RHYHABSIM as a Stream Management Tool: Case Study in the River Kornerup Catchment, Denmark

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Abstract: *This study applied the habitat-hydraulic model RHYHABSIM (River Hydraulic HABitat SIMulation) on three small streams within the River Kornerup catchment in eastern Denmark. The relationship between the flow and habitat area for spawning and juvenile brown trout was modelled to determine flows needed to produce enough habitat area to sustain naturally recruiting populations of brown trout. A comparison of the model results with actual flow data for the streams for the years 1999-2002 found that the stream flow in two of the streams provided enough available habitat for the survival of juvenile brown trout every year, however the stream flows in the third stream failed to provide adequate habitat area for a three week period in 2001. All three streams provided adequate habitat for spawning in all four years. This case study illustrated that the habitat-hydraulic model RHYHABSIM, which was relatively easy and non-labour intensive to apply, could quickly provide useful information for use by water managers in Danish streams. However, it must be stressed that these types of habitat models do not include all factors that affect ecosystem functioning and therefore carrying capacities of streams for indicator species such as fish, but they should be viewed as useful management tools for giving information on how the hydromorphological regime in a river or stream is affecting a chosen indicator species.*

Keywords: Habitat models, water resource management, brown trout, RHYHABSIM, Denmark, management tool

1. Introduction

Stream management, in its basic sense, is the allocation of the resources, water, for specific uses and purposes. The different uses for an individual stream could include drinking water, carrier of treated waste-water, irrigation, fisheries, recreation, and the maintenance of the natural/native biodiversity, just to name a few. At any point in time, the water quantity in a stream is affected by natural factors such as precipitation and geology, as well anthropogenic influences including the physical alteration of the stream, dams\weirs, and surface and groundwater abstraction (Gordon et al. 2004).

Groundwater plays an important part in most surface water systems, as it is often the predominate source of baseflow; the water that is present in a stream even during extended dry periods. Over exploitation of groundwater resources can significantly reduce a stream's baseflow to the point where once permanent streams become ephemeral. This change can have severe consequences for the native flora and fauna of the stream (i.e. Hunt et al. 2001, Nyholm et al. 2002).

Denmark, like many countries, relies on groundwater as an important source of clean, reliable drinking water. In fact, over 95% of its drinking water comes from groundwater (Madsen 1995). This resource is particularly important in the north-eastern part of the island of Zealand, where 1.8 million people (including Denmark's capital, Copenhagen) rely on predominately groundwater resources coming from a limited area of 2700 km^2. According to the Danish Geological Survey, groundwater resources have been over exploited in this area, significantly reducing the streams' spring fed baseflow (Henriksen and Sonnenborg 2003). Without the springs adding to the baseflow, some previously perennial streams are now ephemeral, drying out particularly in the summer (Schroeder 1995; Michaelsen 1986).

In recent years, there has been a strong effort in Denmark to manage its water resources in a more sustainable fashion. The sustainable development of the groundwater resources has been defined by the Danish Environmental Protection Agency to include not only the preservation of a clean water source for future generations, but also to include the protection of streams' flow and, subsequently, the aquatic biology associated with it (Danish EPA 1995). This has led to studies looking at the interaction of groundwater abstraction and baseflow in streams on Zealand, both on the regional level by the Geological Survey of Denmark and Greenland (GEUS) (Henriksen and Sonnenborg 2003) and on the local level by the stream managers at the county level (Roskilde Amt 2003a and 2003b). Groundwater/surface water flow models have been used as the basis for the evaluation of groundwater abstraction permit applications, but these models have not included the actual needs of the flora and fauna they were developed to protect.

In order to manage the freshwater resources, both an inventory of the water resource available and an assessment of the ecology of the natural (unaltered) freshwater ecosystem need to be undertaken. Habitat models such as habitat-hydraulic models are one of the tools available to evaluate how changing flow regimes will affect the physical habitat for the biological communities (Jowett 1997). These models combine the hydrological and biological variables in a system, simulating how available habitat for a particular species will change with differing hydrological responses to resource utilisation (Bovee 1982, Milhous et al. 1984). RHYHABSIM (short for River HYdraulic and HABitat SImulation Model) is one habitat model developed over the last 15 years, intended for use by water managers (Jowett 1989, 1997). RHYHABSIM is able to model habitat responses to changing hydrological conditions, and has been identified as a management tool for assessing current ecosystem condition. This has particular relevance in Denmark for implementing EU stream management directives such as the European Water Framework Directive (Fjorback et al. 2002).

The Kornerup River catchment (figure 1) is an example of the conflict between groundwater abstraction and surface water ecology. Groundwater abstracted in the catchment has been exported in large quantities (up to 18 million m3/year) to the city of Copenhagen since 1937 (Schrøder 1995). From the onset of this abstraction, it was observed that perennial springs in the area went dry and stream flow during the summer was greatly reduced (Bourbon 2004 pers. comm.; Schrøder 1995; Michaelsen 1986). Recent renewal of abstraction permits have been put on hold by the county, citing concerns about the effect on the ecology (Roskilde Amt, 2003a). In this case, precaution is being applied, as the county does not have data on the actual amount of water required in the streams to support a healthy stream ecosystem. Habitat models, such as RHYHABSIM, attempt to quantify the stream flow required to maintain a healthy ecosystem, thus providing stream managers with important information from which to base their water management decisions (such as groundwater abstraction) upon.

This paper looks at the application of RHYHABSIM as a tool to aid the management of freshwater ecosystems. Using a case study on three streams in the River Kornerup catchment on the island of Zealand in eastern Denmark (figure 1), the model is used to predict the flows needed to provide the necessary habitat to sustain naturally recruiting populations of brown trout (*Salmo trutta*). The model results are compared with the actual flow rates to determine whether the streams provide sufficient habitat for different lifestages of brown trout (a Danish ecological indicator). The application of the model is evaluated with regard to its usefulness from a resource manager's perspective.

2. Habitat-Hydraulic Models

Habitat-hydraulic models, a type of habitat modelling, have been developed to answer the basic question "How does a species' physical habitat change with changes in a stream's flow rate?" These models

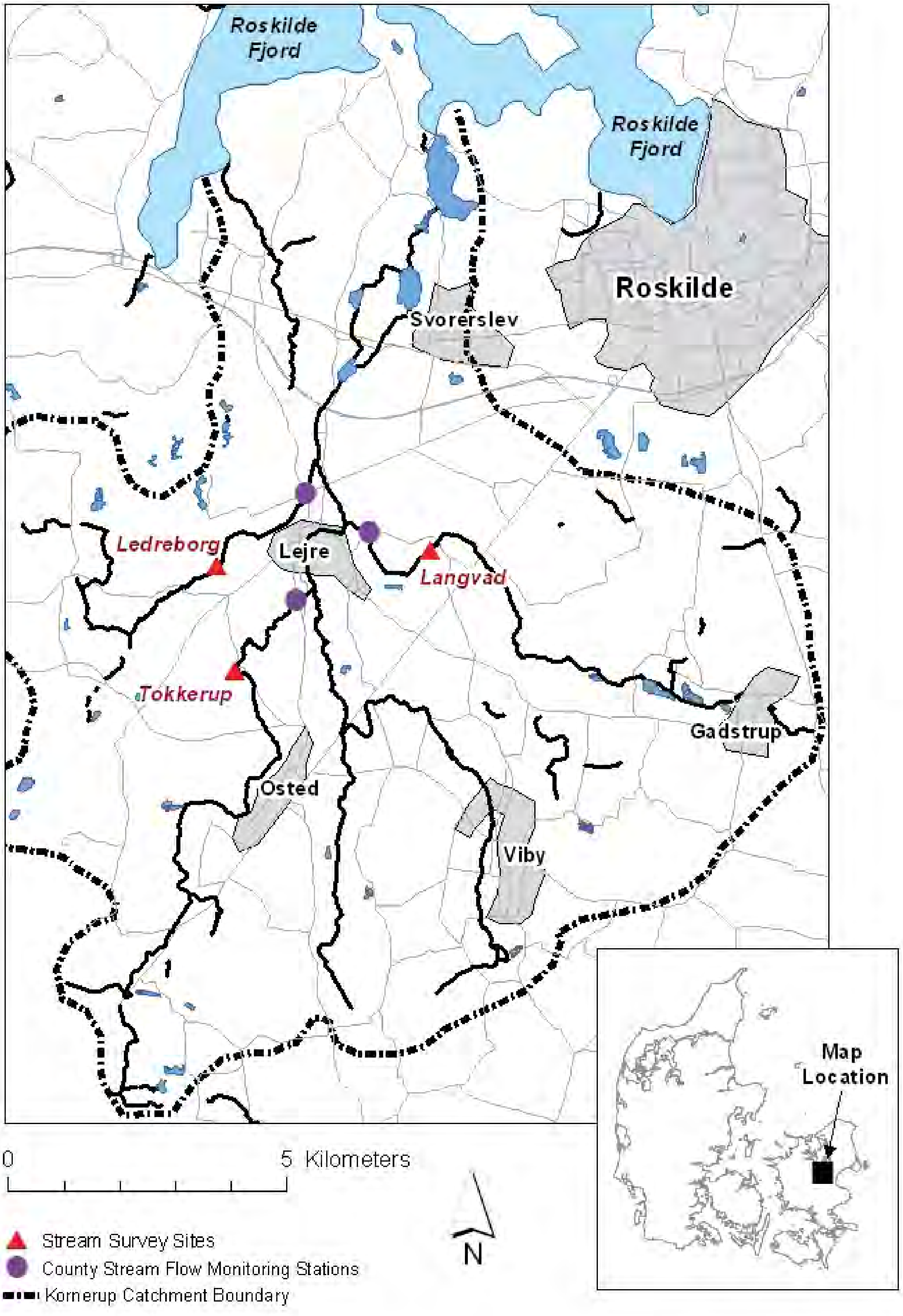

Figure 1. *Map over the River Kornerup catchment. The triangles mark the location of the stream survey sites. The circles mark the location of Roskilde County stream flow monitoring stations.*

