

Catchment Modelling of Pesticide Contamination Risk in East Anglia, UK

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1. Introduction

Metaldehyde is the active ingredient in the most common slug pellets. It is primarily used on arable crops such as oilseed rape and wheat, to protect the crops against slug damage. Metaldehyde has been detected in raw water across the UK since 2007/2008, when most water companies first included it in their routine pesticide monitoring programme of raw water abstractions and treated water. Metaldehyde is not effectively removed using standard water treatment processes such as Granular Activated Carbon (GAC), chlorine and ozone.

During AMP5 (UK water industry 5 year planning period for 2010-2015), water companies implemented agreed legal programmes of work ('Undertakings') with the Drinking Water Inspectorate (DWI) to reduce the risk of breaching the drinking water quality regulations. This primarily included catchment management measures with the aim of reducing the metaldehyde load at source. Catchment management has the potential to reduce the need for energy and carbon-intensive water treatment; protecting the environment and allowing water companies to meet water quality standards in a cost-effective way.

All of Anglian Water's 15 surface water treatment works (WTWs) are affected by metaldehyde, with 14 of these being subject to Undertakings in AMP5. In total, these undertakings covered 23 surface water catchments (some of which comprise sub-catchments within larger catchments), covering an area of approximately 9,000 km². The Undertakings included:

- Catchment management investigations: assessment of the potential of using catchment management solutions to reduce raw water concentrations of metaldehyde.
- Abstraction management: assessment of the feasibility of controlling abstractions to avoid using water containing the highest concentrations of metaldehyde.
- Treatment options: investigation of potential treatment options.

The AMP5 catchment management programme focused on developing an understanding of key stakeholders, understanding catchment characteristics and the use of metaldehyde, to confirm the potential of using catchment management to control pesticide concentrations in waterbodies and to inform the strategy in AMP6 (2015-2020).

The purpose of the work described in this paper was to develop a modelling approach to evaluate the potential effectiveness of catchment management to control metaldehyde concentrations in raw water abstracted from rivers or reservoirs in the Anglian region. This will allow Anglian Water to focus

their resources on catchments where specific interventions provide a viable solution to the problem of metaldehyde contamination.

More specifically, the study aimed to:

- Increase the understanding of the catchments and the cause of the water quality problem currently observed; and
- Identify and assess potential catchment solutions:
 - Will catchment management work?
 - If so, where will catchment management be most effective?
 - What measures should be promoted?

Numerical models have been developed for all 23 catchments using the Soil and Water Assessment Tool (SWAT) (USDA-ARS and Texas A&M AgriLife Research, 2015). The modelling tools have been used to assess the impact of different land management measures on water quality by testing different land management scenarios. Measures can now be targeted where they are most effective.

This project was collaborative, with the work being undertaken by a project team comprising staff from both Anglian Water and Mott MacDonald. The team was co-located at an Anglian Water office to facilitate communication and knowledge dissemination.

This paper outlines the modelling process, starting with the development of a conceptual understanding of metaldehyde transport in the catchments. The model setup and calibration process is then described, followed by the approach taken to modelling catchment management scenarios. Two case studies are used to illustrate the challenges faced and the results of the modelling, and finally the conclusions of the project are summarised.

2. Conceptual understanding of metaldehyde transport

To inform the catchment modelling a conceptual understanding of the hydrological character of each catchment and the sources and transport pathways of metaldehyde was developed. A Source - Pathway - Receptor framework has been adopted. This approach includes identification of the relationship between (i) the sources of contamination, (ii) the route/pathway the contamination takes to the (iii) receptor (e.g. a drinking water supply). This understanding was used to inform and justify the representation of the catchments within the SWAT model and the plausibility of the model's behaviour of internal state variables such as soil moisture status, crop growth behaviour and flow partitioning within the soil as part of the calibration process.

2.1. Sources of metaldehyde

Metaldehyde is a popular product for slug control, due to its high effectiveness coupled with relatively low financial cost. It is mainly used on oilseed rape, winter wheat and potatoes and is applied in pellet form, often from quad bikes. Most diffuse pollution of metaldehyde is associated with use on winter wheat and winter oilseed rape. This is because the use of metaldehyde on potatoes primarily occurs in the late spring or early summer, while usage on winter wheat and winter oilseed rape occurs in the autumn when soils are saturated and the risk of surface runoff and tile flow is significant.

Metaldehyde is also used to control slugs in plant nurseries, garden centres, private gardens, and communal areas. However, given the large proportion of arable land within the study area and the timing of metaldehyde peaks observed during the autumn, the predominant source of metaldehyde is

from application on arable crops. Therefore, metaldehyde used for potential purposes other than arable farming was not included in this study.

