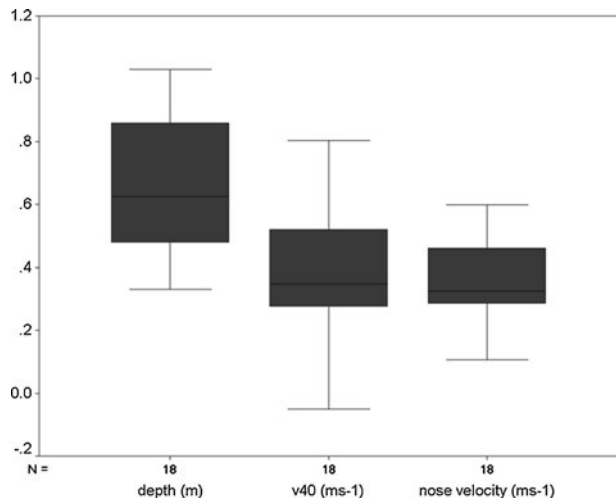
river-morphology (riffle-pool vs. plane-bed). The derived suitability indices (curves) are presented in Table 5 (for mean flow velocity and for water depth). As opposed to the measured habitat data the water depth exhibits a high suitability (SI =1) continuously from 0.5 m upward without an upper limit (e.g. 1.5 m=SI 1). The modification was done based on the matter of fact, that, especially for adult grayling, higher water depths were found to be best suitable in literature (e.g. Nykänen et al. 2001). Mean flow velocity, however, was restricted for being suitable within the range of 0.15 ms^{-1} to 1.0 ms^{-1} featuring the highest suitability (SI=1) between 0.25 ms^{-1} and 45 ms^{-1} (Fig. 6), (Table 5).

Habitat modelling was conducted to test our second hypothesis. Here we evaluated the impact of altered discharge on instream habitats of subadult/adult grayling in response to various morphological patterns (riffle-pool, plane-bed). Various discharge scenarios were selected (especially for summer) to characterize the effect of a downward trend. Specific habitat suitability (spec. HSI) is presented (Fig. 8) for mean discharge (Q_M), MNQT$_{July}$ and Q_L. Modelling results are depict for both approaches velocity/depth (v/d) combined, and separately for water depth (d). Figure 8 clearly reveals a difference between riffle-pool and plane-bed sections with regard to decreasing discharge. Whereas the former (reaches A, D, F) still feature specific habitat suitability under low flow conditions (Q_L) (spec. HSI: 0.11–0.14), the latter show a distinct drop in suitable areas for both velocity/depth- (v/d) and depth- (d) related modelling. As an outlier, even for plane-bed morphology, reach B was modelled as having suitable habitats only under mean flow conditions (0.03 (v/d), 0.11 (d)). Compared to other reaches the major difference between depth-related habitat modelling and the scenario also including depth-averaged velocity reflects the high bed slope (0.0044) for reach B, exhibiting extended areas with a depth-averaged velocity >1 ms^{-1} even during mean flow conditions (Q_M=4.32 m^3 s^{-1}) limiting suitable grayling habitats. Additionally to the presented findings (Q_L, MNQT, and Q_M) Fig. 9 exhibits the sensitivity of instream grayling habitats to altered discharge.

The modelling runs (n=10) for each reach (A–F) once again underline the difference between riffle-pool and plane-bed sections. This supports our second hypothesis that differences in habitat quantity for selected target fish species exist between the two morphological bed forms when discharge changes. The decrease in quantitative grayling habitats for plane-bed sites (reaches B, C, E) is distinctive compared to riffle-pool sections (A, D, F) (Fig. 9). Further, parameter sensitivity to run off change based on velocity/depth suitability (v/d) and discrete depth suitability (d) modelling clearly reveals that habitats in plane-bed reaches are limited by suitable water depth at low flow conditions (MNQT–Q_L). This finding is reached because no or only minor quantitative differences (WUAs) are evident between the two modelling approaches (v/d and d), especially for Q_L (reaches B, C, E). Thus, in a summarized view, two crucial points have to be mentioned for riffle-pool reaches. On the one hand, habitats deviate distinctively between the velocity/depth and discrete depth approach (e.g. reach D, Q_L: 625.5 m^2 (v/d)/1265.0 m^2 (d)). On the other hand, suitable habitats