combine biological data of the indicator species with the hydrologic and morphological characteristics of the stream to produce a quantitative relationship between flow and usable habitat area. The information obtained can then be used to maintain or even improve the physical habitat for selected biota, or a biota's specific lifestage (Jowett 1997). This information is very useful when considering the amount and timing of the allocation of water resources. For example, if a dam is developed on a river, habitat-hydraulic models could be used to determine when water should be held back in the reservoir without significantly impacting the natural fauna and when water should be released to prevent unnaturally low flows, in order to protect the habitat when it is at its most sensitive.

RHYHABSIM is a habitat-hydraulic model with its roots in the habitat-hydraulic model PHABSIM, it is designed to measure the amount of microhabitat available in a stream or river for fish or macroinvertebrates at different lifestages and at different flows (Jowett 1989, Figure 2). The difference between the two models being that RHYHABSIM is simplified, limiting the number of variable inputs, resulting in a model that is easier to use, while still providing accurate results that are reproducible (Gordon et al. 2004).

Figure 2 (modified from Jowett 1998) illustrates the theory behind RHYHABSIM. Figure 2a represents the biological data input into the model; termed habitat suitability curves (HSCs). For each hydraulic microhabitat variable (e.g. depth) that influences a species available habitat, a HSC is developed and included in the model. A suitability of 1.0 represents the optimum amount of usable habitat, 0 represents unsuitable habitat conditions, and values in-between represent varying degrees of suitability. Figure 2b represents the hydraulic modelling of the stream over the selected stream reach. Parameters represented in the hydraulic model are those relevant to the HSCs, which generally include stream geometry, water velocity, water depth, and substrata. A dynamic model is produced, showing how these parameters will change with changes in stream discharge. The model maintains the flexibility so that other factors influencing the biological conditions of the stream, such as temperature, can also be included (Jowett, 1998).

When hydraulic variables are combined with the biological habitat suitability values, the result (figure 2c) is a curve representing the usable habitat area vs. stream discharge; termed a reach habitat curve (RHC) (Jowett 1989, 1992, 1998). This RHC can be expressed as absolute values in terms of physical habitat area in m^2 per meter length of stream or in relative terms as a percentage of the stream (habitat area divided by the total area of the stream). RHCs are achieved by using a simple mathematical algorithm, where the HSCs are simply multiplied against the hydraulic model. For example, any time the stream depth exceeds 0.5m, the area is unsuitable for juvenile brown trout (figure 2a), and has a multiplier of 0. Thus, if 50% of the stream width is over 0.5m, then only 50% of the stream has suitable habitat. As the stream discharge changes, this relationship also will change. The hydraulic model shows how the stream width and depth changes with discharge and when multiplied against the depth HSC, a curve is produced showing the changes in habitat suitability. The biological variables from the other HSCs are also added to the hydraulic model, producing the final reach habitat curve.

It should be stressed that habitat models such as RHYHABSIM only provide information regarding the potential habitat available for the indicator species and how habitat area changes for differing flows. If the model states that optimal habitat area is available for the species, it does not necessarily mean that the species will be able to survive in the stream. Other abiotic factors, such as water quality and biotic factors such as competition also play a role. However, for water managers, RHYHABSIM provides the first step in determining whether or not the stream has the needed habitat in the form of flow to maintain the ecosystem, and if not, how much water is required to achieve the optimal and/or minimum habitat.

One of the benefits of RHYHABSIM is its ability to analyse biological data from different species and/or lifestages. By inputting HSCs (figure 2b) for different species or different lifestages, water managers can obtain information on how the flows will affect different aspects of the stream ecosystem. Therefore stream managers can assess one or more species of interest, or assess a species during life stages that are most vulnerable to change or extreme flow rates (i.e. during spawning or during its juvenile lifestage).

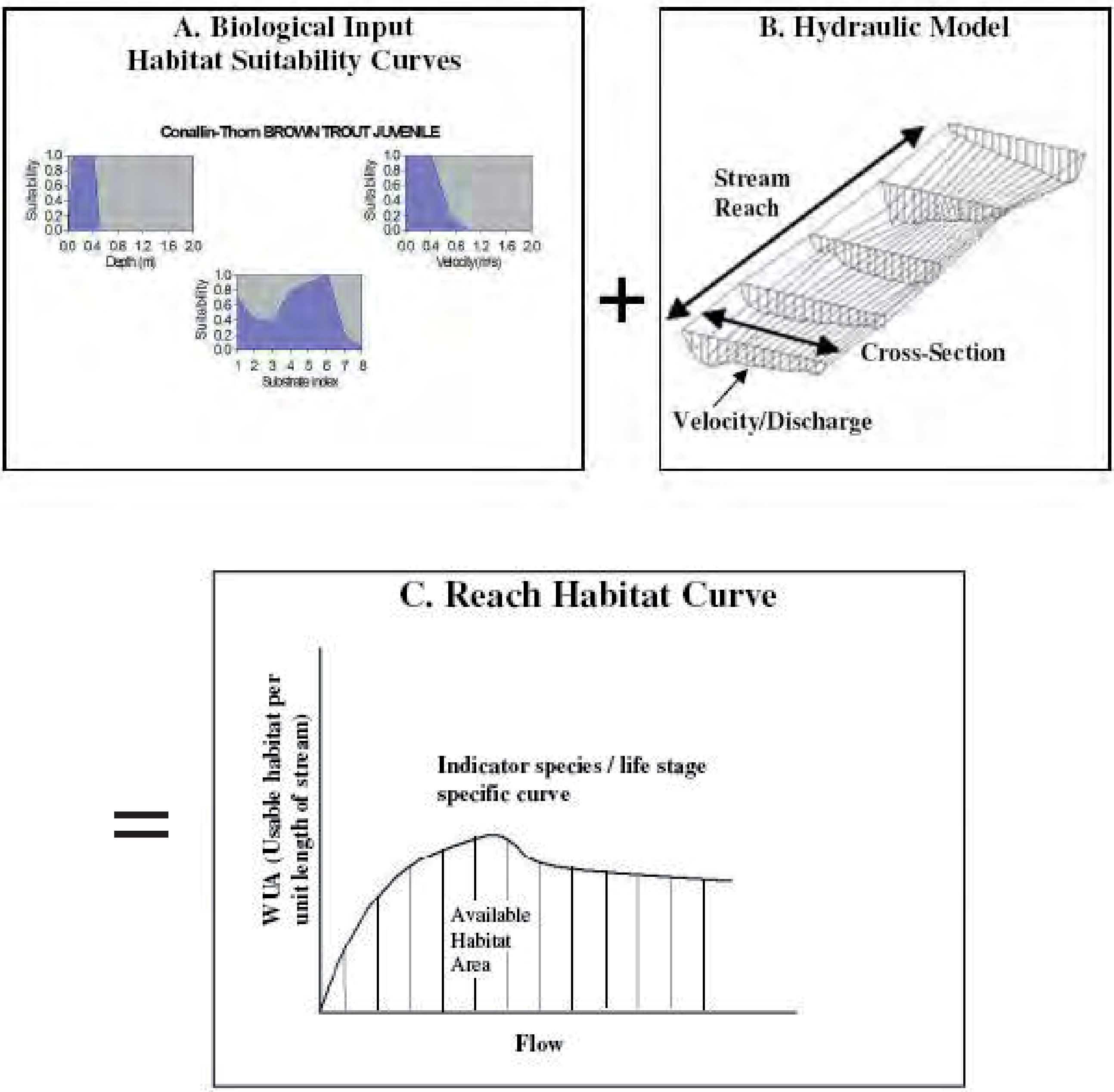

Figure 2. *Illustration of the input behind the RHYHABSIM model.*
A. The biological input to the model in the form of Habitat Suitability Curves. The particular curve shows the habitat suitability for juvenile brown trout, where the blue indicates suitable habitat, and the grey areas are unsuitable. These are displayed in a factor of 0 to 1, where 1 is 100% suitable, and 0.6 is 60% suitable, and 0 is unsuitable. The substrate index is vegetation, mud/silt, sand, gravel, coarse gravel, cobbles, boulders and bedrock, classified as 1-8 respectively.
B. Physical stream model, which is made up of cross-sections where the stream geometry, stream velocity, depth and substrate are measured.
C. Reach Habitat Curve developed by combining the hydrologic model with the biological data. The curve illustrates how the weighted usable area (WUA) changes with changing flow rates.