Metaldehyde may also reach surface waters from point sources from point sources, such as hard surfaces on farms, including filling of applicators, equipment wash-down operations, and accidental direct application to adjacent watercourses (including open drains). However, due to the lack of information on where and how the applicators are filled and how accurately pesticides are applied on fields, point sources have not been included in the modelling study.

2.2. Transport pathways

Figure 1 summarises the potential diffuse pathways and their relevance to the various forms of metaldehyde.

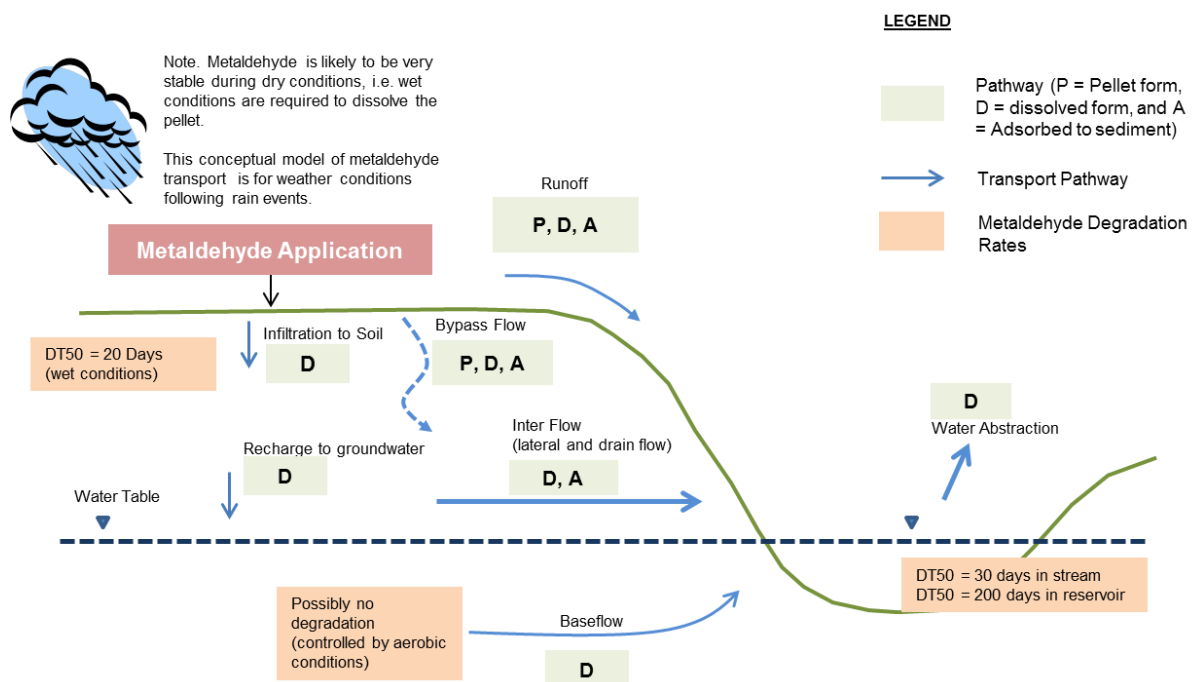


Figure 1: Generic conceptual model of metaldehyde pathways and degradation

The principal diffuse pathways of metaldehyde to watercourses include transport via:

- Surface runoff
- Interflow
- Tile drains

The most rapid pathways for metaldehyde are through surface runoff and flow in tile drains, which are likely to be important in areas with slow-draining, clayey soils. Interflow through the soil profile is a slower process but is also likely to be an important pesticide pathway.

Metaldehyde is applied to crops in pellet form. This means that metaldehyde can be transported in three different forms:

- In pellet form, or fragments of pellets
- In dissolved form
- Adsorbed to sediment.

In its dissolved form, metaldehyde can reach a watercourse through all pathways. Metaldehyde adsorbed to sediments can reach watercourses via surface runoff, drain flow through underdrains and bypass flow. When metaldehyde is in pellet form, it is limited to surface runoff and bypass flow, and the latter will only occur if cracks are large enough. The pellets are unlikely to reach underlying drains as the infilling material will act as a barrier.

The degradation of metaldehyde in the soil will vary depending on factors such as soil temperature, soil moisture, organic material and oxygen conditions; reported values in the available literature for the half-life of metaldehyde in soil vary from 10 to more than 200 days (Mott MacDonald Ltd, October 2011). The degradation of metaldehyde also includes a lag-phase for the pellet to degrade, followed by chemical and biological degradation of metaldehyde, which is not included in reported half-life values.

