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Impact of climate change and population growth on a risk assessment for endocrine disruption in fish due to steroid estrogens in England and Wales

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ABSTRACT

In England and Wales, steroid estrogens: estrone, estradiol and ethinylestradiol have previously been identified as the main chemicals causing endocrine disruption in male fish. A national risk assessment is already available for intersex in fish arising from estrogens under current flow conditions. This study presents, to our knowledge, the first set of national catchment-based risk assessments for steroid estrogen under future scenarios. The river flows and temperatures were perturbed using three climate change scenarios (ranging from relatively dry to wet). The effects of demographic changes on estrogen consumption and human population served by sewage treatment works were also included. Compared to the current situation, the results indicated increased future risk:the percentage of high risk category sites, where endocrine disruption is more likely to occur, increased. These increases were mainly caused by changes in human population. This study provides regulators with valuable information to prepare for this potential increased risk.

1. Introduction

The steroid estrogens estrone (E_1, natural hormone), estradiol (E_2, natural hormone) and ethinylestradiol (EE_2, synthetic hormone) were identified as the main chemicals causing intersex in male fish, which is a widespread issue in the UK (Jobling et al., 1998).

These substances may be referred to as “down-the-drain” chemicals as, after disposal/consumption, they enter river waters via sewage treatment works (STWs). The potential risk of fish intersex is therefore highest immediately downstream of STWs (Jobling et al., 2006). In 2012, the European Commission published a proposal suggesting a new annual average environmental quality standard of EQS 0.035 ng/L for EE_2 and 0.4 ng/L for E_2 (European Commission, 2012). Since then, these drugs have been placed on a watch list of priority substances in the field of water policy, which will be reviewed in 2014. The possibility of regulatory action on EE_2 is creating significant debate amongst a wide community (Gilbert, 2012). This debate re-emphasises the need for quantifying exposure to these substances and an assessment to identify where and to what extent risks might occur today and in the future. Indeed, the identification of regions at risk presently and in the future was identified as one of the top 20 priority questions related to pharmaceuticals and personal care products in the environment (Boxall et al., 2012).

Williams et al. (2009) assessed the risk of endocrine disruption induced by these steroid estrogens for the UK under current flow conditions at a catchment level. The concentrations of E_1, E_2, and EE_2 were estimated using a geographical information system–based model. The estimated concentrations were combined with effect levels to estimate the risk of endocrine disruption across England and Wales. A river network spreading over 21,452 km (10,313 individual reaches) and including more than 2000 STWs serving more than 29 million people was modelled. The study concluded that a very small proportion of the modelled reaches (1–3%) were predicted to be at high risk, and more than a third (39%) were at risk.

It is widely acknowledged that some level of climate change is unavoidable (Stocker et al., 2013). Climate change will affect river flows (Arnell and Reynard, 1996) and thus impact water quality via the dilution of contaminants leading to direct consequences on

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freshwater ecosystems (Delpla et al., 2009; Whitehead et al., 2009). It is recognised that, as for many other chemicals and in particular "down-the-drain" chemicals, climate change might affect steroid estrogen concentrations and thus the potential risk they might cause to the aquatic environment (Green et al., 2013; Sumpter, 2005). Gouin et al. (2013) explored the influence of climate change in multi-media chemical fate models. While they stressed that likely changes due to climate change would be relatively small (about a factor of 2) compared to the uncertainties in the chain of models required to produce such estimates, the processes determining the fate, persistence and bioaccumulation of chemicals would all likely be affected by at least temperature. A previous study from Green et al. (2013) evaluated the possible impact of future flows and demographics in the Erewash catchment in the UK which includes four STWs and has a catchment area of approximately 200 km^2. The study predicted a moderate increase in steroid estrogen concentrations and concomitant risk for feminisation in wild fish by 2050.

The purpose of this study is to test the hypothesis that climate change will result in an increased risk of endocrine disruption in fish due to steroid estrogens in England and Wales by 2050. Williams et al. (2009) previously reported the proportion of reaches at "high risk" of endocrine disruption in the UK as being small (1–3%). For comparison, the present study reproduced this risk assessment with assumed changes in river flows, water temperature and demography to assess how current risk is likely to change across England and Wales. The potential risk under future conditions is derived by comparing predicted environmental concentrations (PECs) with threshold levels defined by environmental effect levels (Williams et al., 2009).

2. Materials and methods

2.1. Overview of the risk assessment method

A risk assessment is available under current conditions, therefore for comparison purposes the same risk assessment method is applied (Williams et al., 2009). The approach adopted in that study was to compare PECs with thresholds levels representative of environmental effect levels.