3. Rhyhabsim Case Study: River Kornerup, Denmark

3.1. The RHYHABSIM Survey Sites

The River Kornerup catchment lies immediately to the southwest of the City of Roskilde, approximately 30 km west of Copenhagen (Figure 1). The catchment consists of four main streams, which converge near the town of Lejre and then continue approximately 10 km north to Roskilde Fjord. The streams within the catchment are small, with discharges ranging from under 20 litres/sec to just over 3000 litres/sec (Roskilde Amt. 2003a). The catchment covers 191 km2 and is predominately agriculture (82%), with some forest (15%) and urban area (3%) (Roskilde Amt 1992).

Three separate survey sites were chosen for the RHYHABSIM survey: River Langvad, River Tokkerup and River Ledreborg (Figure 1). The River Langvad site (Figure 3) is located on a stretch of the stream which has been channelised and retains very little of the stream's natural morphology (Madsen 1995). The site is located just upstream of one section where artificial spawning gravels were placed to increase the successful spawning among resident and sea-run brown trout. The River Tokkerup site is also located along a stretch of channelised stream, however unlike Langvad, no habitat improvements have been made here. The River Ledreborg site is located on an unaltered stretch of stream that maintains the natural meandering morphology with well developed riffles, runs and pools.

Figure 3. *Part of the stream survey site on River Langvad. Note that the stream has been channelised and retains very little of its natural morphology, which is most common for Danish streams.*

The River Kornerup catchment provided an ideal case study on the application of RHYHABSIM in stream management decision making. Both anadromous (sea-run) and resident brown trout are native to the streams in the catchment, and trout are used as the index species for the water quality goals for most of the River Kornerup and its tributaries (Regionplan 2005). Studies produced in 1960's and as late as 1978 showed no trout in the entire stream system (Henriksen et al. 2002). Stream restoration and trout reintroduction projects, aiming to re-establish a self-sustaining population of brown trout, were completed in the 1990's, with the streams stocked with fry, juvenile and 1-year old brown trout released in 1997 (Mikkelsen 2006; Henriksen et al. 2002). These projects have had varying success; surveys in 1997 and 1999 showed acceptable natural recruitment of brown trout in both River Ledreborg and Tokkerup, but little natural recruitment in River Langvad (Henriksen 2000; Mikkelsen 2006). A fish survey conducted in 2005 found an increase in natural recruitment in River Langvad (though still below an acceptable level), a decrease in natural recruitment in River Ledreborg and Tokkerup, with the recruitment in Tokkerup no longer acceptable (Mikkelsen 2006). In addition, it has been observed that recruitment levels vary greatly from year to year (Henriksen et al. 2002; Henriksen, 2000).

It is suspected that low flows caused by groundwater abstraction could be one of the reasons for the complete disappearance of trout by the 1960's, and for the varying results of the natural recruitment after the reintroduction of the trout in the 1990's (Michaelsen 1986; Schroeder 1995; Conallin 2005). This has direct implications for Roskilde County in its implementation of the requirements of the EU's Water Framework Directive, where utilisation of the water resources cannot have a negative impact on the natural ecosystem. The County has also designated the streams as trout spawning and inhabitation streams as part of their environmental quality goals for the fresh water ecosystem, particularly with regard to control of point and non-point source pollution. Therefore, the application of RHYHABSIM provides the ideal opportunity to address the question of whether low stream flows could be a limiting factor for the spawning and inhabitation of brown trout in the stream.

Since 1937, up to 18 million cubic metres of groundwater per year has been abstracted from the basin and exported to the Copenhagen metropolitan area (Roskilde Amt 2003a; Schroeder 1995). Groundwater abstraction sites are located next to the study streams River Langvad (upstream from the survey site) and River Ledreborg (upstream from and along the survey site). There has never been groundwater abstraction along the River Tokkerup. This groundwater abstraction has reduced direct input from natural springs into the streams, particularly Langvad and Ledreborg, resulting in unnaturally low base flows and even going completely dry during long dry periods. As a result of this, Roskilde County reached an agreement 1992 with Copenhagen Water Supply (now Copenhagen Energy) to reduce the groundwater abstraction rate along Rivers Landvad and Ledreborg by a total of 3.8 million cubic

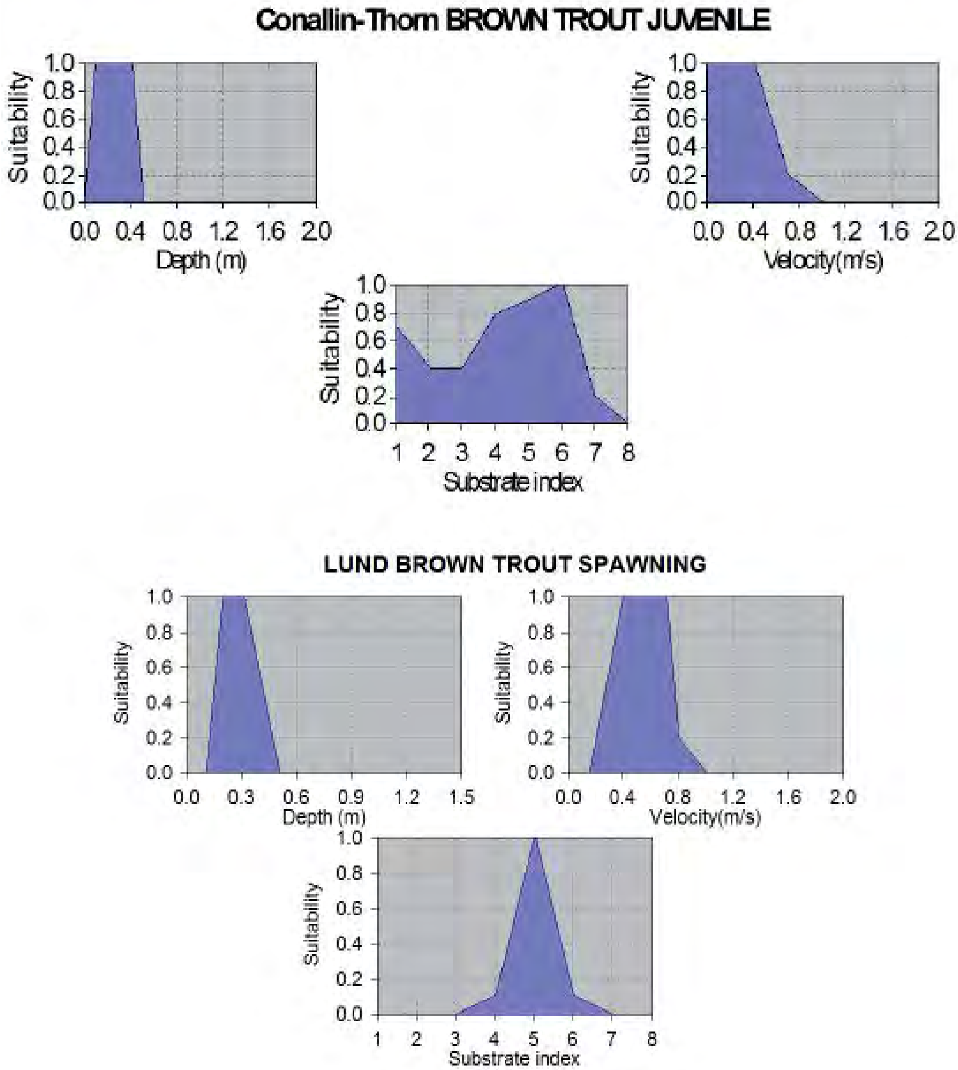

Figure 4. *Habitat suitability curves (HSCs), for brown trout juvenile and spawning life stages, used in this study. The juvenile brown trout curve was modified from the HSC used in the Lund (1996) study using recent electrofish data in the study and nearby streams (Henriksen et. al 2002; Mortensen and Geertz-Hansen 1996). The brown trout spawning curve is unmodified from the Lund (1996) study. The substrate index is vegetation, mud/silt, sand, gravel, coarse gravel, cobbles, boulders and bedrock, classified as 1-8 respectively.*

meters per year (Roskilde Amt 1998). Although the hydrology of the catchment area is well known (i.e. Roskilde Amt 2003a, 1999, 1998; Michaelsen 1986; Schroeder and Bondesen 1979), there have not been any studies conducted on how the ecosystem is being affected by the unnatural flow regimes in the stream, or how an increase in groundwater abstraction will influence the ecosystem (Rasmussen pers. comm. 2004).