2.2.1. Spatial distribution of transport pathways

Each catchment includes areas of different hydrological characters; hence the risk of metaldehyde application resulting in contamination will show spatial variation. The risk of diffuse metaldehyde pollution is dependent on a number of factors including land use, permeability of the soil, the presence of drainage features, land slope and proximity to watercourse. To summarise the conceptualisation of each catchment the sensitivity of different areas to fast pesticide transport pathways and consequent contamination of surface water was assessed and mapped. A series of sensitivity categories were defined as follows:

- High sensitivity: these areas are characterised by clay soils, which have a high runoff potential and are heavily drained. Therefore fast metaldehyde pathways are likely to be important.
- Moderate sensitivity: these areas are also likely to be drained, but the drainage density is likely to be lower than in the more clayey soils. Surface runoff is also likely occur in these areas, but is less significant than that in the high sensitivity areas.
- Low sensitivity: these areas are characterised by arable land which is subject to metaldehyde application. However, permeable soils dominate, resulting in slower transport of metaldehyde to streams and increased attenuation and more opportunity for degradation.
- Enhanced sensitivity due to proximity to channel: the characteristics of these areas are mixed, with a range of soil permeability. Therefore, whilst they may not be subject to the fast pathways of runoff and drain flow, their proximity to the channels means the time for attenuation of metaldehyde is reduced and there is a greater chance of high concentrations reaching the streams from these areas.

3. Modelling approach

The SWAT modelling software (USDA-ARS and Texas A&M AgriLife Research, 2015) was used to simulate catchment hydrology and metaldehyde transport processes in each catchment supplying a surface water treatment works (WTW) via a river intake and/or a reservoir. SWAT is a physically based model which uses readily available data to predict the impact of land management practices on water, sediment and agricultural chemicals yields in large complex watersheds with varying soils, land use and management conditions over long periods of time.

3.1. Model setup and parameterisation

The model set up and parameterisation were informed based on the conceptual understanding of each catchment developed as described above using the available data on climate, soils, geology, topography, hydrology, land use and land management practices.

3.1.1. Watershed, subbasin and hydrological response unit definitions

SWAT processes a Digital Terrain Model (DTM) to delineate a watershed, then partitions the watershed into a number of subbasins. A portion of stream, or reach, is associated with each subbasin. The subbasins are defined by SWAT according to the topography of the catchment and location of confluences with some manual addition of subbasins, so that all available calibration locations (see below) are coincident with subbasin outlets.

Each subbasin is sub-divided into hydrological response units (HRUs) which represent unique combinations of land use, soil type, and slope. SWAT calculates a water balance for each HRU using its associated parameters and then aggregates the results into a subbasin water balance. The number of HRUs in the model affects the run-time of the model. To enable model efficiency, the number of HRUs is rationalised by only including the dominant combinations of land use, soil and slope within each subbasin.

3.1.2. Hydrological parameterisation

Hydrological inputs broadly fall into two categories: spatial parameters describing the catchment; and time-series model inputs. The time-series inputs to the model are data series and are fixed at model setup after the catchment is defined using the DTM, other spatial inputs are used for model parameterisation and calibration.

Key inputs for hydrological parameterisation include:

- Climatic data: time-series of rainfall, potential evapotranspiration (PET), wind speed, relative humidity, solar radiation, temperature;
- Abstraction and discharge data: time-series of recorded abstraction and discharge volumes;
- Hydraulic parameters: Manning's 'n' roughness coefficient, stream length adjustments to account for meandering, hydraulic conductivity of the channel;
- Rainfall-runoff parameters: runoff routing based on the curve number method, surface runoff lag time;
- Tile drainage: assumed to be present within selected HRUs according to their soil type and land use; for example arable land on slow-draining soils is assumed to be drained using tile drainage;
- Groundwater storage and flows: groundwater parameters control amount and timing of baseflow, baseflow recession rate and groundwater losses to deep aquifer storage;
- Reservoir data: reservoir dimensions and operation. Where available, recorded time-series of reservoir inflow and outflow data were included in the SWAT model.

3.1.3. Cropping and land management

Crop growth influences the modelled hydrology by affecting catchment runoff, actual evapotranspiration and soil moisture dynamics. SWAT contains a plant database describing the properties of each plant which determines how its growth is modelled and its dependence upon factors such as climatic conditions and soil nutrients. The default crop parameters were left largely unaltered during this project.