Table 5 Suitability indices of subadult/adult grayling (*Thymallus thymallus*), which were used to model the impact of discharge change within the Gr. Mühl River catchment

SI	Very high	High	Low	No SI
grayling depth (m)	>0.60	0.60–0.50	0.50–0.35	<0.35
grayling velocity (ms^{-1})	0.45–0.25	0.45–0.60/0.25–0.20	0.60–1.00/0.20–0.15	>1.00<0.15

SI Suitability indices

are still found even under low flow conditions (for Q_L: reach A=173.6 m^2, reach D= 625.5 m^2, reach F=599.4 m^2, depth-velocity suitability used). In particular, pool and deep run habitats at the outer bend of curved sections (e.g. Fig. 3a) exhibit (high) suitable habitats for (subadult/adult) grayling even under low flow conditions (Q_L). Those suitable morphological features (e.g. pools) are given as well by the longitudinal profile plot (Fig. 2a, b, f) or the variance in depth (based on the one-dimensional cross sectional modelling, (Table 5)).

5 Discussion

5.1 Climate change impacts

The impacts of decreasing discharge, however, were statistically significant in creating trend changes, especially around 1990 (spring, summer). This supports Alley et al. (2003), who indicated a significant temperature increase since 1990 (>0.2 °C) globally, especially in the Northern Hemisphere. We demonstrate that the determined decrease in summer discharge at the Gr. Mühl River is affected by climate change (higher temperature) by two crucial facts. On the one hand, no land-use change was documented in the sensitive 1990–2000 period (CORINE data); on the other hand, the signals of significant change in air temperature (T_Kollerschlag) were closely related to the increase in days below MNQT$_{Summer}$ (increase in low flow periods). Moreover, the impact of increasing temperature on precipitation, measured at gauging station Schlägl (N:48°38′15″/E:13°57′37″), exhibits no correlation between the cumulative deviation of the mean for precipitation and the cumulative deviation of the mean for air temperature (R^2=0.18). No significant trend changes for precipitation could be documented for those years with significant changes in air temperature trend. Thus, the impact on discharge has to be related to a higher evapotranpiration rate.

Furthermore, the results of the presented study point to a clear difference between various morphological patterns (riffle-pool and plane-bed sections) at decreasing discharge due to climate change. Findings which were so far neglected in terms of investigating climate change impacts on channel characteristics and instream habitats. In the literature, the impact of climate change on river morphology and on the sedimentological regime was mainly presented as an increase in stormwater flows, leading to a partial increase in bankfull width and bankfull depth, especially for gravel dominated rivers (Ashmore and Church 2001; Knox 1993). At the mainly plane bed reaches (cobble bed) of the Gr. Mühl River, potentially increased stormwater flows, however, would not significantly alter river morphology or the distribution of e.g. riffle-pool sections. This is because plane-bed and/or riffle-pool reaches at the investigated sites have a very low bankfull discharge capacity (partially 3 times Q_M), leading to lower stream power during high flows due to pronounced discharges into the floodplains (Hauer et al. 2011b). Thus, the initiation of motion of bed surface material was not even calculated for a thirty- (partially hundred)-year event (Hauer et al. 2011b). Based on the conducted (two-dimensional depth-averaged) habitat modelling, a regional sensitivity analysis could be performed (within the presented study) to assess those river reaches (plane-bed sites) where fish are most threatened by the documented (and predicted) impacts of climate change, as e.g. shown by Poff (1992). Semi quantitative electro-fishing results at the various study reaches yielded further insight into the impact of discharge change on instream habitats related to differences in river morphology. For reach E (Haslach), grayling density decreased with 520 ind./ha in 1997, 166 ind./ha in 2003, 80 ind./ha in 2005, and 65 ind./ha in 2008 (BAW-IGF 2008) and that riffle-pool reaches showed higher abundances (reach D:

390 ind./ha; reach F: 640 ind./ha) in general than plane-bed sections (reach C: 24 ind./ha; reach E: 65 ind./ha). An exception is riffle-pool reach A (Vorderanger: 70 ind./ha; Csar and Gumpinger 2008) which has a lower width and lower depth in general due to its upstream characteristic (Q_M=2.98 $m^3 s^{-1}$ versus 7.50 $m^3 s^{-1}$ for e.g. reach E).