4. Rhyhabsim Methodology and Results

4.1. Biological data – The Habitat Suitability Curves

The first part of the input to the computer model is biological data in the form of habitat suitability curves (HSCs) (Figure 4) for the chosen indicator species – brown trout. Authors from different areas in the world have devised HSCs (i.e. Bovee 1978; Jowett 1998; Fjorback et al. 2002), which provide a quantitative method for determining the applicability of a physical habitat feature (i.e. stream velocity, depth or substrate) to a particular species or lifestage. The HSCs used in this study were for brown trout spawning and juvenile lifestages. The objective of Roskilde County is to have a self-sustaining population of sea-run brown trout spawning in the streams (Roskilde Amt 1992). In order to accomplish this, conditions must be adequate for the juvenile brown trout survive in the streams for a minimum of 1 year before they are mature enough (smoltify) to migrate to the sea (Titus and Mosegaard 1992). Furthermore, there must be conditions suitable for the sea-run trout to migrate back up their natal stream and spawn. Therefore, when analysing the habitat needed to provide for a self-sustaining population of spawning trout, one must analyse both the spawning and juvenile life stages at a minimum.

It is important that the HSCs used in the RHYHABSIM model be formulated in the area which is being studied or in streams of similar morphological characteristics and climatic conditions. For example, suitability curves developed in large, braided streams (such as those found in New Zealand) will be very different from those developed for small meandering streams (such as the natural streams in Denmark). If the curves are not applicable to a region, then the model results may be misleading and inaccurate (Lund 1996).

Finding HSCs to use in this study proved to be somewhat problematic. No HSCs for spawning or juvenile brown trout have been developed specifically for small Danish streams, such as those found in the study area. However, in a previous study, Lund (1996) modified curves developed in the U.S. by Bovee (1978) using local biological data available for both juvenile and spawning brown trout to suit the conditions for the River Elverdam on the island of Zealand in Denmark. This stream has a similar morphology and ecology to that of the River Kornerup, making them the most appropriate published curves to date. However, more recent electrofishing data taken directly from the study area and nearby streams (Mortensen and Geertz-Hansen 1996; Henriksen et al. 2002) provided further opportunity to modify (or rather fine tune) the curves, resulting in the final HSC's used in the RHYHABSIM model for this study (figure 4).

4.2. Stream Survey Methodology

The objective of the stream survey was to obtain the measurements needed to model the stream parameters that influence trout habitat: stream depth, velocity, discharge and substrate. The three sites were surveyed according to standard RHYHABSIM protocol and methodology (provided in Jowett 1998). For this study, each survey site contained 15 cross-sections, with an even distribution of cross-sections between riffles, runs and pools. The survey took place in two parts – the initial, more intense survey, and follow-up visits. The initial visit was used by the model to establish the basic hydraulic parameters for the stream (Jowett 1998). The follow-up visits, conducted at different stream discharge rates, were used to calibrate the model, which was then used to predict how the stream's physical attributes (velocity, width, depth and substrata) change with stream discharge.

At the initial survey for each of the 15 cross-sections, the following parameters were measured:

1. Stream profile from the top of the stream bank (bank at flood stage) on each side of the stream – the stream profile defined the confines of the stream.
2. Flow velocity and discharge rate – velocity is particularly important, as it will vary across the cross-section, influencing the model results.
3. The stream stage (water level) at one fixed point in the stream for each cross-section. The stream

stage was measured at this point in the three follow-up visits.

4. The substrata across the profile of the streams. The parameters measured include vegetation (1), mud (2), silt and sand (3), fine gravel (4), gravel (5), cobbles (6), boulders (7) and bedrock (8) (Figure 4).

After the initial survey, three follow-up surveys at varying stream flow rates were conducted. The follow-up surveys included:

1. The stream stage at all 15 cross-sections at the point established at the main survey.
2. The water velocity and discharge at one cross-section at each survey site. This was conducted at the same cross-section for each follow-up visit.

4.3. Model Results

Three basic flow ranges, modified from Tunbridge and Glenane 1988, and Gordon et al. 1994, were used in the interpretation of the reach habitat curves (RHCs). These are as follows:

Optimal Available Habitat Range (OAHR) – the range of flows that provide the maximum amount of habitat for the stream. Variations of stream discharge within this range result in little change of available habitat for the species/lifestages analysed.

Degrading Available Habitat Range (DAHR) – the range of flows where the available habitat decreases as discharge decreases. The rate in which habitat area decreases is moderate.

Severely Degrading Available Habitat Range (SDHR) – the range where available habitat decreases significantly with only minor decreases in stream discharge. A slight decrease in discharge results in a significant decrease in usable habitat area.

The boundaries between the ranges are identified by inflection points on the RHCs produced by the model, as illustrated in Figure 5. The inflection points usually occur where there is a change in the slope of the RHC. The inflection points represent the specific flows where there is a change in the response of available habitat area to stream flow (Jowett 1998; Figure 5).

The RHCs obtained for the Rivers Langvad, Tokkerup and Ledreborg for the juvenile and spawn-

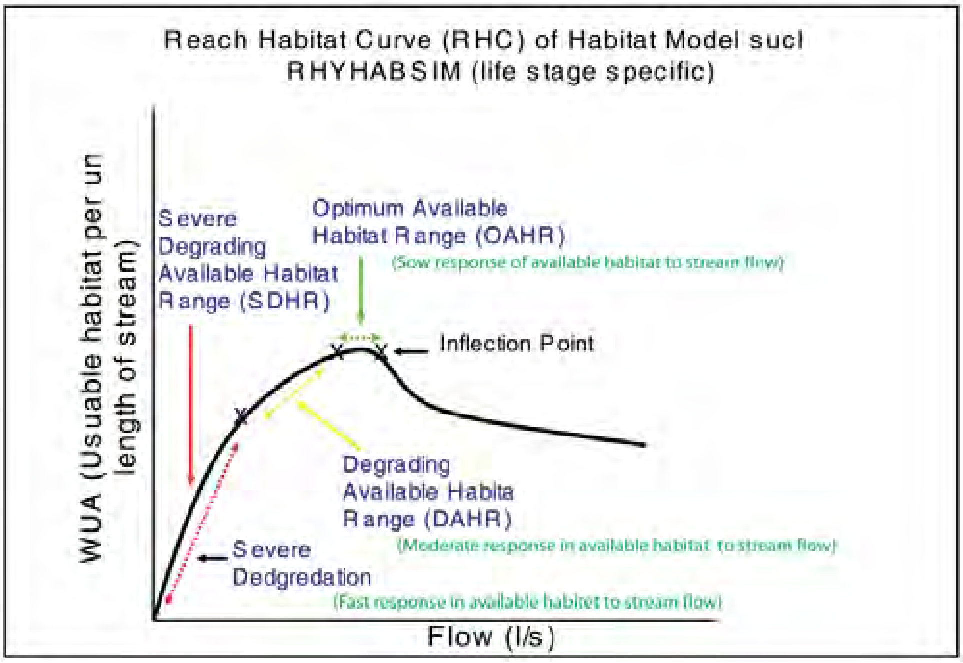

Figure 5. *Diagram illustrating the different flow ranges (SDHR, DAHR and OAHR) as interpreted from a reach habitat curve.*
Note that the boundaries between the ranges are interpreted from changes in the slope (inflection points) of the reach habitat curve. (Modified from Tunbridge and Glenane, 1988.)

ing brown trout life stages are shown in Figures 6 and 7. It provides the basis of the interpretation of the effects of flow changes on brown trout habitat. Interpretation of the RHCs into environmental flow ranges is important for stream managers, and provides a foundation from which the resources can be managed and negotiations can take place. Because of the nature of the curves, this interpretation is subjective, but well developed definitions (described above) can aid in the interpretation of the curves so that defendable results are obtained.

Table 1 provides the ranges from the interpretation of the curves in Figures 6 and 7. As can be seen in the curves, there are no clear inflection points present. In this case, the boundaries were estimated by the relative steepness of the curves. Though the curves do not provide the exact ranges on the inflection points, it does provide an approximation on how habitat changes with discharge. Without clear inflection points it is imperative, when deciding flow ranges, that factors such as expert opinion, previous studies and historical flow etc. are taken into account when deciding the boundaries.