The type of crops grown in each of the catchments was informed using agricultural census data from 2010, which is aggregated to a 2km grid resolution (EDINA, 2010). Crop rotations, used widely in arable farming to improve productivity, were taken into account when assigning crop types to each HRU for each year of the model period. There is insufficient data to accurately assign crop rotations to any portion of land or to establish exactly what crop rotations have been used. Instead, general knowledge of cropping patterns and information on the proportions of crops planted in each year has been assumed to synthesise a crop planting schedule for each HRU. Crop rotations were selected so that the overall percentage of arable land planted with key crops in each catchment was consistent with cropping data (EDINA, 2010).

SWAT uses management operation parameters to simulate planting, fertilising, pesticide application and harvesting in each HRU. Typical dates for planting and harvesting in the Anglian region were informed by external guidance and agronomist advice (Holman & Whelan, 2012) and included as generalised dates. Auto-fertilisation, where fertiliser application is simulated as required by the plants, has been used as it was important that plant growth was not constrained by a lack of nitrate in the model.

Metaldehyde application is input into the SWAT Model as a load (as kg/ha) which can be defined for each HRU. Initial application loads and timings were based on survey data from the East Anglian region (Food and Environment Research Agency (FERA), 2008 - 2010). This data is similar to the results of a farm survey conducted on behalf of Anglian Water from 2008 to 2011 in the three catchments in the region. Therefore the data was considered an appropriate indication of applications in the Anglian region as a whole.

3.1.4. Metaldehyde transport

As described above, metaldehyde is transferred via the hydrological pathways and degrades on route. The degradation in SWAT is directly dependent on the rate constants assigned to metaldehyde and indirectly dependent on hydrological parameters associated with the hydrological pathways. Chemical and physical characteristics of metaldehyde were added to the SWAT pesticide database, based on the values found in a literature review (Mott MacDonald Ltd, October 2011).

3.2. Model calibration

The initial build and parameterisation of the model derives from the conceptual model which is a simplified representation of the catchment system. Each SWAT model is then refined through calibration to reproduce the hydrological conditions identified in the conceptualisation stage and to reproduce the observed water quality conditions at monitoring points on the river system.

Along with data uncertainties and the estimation of parameters, there will be a certain amount of variability in the model outputs. Consequently, the model results will never exactly reproduce measured field data or recorded water balances. The method of adjusting parameters through calibration is carried out to achieve an acceptable match between recorded and simulated values, while retaining a physically realistic representation of the conceptual model..

To ensure that all the Anglian Water SWAT models are constructed to consistent specifications and accuracy, calibration targets have been defined. It is not the objective that these calibration targets be rigorously adhered to, they are in place to provide guidelines for each model calibration.

3.2.1. Hydrological calibration

Simulated flows were calibrated against the available time series data from the extensive flow gauging network across the UK, with calibration points defined based on the location of flow gauges.

Nash-Sutcliffe efficiency (Nash & Sutcliffe, 1970) was used as a hydrological calibration metric. This is a recognised coefficient which is commonly used to assess the predictive power of hydrological models. An efficiency of one indicates a perfect match between modelled and observed data, whereas an efficiency of less than zero indicates that the observed mean is a better predictor than the model. All calibration metrics below were calculated for the whole modelling period (excluding a model warm-up period) and for specified calibration and verification periods.

The starting point for the model hydrological calibration was matching the simulated average annual water balance produced by the model with the observed water balances at each calibration point. For calibration, the total flow and the total baseflow were summed over the modelling period. These amounts and the ratio between them provided the target for initial calibration. The target percentage difference between recorded and modelled flows was 5%.

Following calibration of the water balance, the baseflows were calibrated. “observed” baseflows were derived from the observed flow data using an automated baseflow separation technique (Arnold, et al., 1995). The calibration then entailed “matching” the baseflow profiles produced from observed data with SWAT modelled baseflows for each calibration data series. Here, the calibration target was a Nash-Sutcliffe efficiency of 0.5.

Calibration of total flows then took place; this comprised “matching” recorded total flow series with SWAT modelled flow series at each calibration point. The calibration target was a Nash-Sutcliffe efficiency of 0.5. In this process the timing and magnitude of modelled peak flows was prioritised over lower flows, as peak flows are responsible for metaldehyde transport through a catchment. The aim was to produce modelled peak flows within two days of the observed peak flows and within $\pm 33\%$ of recorded flow magnitudes (prioritising bigger peaks over smaller ones).

To ensure that the model is behaving sensibly internal state variables were also assessed. The variables assessed were actual evapotranspiration, crop growth and soil moisture deficits. The modelled values were compared to recorded data (soil moisture deficit and evapotranspiration) or reference target values (crop growth).