5.2 Error estimates and uncertainties

Our paper determines the increase in (summer) low flow periods using specific hydrological thresholds ($MNQT_x$). Those statistically determined thresholds (by the Hydrological Survey Austria), however, include the impacts in trend changes (over the last 20 years) and are thus not entirely representative for describing mean low flow conditions for e.g. July in the period 1950–1990 (before the trend changed). The modelling results predicted, that summer (and partially autumn) discharge will continuously decrease and thus prolonging low flow periods by up to 20 % for scenario A1B (realistic concerning greenhouse gas emission), 8 % for scenario A2 (pessimistic), and 5 % for scenario B1 (optimistic) (Haslinger 2009).

For determining the impact of decreasing discharge on physical instream habitats and its response to river morphology numerical (micro-)habitat modelling was selected as an integrative evaluation tool. Habitat selection models (often referred to as "preference or habitat index" models or simply habitat models) are widely used to evaluate habitat quality and predict effects of habitat alterations on animal population (Railsback et al. 2003). These models involve observing the frequency with which animals use various habitat types and the availability of the habitat types: the ratio of habitat use to habitat availability is then transformed into a measure of habitat selection (Manly et al. 2002). Such habitat-based methods are limited by making simplifying assumptions about biotic (e.g. preferences) and abiotic (velocity/depth) relationships, and by focusing on only one or a few species (Meyer et al. 1999). In the present paper, we applied habitat modelling based on two-dimensional depth-averaged hydraulics to determine the impacts of discharge change on instream habitats of subadult/adult European grayling (*Thymallus thymallus*). European grayling microhabitats (subadults/adults) corresponds to certain flow velocity and water depth (Nykänen et al. 2001; Vehanen et al. 2003; Nykänen et al. 2004) without a clear preference for bed material (grain size distribution). The Gr. Mühl River has coarse bed material (cobbles, partially boulders), making the depth-averaged velocity distribution a sometimes unreliable parameter for evaluating habitats of the selected target species. Related to the dominating bed material, the range of preferred (especially nose) velocities (0.25–0.45 ms^{-1}) might be found close to the bed surface or behind obstructions, even though the calculated depth-averaged velocity had a magnitude >1 ms^{-1} (being unsuitable according to Fig. 7, Table 5) as it was exemplarily exhibited for reach B during mean flow conditions (4.32 $m^3 s^{-1}$). Thus, especially for the three plane-bed reaches on this river (classification according to Montgomery and Buffington 1997), with their coarse bed surface material (Hauer et al. 2011b), habitat modelling results must be interpreted with caution.