5. Comparison of Rhyhabsim Results and Stream Flow

Figures 6 and 7 and the figures provided in Table 1 list the flow ranges needed in the Rivers Langvad, Tokkerup and Ledreborg in order to provide the necessary habitat for spawning brown trout according to the RHYHABSIM model. The next step was to compare this with how the streams were performing – i.e. the stream discharge history. The stream discharge compared with the RHYHABSIM results revealed whether or not the current stream discharge supplies enough flow for the habitat requirements of local brown trout.

5.1. Characterisation of Stream Flow 1999-2002

The stream flow for the three streams was analysed over a four-year period between 1999 and 2002 with the four years being indicative of average rainfall and groundwater abstraction.

Table 2 provides the basic statistics of the flow for the three streams. The figures are broken down into two seasons since the habitat for the two lifestages analysed, spawning and juvenile, are affected most by differing flow rates at different times of year. The winter months are important for spawning, as brown trout spawn from November to around late January in Denmark, depending on the year (Rasmussen 2004). The summer months are the most important for the juvenile life stage because this is when flows are traditionally the lowest for extended periods of time (Michaelsen 1986; Schroeder 1995), and thus juvenile brown trout will be most vulnerable during this period.

Table 2 illustrates the highly variable discharge rate in all three streams. For example, in all three streams, the summer flow minimum is less than 1% of the maximum summer discharge rate. However, the most important statistical figure is the minimum flow. Here, one can see that the stream discharge is as low as 5 l/sec, 3 l/sec, and 6 l/sec in Rivers Langvad, Tokkerup and Ledreborg, respectively (Table 2). In addition, stream flows were less than 17 l/sec, 5 l/sec and 9 l/sec 5% of the time (average of 7 days per summer) in Rivers Langvad, Tokkerup and Ledreborg respectively (Table 2). From these statistics, the River Tokkerup is in the greatest danger of having stream flows in the critical SDHR range for extended periods for the juvenile life stage. The risk appears to be less for both Langvad and Ledreborg, where absolute minimum flow for the two streams approached the SDHR range during the four year period, but the minimum flow (as indicated by the

Table 1. The environmental flow requirements as determined from the interpreted reach habitat curves for each stream, shown in figures 6 and 7.

		Langvad	Tokkerup	Ledreborg
OAHR	Juvenile	>17 l/sec	>16 l/sec	>12 l/sec
	Spawning	>150 l/sec	>120 l/sec	>150 l/sec
DAHR	Juvenile	4 – 17 l/sec	4 – 16 l/sec	4 – 12 l/sec
	Spawning	40 –150 l/sec	30 – 120 l/sec	32 – 150 l/sec
SDHR	Juvenile	<4 l/sec	<4 l/sec	<4 l/sec
	Spawning	<40 l/sec	<30 l/sec	<32 l/sec

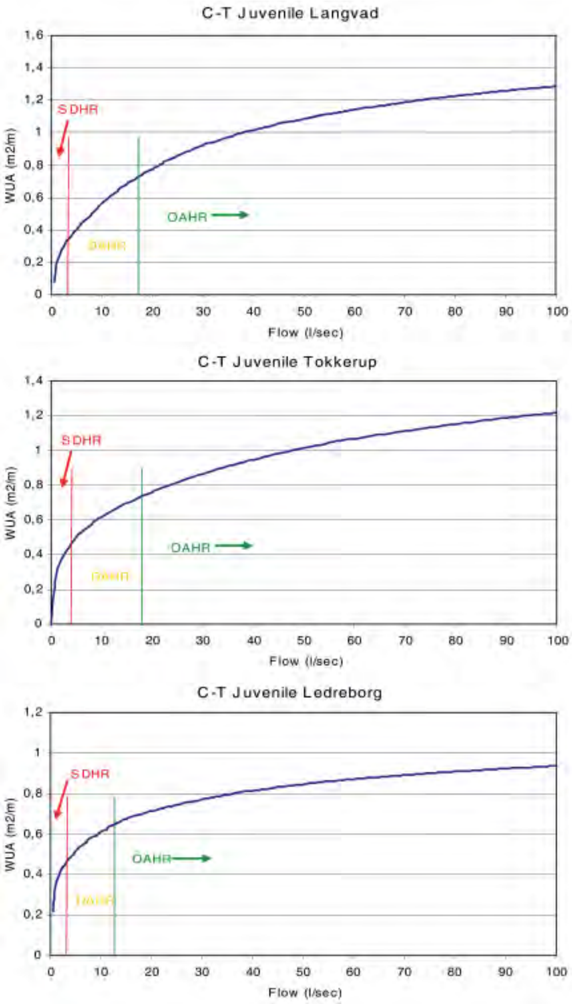

Figure 6. *Reach habitat curves (RHC's) for juvenile brown trout for Rivers Langvad, Tokkerup and Ledreborg. OAHR represents the flows that provide the optimal available habitat range, DAHR represents a degrading (sub-optimal) available habitat range, and SDHR represents severely degrading (critical) habitat range.*

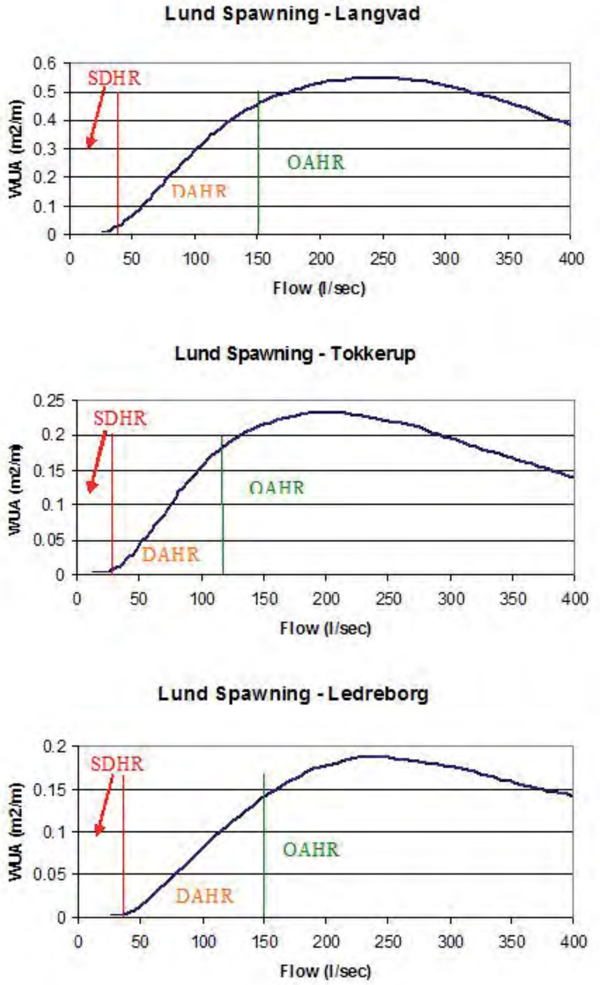

Figure 7. *Reach habitat curves (RHC's) for spawning brown trout for Rivers Langvad, Tokkerup and Ledreborg. OAHR represents the flows that provide the optimal available habitat range, DAHR represents a degrading (sub-optimal) available habitat range, and SDHR represents severely degrading (critical) habitat range.*

Table 2. Characterisation of the daily average flow (DAF) for the years 1999-2002. The summer months analysed are May 1 – September 30, and the winter months include November 1 – January 31. The flow presented in the 25% and 5% column represents the rate at which DAF was observed to be lower 25% and 5% of the time respectively. All flows are given in litres per second (l/sec). The data for the analysis was collected and provided by Roskilde County.

Stream	Period	Maximum Flow	Minimum Flow	Median Flow	Average Flow	25%	5%
Langvad	Summer	1142	5	89	120	48	17
	Winter	1999	61	430	518	288	71
Tokkerup	Summer	1787	3	64	107	29	5
	Winter	1094	47	333	364	173	72
Ledreborg	Summer	639	6	35	52	21	9
	Winter	907	39	179	205	118	47

5% frequency in Table 2) tended to remain well above the SDHR level in both streams.

When comparing the actual number of days the stream flow has been in the SDHR and outside the OAHR for juvenile brown trout from 1989-2002 (Figure 8), Rivers Ledreborg and Langvad have not been within the SDHR since 1990, where as Tokkerup has in 6 of the 12 years (Figure 8). This trend is also the same for flows outside of the OAHR, where for Ledreborg and Langvad, this has been steadily decreasing since 1990, whereas Tokkerup has remained the same. This data confirms that Tokkerup currently remains the most sensitive stream for juvenile trout. However, before the groundwater abstraction reduction in 1991, the situation for River Ledreborg was critical; both in 1989 and 1990, the stream was in the SDHR for over 70 days (Figure 8).