The LF2000-WQX (LowFlows2000 Water Quality eXtension) model was used to generate PECs of estrogens for each river in England and Wales. LF2000-WQX is a mixed deterministic and stochastic model that combines hydrological models and water-quality models to produce spatially explicit statistical distributions (mean, standard deviation and percentiles) of "down-the-drain" chemicals in surface waters across England and Wales (Williams et al., 2009). The steroid estrogen input loads were determined based on the model described by Johnson and Williams (2004). Within LF2000-WQX, several processes were accounted for whilst estimating PECs, these included: STWs removal (which can vary depending on sewage treatment type), biodegradation and dilution within the water column, and parent to metabolite transformation (E_2 transforms to E_1). The model outputs consisted of a series of maps and tabulated data providing distributions of PECs (mean, standard deviation and percentiles) for each river reach modelled across England and Wales.

Estrogens occur in the environment simultaneously, it was therefore more appropriate to study their combined biological effect rather than the effect of each estrogen separately. Thus, Williams et al. (2009) applied a combined "toxic equivalent" approach based on estradiol equivalent (EEQ). The PECs of E_1, E_2, and EE_2 were then aggregated to produce an EEQ concentration ([EEQ]) which provided a quantification of the combined exposure of these three steroid estrogens:

$$[\mathrm{EEQ}] = \frac{[\mathrm{EE_2}]}{0.1} + \frac{[\mathrm{E_2}]}{1} + \frac{[\mathrm{E_1}]}{3} \qquad (1)$$

where $[EE_2]$, $[E_2]$ and $[E_1]$ represent the concentration of EE_2, E_2 and E_1 respectively.

The potential risk for fish endocrine disruption was then assessed based on the EEQ concentrations and each river reach was classified according to one of the following categories: "no risk" ($[\mathrm{EEQ}] < 1$ ng/L), "at risk" ($1 \leq [\mathrm{EEQ}] < 10$ ng/L) and "high risk" ($[\mathrm{EEQ}] \geq 10$ ng/L). The threshold between no risk and at risk was based on the predicted no effect concentrations (PNEC) for population level effect endpoints; a full description is given in Environment Agency (2008a). Briefly, for EE_2 this was the geometric mean of the lowest observed effect concentration (LOEC, 1.1 ng/L) and the no observed effect concentration (0.3 ng/L) taken from Wenzel et al. (2001) (= 0.57 ng/L) with a safety factor of 5 applied to give a PNEC of 0.1 ng/L. For E_2, the PNEC was based on 100% feminisation of medaka fish at 10 ng/L (Nimrod and Benson, 1998) with a safety factor of 10 applied. No suitable data were available for E_1 so it was set based on a relative potency to E_2 for vitellogenin induction (three times less potent). The high risk thresholds were set to give a high likely hood of a population realted effect were it to be exceeded. They were therefore based on the LOEC from the Wenzel et al. (2001) study for EE_2 and the PNEC from the Nimrod and Benson (1998) studies for E_2 without any safety factors applied. The value for E_1 was again set to be three times that of the value for E_2 (Environment Agency, 2008a).

2.2. Predicted environmental concentrations under future conditions representative of the 2050's

Whilst predicting concentrations for down-the-drain chemicals and in particular steroid estrogens, there were two main drivers: population (pollutant emission) and river flows (dilution in receiving waters). Both are likely to change in the future: climate change will give different river flows (Arnell and Gosling, 2013; Prudhomme et al., 2012) and the population of England and Wales is likely to increase (Shaw, 2002). Although the impact of in-stream biodegradation has been shown to have a negligible role in the overall dissipation of a range of pharmaceuticals in several UK rivers (Boxall et al., 2014), the influence of biodegradation was included. It was not expected to be very significant, but it makes a difference for short half life chemicals such as E_1 and E_2. The influence of in-river temperature changes on decay rates was also included for completeness.

2.2.1. Incorporating climate change impact on river flows

Climate change may affect many characteristics of the aquatic environment including river flow, river temperature, fish habitat, and the possible fish response to pollution (Hooper et al., 2013). Landis et al. (2013) recently published a set of recommendations for conducting ecological risk assessment in the context of climate change, and stressed the need to determine to what extent climate change should be incorporated. The authors also recommend the identification of the major drivers of uncertainty, and their quantification both spatially and temporally using methods such as the Monte-Carlo method. It has been acknowledged that dilution is currently the main driver in water quality (Whitehead et al., 2009) and in particular whilst estimating PECs for down-the-drain chemicals (Johnson, 2010; Price et al., 2009). It was therefore crucial to predict changes in river flows resulting from climate change.

Prudhomme et al., (2013; 2012) estimated changes in flow for Britain in the 2050s for the 11 different climate change scenarios