Therefore, the habitat modelling results, using a discrete depth parameter (Figs. 8 and 9), are more meaningful for testing our second hypothesis. Generally, two-dimensional depth-averaged velocity models should be limited to rivers with a maximum substrate diameter of 264 mm (sand, fine gravel, cobbles) (Hauer et al. 2009). In mountain streams with boulders (>264 mm) it is no longer possible or feasible to obtain high-quality DTM of the river bed topography based on terrestrial surveys under low-flow conditions because a simplification of the boulder cluster would lead to imprecise hydraulic parameters (velocity, depth, bottom shear stress) based on the two-dimensional depth-averaged modelling approach (Diplas and Shen 2007). Moreover, bed material characteristics (gravel, cobble, boulder classification) are frequently representing various
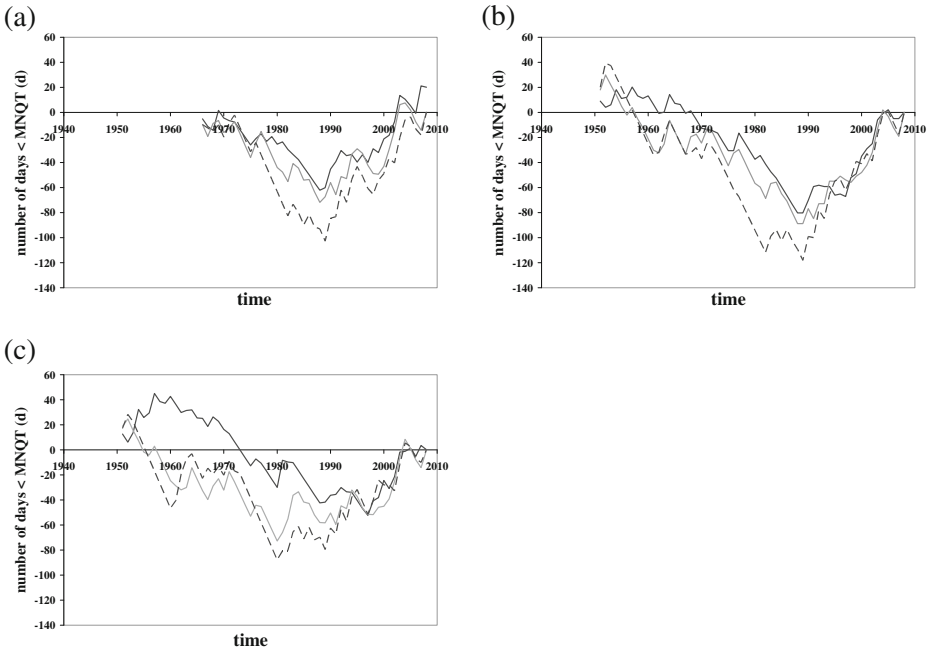
Fig. 7 Cumulative deviation of the mean for the number of days below MNQT (**a**) gauge Vorderanger, (**c**) gauge Furtmühle and (**c**) gauge Teufelmühle; *black solid line*=June, *grey solid line*=July, *black dashed line*=August

morphological patterns on the reach scale (cascade, step-pool, and riffle-pool) (Montgomery and Buffington 1997). Our paper focuses on changes of physical instream habitats, which, in case of the European grayling, might differ for different seasons (Nykänen et al. 2004).
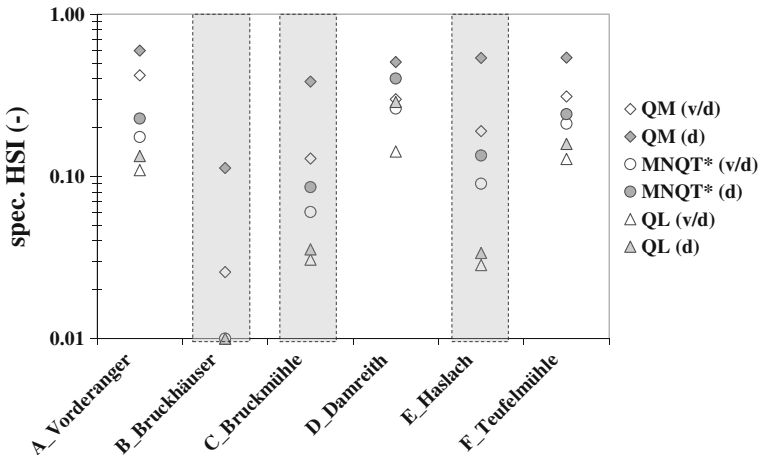
Fig. 8 Specific Habitat Suitability (HSI) for the various study reaches (*n*=6), evaluated for three different discharges (Q_M, MNQT, Q_L). White symbols are used for habitat evaluation based on mean flow velocity (ms-1) and water depth (m) (Table 5), grey symbols represent habitat modelling results only for the water depth criteria; grey bars=reaches with plane-bed morphology
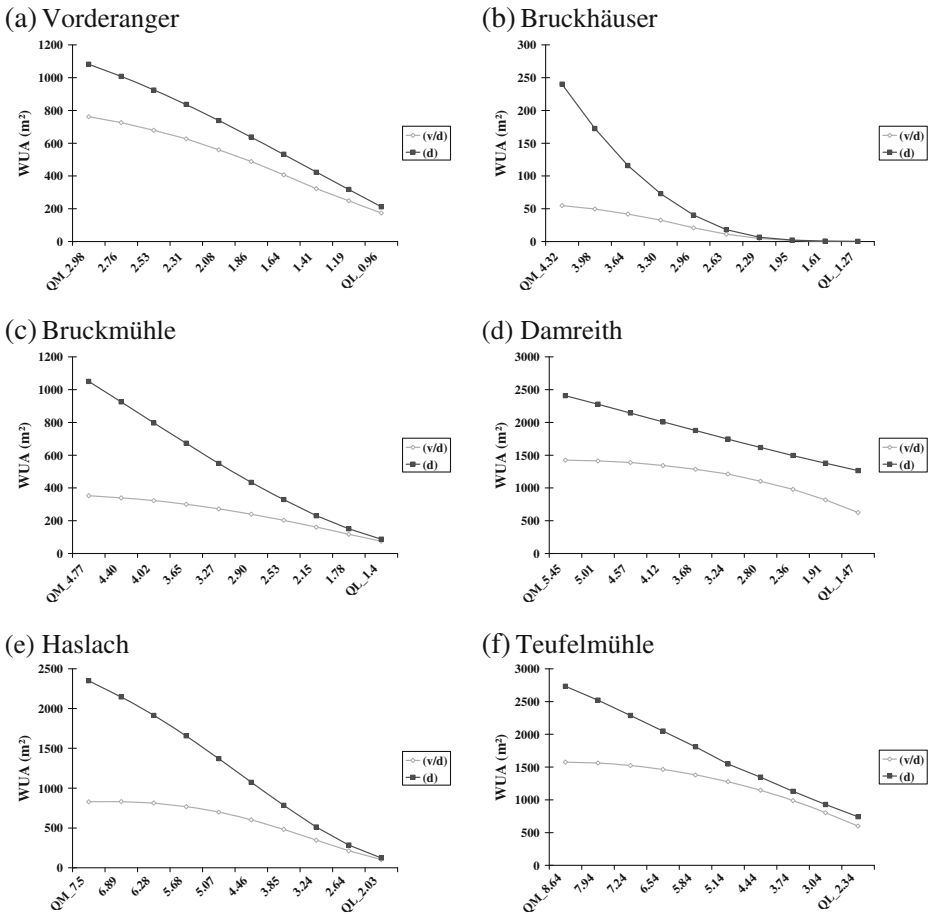
Fig. 9 Weighted Usable Areas (WUAs) of subadult/adult grayling, presented for the various study reaches (*n*=6); *black solid line*=WUAs based on depth suitability indices, *grey solid line*=WUAs based on modelling depth- and velocity (v40) suitability