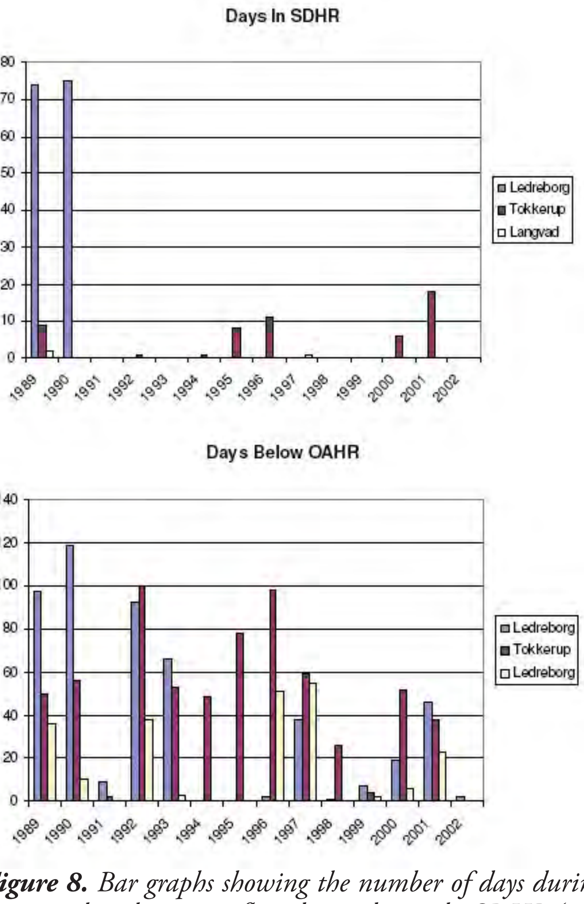

Figure 8. Bar graphs showing the number of days during the year that the stream flow dropped into the SDHR (top) and was below the OAHR (bottom).
Note that River Ledreborg never dropped into the SDHR and that the number of days in below the OAHR have decreased steadily after groundwater abstraction was reduced in 1991.

5.2. Comparison of Stream Discharge and RHYHABSIM for Juvenile Brown Trout

A simple hydrograph with the modelled environmental flow limits assesses the stream performance in relation to the RHYHABSIM ranges. Figure 9 shows this comparison using the limits modelled by RHYHABSIM (Table 1) on the hydrograph for the summer months for all three streams. Using the hydrographs in addition to the simple statistics is important because the hydrograph shows the duration that a flow stays within an individual range. This stresses the importance of considering time series flow data in relation to flow management and that simple statistics such as 5% or 25% bands are not adequate enough. If the flows are only in the DAHR and SDHR for short periods (i.e. a couple of days), then the juvenile brown trout may not be severely affected by the low flows, compared to if the flow remains within the SDHR range for extended periods of time (i.e. weeks or months). This would lead to critical limits for available habitat area needed to sustain the natural aquatic biota to be exceeded and lethal limits for the juvenile brown trout reached (Beecher 1990, Jowett 1992). Even short periods in the SDHR will negatively impact on the juvenile brown trout, and any ranges below the OAHR need to be avoided as much as possible, and are only really acceptable in natural situations such as droughts.

When the stream flow hydrographs for the summers of 1999-2002 are compared with the RHYHABSIM data (Figure 9), a different picture is presented than what the statistical comparison provided. Here it can be seen that there is a significant variation in the minimum flow from year to year in all three streams, with 2000 and 2001 producing the lowest flows. Similar to the results obtained from the statistics, the River Tokkerup appears to be the most affected with respect to low flows. In both 2000 and 2001, flows receded into the SDHR range, with flows in 2001 remaining in the SDHR for almost a three week period (Figure 9). The River Langvad for most of the years retained a summer flow in the optimal range for most of the time (Figure9). However, there was a two week period in 2001 where the flows reached the SDHR boundary (Figure 9). The River Ledreborg during the entire four year period remained above the SDHR boundary, with 2001 being the only year out of the optimal range for more than week (Figure 9).

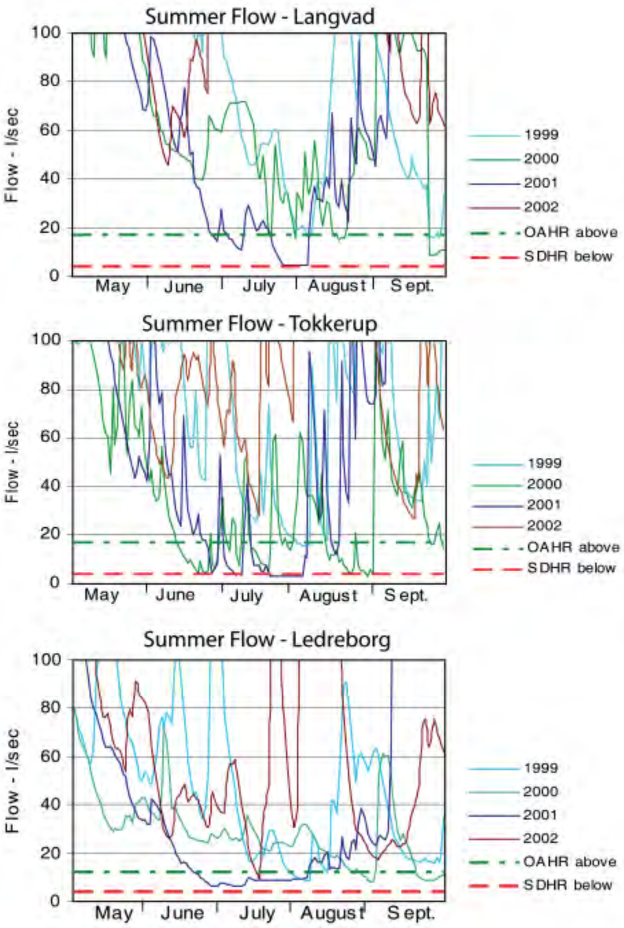

Figure 9. Hydrograph of the flows recoded over the summer months (May 1 – Sept. 30) for the three streams.
The habitat limits for juvenile brown trout, as determined by the RHYHABSIM model, are shown. The flows that were above the OAHR line provided the optimal habitat area, where as the flows below the SDHR line were in the critical flow area. Note how in 2001 Langvad and Tokkerup reached SDHR limit for more than one week, where as Ledreborg remained above the SDHR limit during the same period.

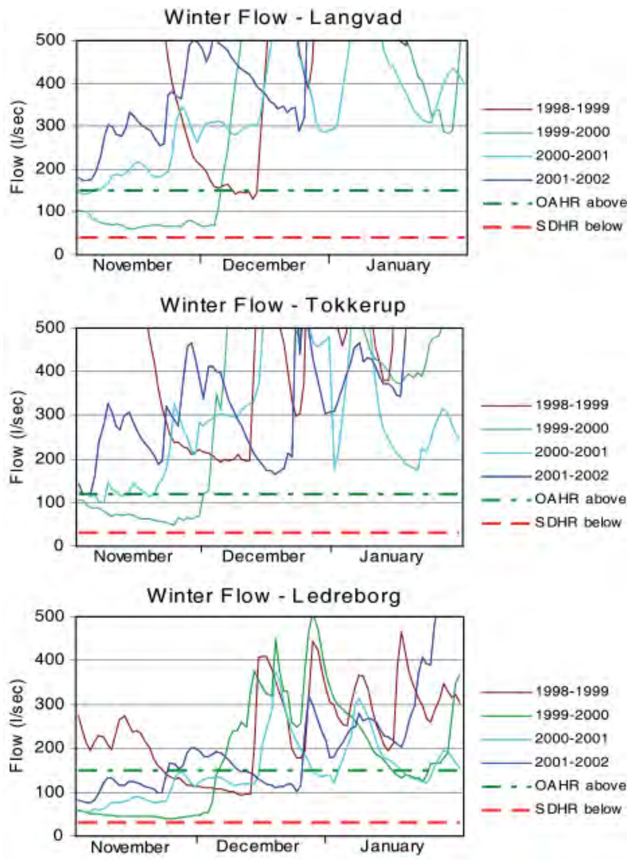

Figure 10. Hydrograph of the flows recorded over the winter months (November 1 – January 31) for the three streams. The habitat limits for spawning brown trout, as determined by the RHYHABSIM model, are shown. The flows that were above the OAHR line provided the optimal habitat area, where as the flows below the SDHR line were in the critical flow area. Note how flows are only in the SDHR region for between 4 – 6 weeks in each year, allowing spawning to take place in optimal to nearly optimal conditions for at least 6 weeks of the spawning period.

5.3. Comparison of Stream Discharge and RHYHABSIM for Spawning Brown Trout

The hydrographs with the environmental flow limits for spawning brown trout (Figure 10) show a more positive picture. In only one winter, 1999/2000, did the flows fall out of the optimal range (OAHR) in all three streams. Rivers Langvad and Tokkerup had the best flows, with only the month of November, 1999 remaining out of the OAHR. In River Ledreborg all four winters had flows during part or all of November and the first half of December below the OAHR boundary. However, in all three streams, the December/January flows remained within OAHR, providing the needed habitat for spawning to occur.

In the case of the spawning life stage of the brown trout, it is not essential that the flows are in the OAHR for all of the spawning season, as long as the flows do reach up in the OAHR for a significant period to allow migration and spawning to occur. As most of the trout are sea-run and migrate up the streams, they can remain in the fjord during times of sub-optimal spawning flows, until the time when flow levels become optimal for spawning (Elliot 1994). In the case of all three streams, the flows have exceeded the optimum flows for 6-8 weeks

– over half of the total spawning season. Therefore, it is likely that the flows are not having a significant affect on the spawning potential for the brown trout in Rivers Langvad, Tokkerup and Ledreborg.

6. Discussion

The European Water Framework Directive (WFD) requires that all streams achieve a 'Good Ecological Status', where only low levels of disturbance on the biological community come from anthropogenic activity (European Commission, 2000). Furthermore, the WFD requires that tools be available to quantify ecological consequences of water resources utilisation, such as water abstraction and river maintenance (Fjorbeck et al. 2002). The RHYHABSIM model is a tool that quantifies how flow affects in-stream habitat. Correctly applied, the model can provide an indication as to whether or not the current or planned utilisation of the water resources will significantly affect the fresh water habitat area.

It must be stressed that this study only assessed whether or not there is enough habitat available for streams to sustain a healthy ecosystem. Even if the streams are achieving the needed flows for suitable habitat, they still could be underperforming according to the environmental goals set (i.e. not achieving a 'good ecological condition'). Other factors could be influencing the biota, including pollution, predation, invasive species, sedimentation and alteration of stream morphology etc. For example, an evaluation in autumn 1999 on Langvad showed very poor juvenile brown trout populations, but had very good flows during that summer (Figure 9). In addition, the River Ledreborg realized a decrease in the natural recruitment rates of brown trout between 1997 and 2005 in spite of the maintaining of decent base flows. In these two cases, it is likely that other factors, such as dissolved oxygen, temperature, sedimentation or pollution are affecting the stream (Conallin, 2005). Particularly with respect to River Ledreborg, increased sedimentation in the spawning gravels observed over the last several years is a likely threat to the natural recruitment (Conallin 2005). Water temperature (above 20 degrees C) and dissolved oxygen (below 6 mg/l) are two factors which also can have a significant impact on trout survival (Danish EPA 1983), and these factors can be flow dependent (i.e. lower flows, with a slower stream velocity and volume, can increase water temperature faster during the day than higher flows). These two factors can be added to the RHYHABSIM model (Clausen et al. 2004), however it was not within the scope of this project to incorporate these factors.

In this study, two life stages of the brown trout, the juvenile and spawning, were evaluated, as it is the county's goal to re-establish a self-sustaining population of brown trout (both resident and sea trout spawning in the streams). These are the two most critical life stages for establishing and maintaining a self-sustaining trout population (Elliot 1994). For the survival of the juvenile trout in the stream, the model results from this study indicate a minimum flow of 4-5 l/sec in the streams before the loss of habitat area becomes critical. These results are similar to those generated from a model conducted from a separate study on the River Ledreborg in 2005 (Clausen et al. 2006). The model calculated ideal spawning conditions being in flows above 120-150 l/sec. In this case, the streams were meeting this requirement during the spawning months of November through January.

One of the primary concerns regarding water management within the study area is that groundwater abstraction is reducing the base flow in the streams significantly, and ultimately degrading the freshwater ecology (particularly available brown trout habitat) within the streams. This concern led to an agreement to reduce groundwater abstraction reduction in 1992. Currently, no new groundwater abstraction permits are being allocated and the current permits are not being renewed (Roskilde Amt 2003a). The reduction in 1992 resulted in an increase in baseflow for both Rivers Langvad and Ledreborg – the two streams with groundwater abstraction sites right along their courses. This study has shown that the base flows, even in the drier years such as 2001, are now high enough to provide the physical habitat for the survival of juvenile brown trout. This is in contrast to before 1992, where both streams (particularly Ledreborg) were not meeting these requirements. These stream's baseflow levels after 1992, however, are still approaching critical levels, and there is no possibility for any further decrease in baseflow for either stream. Therefore, when considering the issuing of groundwater abstraction permits based on its affect on available habitat in Rivers Langvad and Ledreborg, the goal would be to maintain or even slightly reduce the current groundwater withdrawal rates in order to maintain or even slightly increase baseflow. With that in mind, the current groundwater abstraction permits could be renewed, but additional permits should not be approved.

In the case of River Tokkerup, in 50 percent of the years between 1989 and 2002, the stream is not meeting the minimum base flow to protect the juvenile trout habitat. As this stream has no groundwater abstraction in its immediate area and it realized no increase in its base flow even after the groundwater abstraction reduction in 1992. Its low baseflows likely approximate its natural levels, therefore a further decrease of groundwater abstraction would probably not affect Tokkerup's stream flow. Therefore, from a management perspective, no action needs to be taken with respect to the groundwater abstraction and stream flow, even though this stream is not meeting the appropriate levels to sustain a naturally recruiting population of brown trout. A further reduction in groundwater abstraction would likely not increase the stream's baseflow. It is likely that the trout population in River Tokkerup has always been marginal in this stream, fluctuating from year to year depending on the natural precipitation, but this does not consider the effect that other management practices have had on the hydrology of the stream such as field drainage, and wetland destruction. Natural wetlands could have supplied the stream with enough baseflow to bring it up into the OAHR and support a naturally recruiting population.

When using this model, one needs to be particularly aware of the biological data available (Lund 1996; Clausen et al. 2006). In the case of this study, one of the weakest points was the lack of directly applicable biological data. No HSCs are derived for brown trout in eastern Denmark. As the development of HSCs is time consuming and a large task in itself, it was not within the scope of this study to develop the HSCs for the study site. Rather, the curves used were modified from curves developed for western Denmark and more indirectly American streams (Henriksen et al. 2002; Lund 1996; Bovee, 1978). Since these habitat suitability curves come from streams of similar size and morphology, it is believed that the curves provide the closest estimation of the habitat preferences for the study streams. Should the HSCs be developed for streams in eastern Denmark, the model should be revised to incorporate this more appropriate data. One of the assets of the RHYHABSIM model is its simplicity and ease of use, and like the case of this study, stream managers may not have the time or resources to develop these curves directly. Therefore, close attention must be made to the biological data used to make sure that it is the most appropriate data available in order to provide the most accurate results.

Monitoring and follow-up of the data is also important to assure the accuracy of the model results. Continual monitoring of the stream ecosystem is important to assure the accuracy of the model results. Monitoring of the actual flow recommendations, when they are in place, should include visual observations to decide if the flow limits set by the model and the following negotiation are actually meeting the hydromorphological demands of the streams such as covering riffles, providing enough depth in pools etc. The biological component should also be monitored to ensure that the flows are adequate. Monitoring will allow the data input and model output to be assessed and refined as conditions change both in the stream and as a result of management decisions. This will create a more solid basis for ongoing and future management decisions.

7. Conclusion

The River Kornerup catchment in Denmark is an excellent example of the challenges that will be faced by numerous water managers across the EU with regard to the implementation of the EU Water Framework Directive. Seventy-five years of groundwater abstraction has depleted the flow in the streams adversely affecting the stream's ecosystem. Authorities are now in the position where they need to find out how the stream is being affected ecologically, and devise management strategies in order for the stream to obtain a 'Good Ecological Condition' by 2015, as stated in the directive.

The ecological model RHYHABSIM was applied on three streams within the River Kornerup catchment in order to assess how stream discharge affects habitat for brown trout, which is being used as the ecological indicator for ecosystem health by the county. The model provided simple flow ranges for both the minimum and optimal discharge rates needed to sustain the ecosystem. When these flow rates were compared with stream flow data, it became apparent that the stream base flow was sufficient to provide the minimum habitat needed the survival of juvenile brown trout in Rivers Langvad and Ledreborg, but is not at Tokkerup during the driest summers, but was not adequate to supply the optimum amount of habitat needed in the streams for the entire summer periods for all years. However, it is apparent that there is enough stream discharge to provide the habitat to support the spawning of the trout during the winter months.

This model has been able to provide information not only on which life-stage is being affected the most, but also give an indication on how much the current flow regime needs to be increased (in the summer months) in order to meet the needs of the juvenile brown trout. Under current conditions, we recommend that the status quo be maintained for Rivers Langvad and Ledreborg. River Tokkerup is not directly affected by groundwater abstraction and probably has its natural base flow, except for the possible decrease from drainage, thus no action needs to be taken in relation to groundwater abstraction to increase its baseflow.