At the same time, the mean daily water temperature at the Gr. Mühl River (available only for gauging station Teufelmühle) also reflected climate change impact with corresponding trend developments as determined for air temperature at T_Kollerschlag. This increase (41 days >20 °C in summer period since 1997) puts additional pressure on grayling, and salmonid habitats in general, here. Another important factor not addressed in this paper is that the estimated periods of low flow might lead to poorer water quality and increased pollutants (Meyer et al. 1999). For grayling Schmutz (1995) argued furthermore, that grayling would be heavily impacted because certain habitat factors—such as river width or competition with the more temperature-tolerant rainbow trout—are expected to limit their upward shift due to higher water temperature. This possible upward shift of cold-water fish species was further highlighted in Mattula et al. (2007), and Rahel et al. (1996). Rahel et al. (1996) estimated losses of up to 76 % for populations of brown trout, brook trout, and rainbow trout as a result of warmer summer conditions (for Wyoming streams); these fish would retreat to remaining cool waters in headwater reaches. Our findings suggest, however,

that this upward shift might be additionally limited due to the physical habitat constraints related to (natural) river-morphological characteristics (plane-bed morphology).

5.3 Challenging issues and predictions

Haslinger (2009) predicted that those trends of climate-induced discharge changes for the Gr. Mühl River catchment will continue due to a further increase of global temperature from 1 to 5 °C (depending on different emission scenarios of the IPCC; Houghton et al. 2001). In general, such an increase in global atmospheric temperature of 3 °C, would yield an intensification of the hydrological cycle by about 10 %, i.e. 10 % higher global evaporation and precipitation rates (Bronstert 2004). For the investigated Gr. Mühl river catchment, a 3 °C increase in air temperature was calculated for the period 2071–2100 based on a downscaled regional ECHAM5/REMO model (Haslinger 2009) with significant impact on run-off (discharge).