The application of the RHYHABSIM model was quick, simple and easy; a definite advantage for water managers whose time is already limited. The model is based on scientific information and provides a good assessment based on hydrological and biological principles rather than a "best guess". However, care must be taken that data – particularly the biological – is accurate and applicable to the stream conditions being studied. Like any model, the quality of the results is dependent on the quality of the data input. RHYHABSIM can provide a reasonable and valuable evaluation of the habitat conditions within a stream which can be used directly in the administering of water resources for a stream.

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References

Beecher, H.A. (1990): *Standards for instream flows.* Rivers 1:97-109.

Bourbon, P. (2004): *Local resident.* Personal Communication.

Bovee, K.D. (1978): *Probability of use criteria for the family Salmonidae.* Instream Flow Information Paper. No 4. Fort Collins, U.S. Fish and Wildlife Service (FWS/OBS/78/07).

Bovee, K.D. (1982): *A guide to instream habitat analysis using the instream flow incremental methodology.* Instream Flow Information Paper. No. 12. Fort Collins, U.S. Fish and Wildlife Service (FWS/OBS/82/26).

Bovee, K.D., and R.T. Milhous. (1978): *Hydraulic simulation in instream flow studies: Theory and techniques.* Instream Flow Information Paper No. 5. Fort Collins, U.S. Fish and Wildlife Service (FWS/OBS/78/33).

Clausen, B., Olsen, M., Pedersen, S., and Pedersen, M.L., (2006): *Habitatmodellering i Ledreborg Å. Effekten på ørred ved reduceret vandføring (in Danish).* Denmarks National Environmental Reserch Institute, report nr. 580, 58pp. http://faglige-rapporter.dmu.dk.

Clausen, B., I.G. Jowett, B.J.F. Biggs., and B. Moeslund. (2004): *Stream ecology and flow management.* In Tallaksen and Vanlanen (eds): Hydrological Drought – Estimation methods for streamflow and groundwater. Developments in Water Sciences, 48. Amsterdam, Elsevier.

Conallin, J. C. (2005): *The negative impacts of sedimentation on brown trout (Salmo trutta) natural recruitment, and the management of Danish streams.* Journal of Transdisciplinary Studies. Vol.3, No 2:1-12.

Danish EPA, (1983): *Vejledning i recipientkvalitetsplanlægning, del I vandløb og søer (in Danish).* Danish Environmental Protection Agency Instructional Guide (Vejledning) nr. 1.

Elliot, J.M., (1994): *Quantitative ecology and the brown trout.* Oxford University Press Inc., New York.

European Commission, (2000): Directive 2000/60/EC. *Establishing a framework for community action in the field of water policy.* European Commission PE-CONS 3639/1/100 REV 1. Luxemburg.

Fjorback, C., Pedersen, L.M., Kronvang, B. and Friberg, N. (2002): *Can the RHYHABSIM model be applied for evaluation of habitat improvement following river restoration: Case of remeandering the River Gels, Denmark.* ENVIRO Flows 2002. Proceedings of the international conference on environmental flows for river systems incorporating the 4th International Ecohydraulics Symposium, Cape Town, South Africa, March 2002. 20 pp.

Gordon, N.D., T.A. McMahon, and B.L. Finlayson. (1994): *Stream Hydrology: An introduction for ecologists.* John Wiley and Sons, Chichester.

Gordon, N.D., T.A. McMahon, Finlayson, B.L., Gippel, C.J., and R.J. Nathan. (2004): *Stream Hydrology: An introduction for ecologists.* Second Edition John Wiley and Sons, Chichester.

Henriksen, H.J., and Sonnenborg, A., (2003): *Ferskvandets kredsløb (in Danish).* NOVA 2003 Theme Report, Denmark and Greenland's Geological Survey, pp. 1-29.

Henriksen, P.W., Frederiksborg, Roskilde, Storstrøms og Vestsjællands amter, (2002): *Ørreder på Sjælland og Lolland-Falster. Bestande og gyde-forhold 1998-2002 (in Danish).* Udgivet af Frederiksborg, Roskilde, Storstrøms og Vestsjællands amter, ISBN nr. 87-7800-545-0, 108pp.

Henriksen, P.W., (2000): *Ørredbistanden i Langvad Å-systemet 1999 (in Danish).* Rapport conducted by Limno Consult for Roskilde Amt Technical Department, 50pp.

Hunt, B., Weir, J. and Clausen, B., (2001): *A stream depletion experiment.* Ground Water, v. 39, No.2, pp.283-289.

Jowett, I.G. (1989): *River hydraulic and habitat simulation, RHYHABSIM computer manual.* New Zealand Fisheries Miscellaneous Report 49, Ministry of Agriculture and Fisheries, Christchurch, New Zealand.

Jowett, I.G. (1992): *Models of the abundance of large brown trout in New Zealand rivers.* North American Journal of Fisheries Management 12: 417-432.

Jowett, I.G. (1997): *Instream flow methods: A comparison of approaches: Regulated Rivers:* Research and Management 13:115-127.

Jowett, I.G. (1998): *Survey and analysis of instream habitat.* Computer Manuel. (Revised by B. Clausen 2001). NIWA, Hamilton. New Zealand.

Lund, T. (1996): *Elverdamsaaen. Hydraulikkens og vandfoeringens betydning for oerredbestandens fysiske vilkaar.* Final Master Thesis. Geography institute, Aarhus University.

Madsen, W.J., (1995): *Danish Watercourses – Ten years with the new Watercourse Act.* Collected Examples of Maintenance and Restoration. Miljønyt nr. 11, 1995. Danish Environmental Protection Agency.

Michaelsen, Anne-Sofie. (1986): *Samspillet mellem vandindvinding, recipientforhold og fredningsplanlægning omkring Lejre (In Danish).* Statusrapport, Institute for Environment, Technology and Society, Roskilde Unviersity.

Mikkelsen, J. S., (2006): *Udsætningsplan for vandløb til Roskilde fjord: Distrikt 3 – vandsystem 1-26 (In Danish).* Danish Institute for Fisheries Research Report #3010, 32p.

Milhous, R. T., D. L. Wegner, and T. Waddle. (1984): *Users guide to the Physical Habitat Simulation System (PHABSIM).* Instream Flow Information Paper. No 11. Fort Collins, U.S. Fish and Wildlife Service (FWS/OBS/81/13).

Mortensen, E., and Geertz-Hansen, P. (1996): *Elektrofisheri til bestemmelse af fiskebestande i vandløb (in Danish).* 2nd Edition, Denmarks National Environmental Research Institute, 38pp. Technical Paper from DMU, Nr. 13., http://tekniske-anvisninger.dmu.dk.

Nyholm, T., Christensen, S., and Rasmussen, K. R., (2002): *Flow depletion in a small stream caused by ground water abstraction from wells.* Ground Water, vol. 40, No.4, pp. 425-437.

Rasmussen, J. (2004): *Biologist, Roskilde Amt.* Personal communication.

Regionplan 2005, for the Greater Copenhagen Region, Visions and Structure, Directions and Evaluation (in Danish). Report by Greater Copenhagen Authority (HUR), including members from Copenhagen Municipality, Copenhagen County, Roskilde County and Frederiksborg County. Report found at http://regionplan.hur.dk.

Roskilde Amt (1992): *Regulations for River Langvad: County Stream number 3 (in Danish).* 27 pp.

Roskilde Amt. (1998): *Hule Moelle Well Site: Effect of reduced groundwater abstraction (in Danish).* Roskilde County Technical Department. 13pp.

Roskilde Amt (1999): S*tatus for the condition of, and evaluation of groundwater abstraction's influence on the ecosystem in Ramsoe valley (in Danish).* Roskilde County Technical Department. 25pp.

Roskilde Amt (2003a): *Groundwater abstraction in the Lejre area: scenario calculations for changes in water withdrawal (in Danish).* Roskilde Amt Technical Department. 15pp.

Roskilde Amt (2003b): *Evaluation of the water balance in Ledreborg catchment area (in Danish).* Roskilde Amt Technical Department. 15pp.

Schroeder, N. (1995): *Water resource planning and administration near Roskilde (in Danish).* Pages 179-232 *in* Planning Between Conditions, Knowledge and Power (in Danish). TEKSAM Press, Roskilde University, Denmark.

Schroeder, N., and Bondesen, E. (1979): *The southern Hornsherred – consequences of water abstraction (in Danish).* Institute for Environment, Technology and Social Studies, Roskilde University. 38pp.

Titus, R.G., and H. Mosegaard (1992): *Fluctuating recruitment and variable life history of migratory brown trout, Salmo trutta L., in a small unstable stream.* Journal of Fish Biology. 41, 239-255.

Tunbridge, B. R., and Glenane, T. J. (1988): *A study of environmental flows necessary to maintain fish populations in the Gellibrand River and estuary.* Technical report series No 5. Arthur Rhylah Institute for Environmental Research. Department of Conservation . Forest and lands, Victoria, Australia.