The importance of decreasing discharge is highlighted by the fact that ecologists consider streamflow to be a master variable which integrates many important environmental conditions and limits the distribution and abundance of riverine species (Minshall 1988; Poff and Ward 1989; Power et al. 1995). Hydrologic variability strongly affects food web structure (e.g. Power et al. 2008; Strayer et al. 2008), primary production (e.g. Marks et al. 2000; Schemel et al. 2004) and fish assemblage structure (e.g. Bernardo et al. 2003; Magalhães et al. 2007; Bêche et al. 2009). Adult (subadult) European grayling, for example, prefer water depths >0.35 m (Nykänen et al. 2001; Vehanen et al. 2003; Nykänen et al. 2004) which exhibits high sensitivity in case of decreasing discharge (compared to juvenile European grayling which prefer shallow water habitats). Thus, the morphological characteristics at the Gr. Mühl River (riffle-pool, plane-bed) mean that discharge changes (decreases) lead to habitat fragmentation due to low water depth, an effect also discussed in Flebbe et al. (2006), Rahel et al. (1996) and Williams et al. (2009).

However, the potential long-term impact on river morphology and instream habitats at the Gr. Mühl River might be related more to a change in land use (land drainage–increasing fine sediment input) than to climate change. At the entire study site (34.2 km), plane-bed reaches, featuring a historically high grayling density, dominate (53.6 %); they represent the typical bed form feature of the Gr. Mühl River catchment (Hauer et al. 2011b). The differences in river-morphological characteristics here are related to natural geomorphic boundaries (e.g. riffle-pools in former finer material deposits) and are only minimally impacted by anthropogenic measures (e.g. for flood protection). Only small hydropower dams ($n=12$) interrupt the sediment continuum here. Apart of those river reaches at the Gr. Mühl, containing natural plane-bed characteristics, featureless cross sectional shape (low width and depth variance) is often given (and required) in terms of river training measures (Habersack and Piégay 2008). Such regulated reaches, especially pristine riffle-pool rivers (fine gravel or gravel predominate), are therefore at high risk of having limited physical habitats (especially for adult grayling) in the event of climate change, which promotes habitat fragmentation. In a contrasting interpretation, Meyer et al. (1999) stated that regulated rivers may experience less climate-related variability in flow than unregulated rivers. This might be found because only control structures (dams) were addressed in Meyer et al. (1999), neglecting the impact of other anthropogenic measures (e.g. trapezoidal cross sections due to river training or gravel mining).

Our data, however, indicated clearly that habitat heterogeneity (e.g. higher variance in width-depth) created improved abiotic habitat conditions in terms of a climate-induced discharge decrease. Overall, numerous studies highlighted the necessity of considering morphological features and (mid- to long-term) sedimentological processes for achieving a sustainable, good ecological status according to the aims of the European Water Framework Directive (Hauer et al. 2008; Mounton et al. 2007; Wheaton et al. 2009). Accordingly, the

impact of climate change on discharge is an additional argument for improving the morphological conditions of regulated rivers. This is because habitat heterogeneity (partially described by width-depth variance; e.g. (Jungwirth et al. 1993)) provides suitable physical habitat even under extreme low flow or extended low flow periods.

6 Conclusions

The present findings demonstrate the impact of climate change (increasing air temperature) on discharge at the Gr. Mühl River catchment. A significant trend change of air temperature was determined for spring (1989) and summer (1990), increasing the frequency of low flow periods. Within the analysed river reach, plane-bed and riffle-pool morphology responded differently, especially to the reduced summer discharge. On the one hand, subadult/adult grayling habitats (the target species) were limited within plane-bed reaches, leading to extensive habitat fragmentation during summer periods since 1990. On the other hand, riffle-pool reaches continue to feature suitable habitats even under extreme low-flow conditions. Thus, contrary to other studies, climate change (higher water temperature) would limit a shift of grayling into headwater regions, because plane-bed reaches are dominant and present at upstream sites as well. The results highlight the necessity of including morphodynamic processes and river morphological heterogeneity for a sustainable habitat preservation and improvement, even under the aspect of future climate change.

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