3.2.2. Metaldehyde concentration calibration

In-stream and reservoir metaldehyde concentrations were calibrated against water quality data collected by Anglian Water. The calibration of recorded and modelled pesticide was achieved principally by eye. This is due to the recorded values being much less frequent (weekly or less) than the daily time step of the SWAT model. The following approach was adopted:

- Ensure pesticide is applied to crops before the observed in-stream peaks in metaldehyde concentration.
- Prioritise the timing and shape of the peaks over the magnitude of the peaks. Given the high degree of uncertainty with regards to application quantities and management practices it is very difficult to replicate the exact magnitude of the peaks.
- Adjust the timing of pesticide application so that the modelled and observed peak timings are as closely matched as possible, whilst accounting for the fact that observed data is not available for every modelled peak.
- Adjust the metaldehyde degradation parameters (half-life in soil) so the recession curve passes through the observed points, and so that the tail of the modelled metaldehyde peak reaches equilibrium levels at the same time as the observed (but not necessarily the same value).

4. Catchment management scenarios

4.1. Objectives

The objectives of the modelled catchment management scenarios are to identify and assess the potential catchment management measures and to establish:

- i. Will catchment management measures reduce metaldehyde concentrations to below the regulatory limit of 0.1µg/l?
- ii. If so, where will catchment management be most effective and what type of solutions should be promoted?

4.2. Scenario definitions and approach

The scenarios implemented in the model are summarised in Table 1. These scenarios were developed for use in all surface water catchments included in the catchment management programme. These scenarios were selected to give an initial indication of the reduction in metaldehyde concentrations that may be possible with a programme of catchment management. The aim was to use the first five scenarios to determine the impact of these measures, then to refine and/or combine the most effective of these to meet the objective of no metaldehyde concentrations over 0.1µg/l at the abstractions for water supply.

The WTWs under investigation are fed by their natural catchments and by pumped transfer from one or more nearby catchments. The catchment management scenarios were applied to each of these catchments individually to determine which has the greatest impact on metaldehyde concentrations.

Table 1: Summary of catchment management scenarios

Scenario	Natural catchments	Pumped catchments
1	Product substitution across all arable areas (% of arable areas)	
1a	80%	0%
1b	0%	80%
1c	80%	40%
2	Product substitution on clay soils	
2a	100%	0%
2b	0%	100%
3	Product substitution in steeper areas (>3 deg slope)	
3a	100%	0%
3b	0%	100%
4	Reduced metaldehyde close to watercourses (using pre-defined buffer areas appropriate to each catchment's size)	
4a	100%	0%
4b	0%	100%
5	Reduced metaldehyde through guideline dose rate (g/ha)	
5a	60	No change
5b	60	160
5c	160	No change
5d	160	160
6	Combination of most effective measures	
6a	Scenario 1a plus additional of the most effective measures to identify how the 0.1µg/l target might be achieved.	
6b, 6c...	Alternative combinations of measures to identify how the 0.1µg/l target might be achieved.	

The scenarios have been implemented by adjusting the amount of metaldehyde applied to each HRU, or by adjusting the metaldehyde loading in flows to the Reservoirs. For scenario 1 a tool has been developed to randomly select arable HRUs that cover 80% or 40% of the total arable land in either catchment, as relevant for each scenario. The areas targeted in the management scenarios 2, 3 and 4 are classified as those areas that are expected to represent a high risk of metaldehyde transport. These high risk areas are located on arable land on clayey soils (scenario 2), steep slopes (scenario 3) and close to streams (scenario 4).

In scenario 5 the maximum metaldehyde dose rate has been reduced to either 60g/ha or 160g/ha. The 160g/ha value represents the UK Metaldehyde Stewardship Group guideline amount for additional protection of water (Metaldehyde Stewardship Group, 2013). The 60g/ha value was used to investigate the effectiveness of a more stringent maximum guideline amount. This scenario has been implemented by reducing any calibrated applications that exceed the selected guideline rate to the relevant value.

The scenarios that proved most effective in reducing metaldehyde concentrations were then combined or refined for scenario 6.

5. Case studies

The effectiveness of the simulated catchment management scenarios on reducing metaldehyde concentrations at the surface water sources varied considerably. Two case studies are used to demonstrate the results.

5.1. Ardleigh water treatment works

5.1.1. Catchment overview and conceptualisation

Ardleigh WTW is fed by Ardleigh Reservoir, which receives large volumes of water from the East Mills intake on the River Colne and the Northern and Western Salary Brooks in the direct reservoir catchment, as shown in Figure 2. The direct catchment of Ardleigh Reservoir covers approximately 12km² and the River Colne's catchment area is approximately 256km².

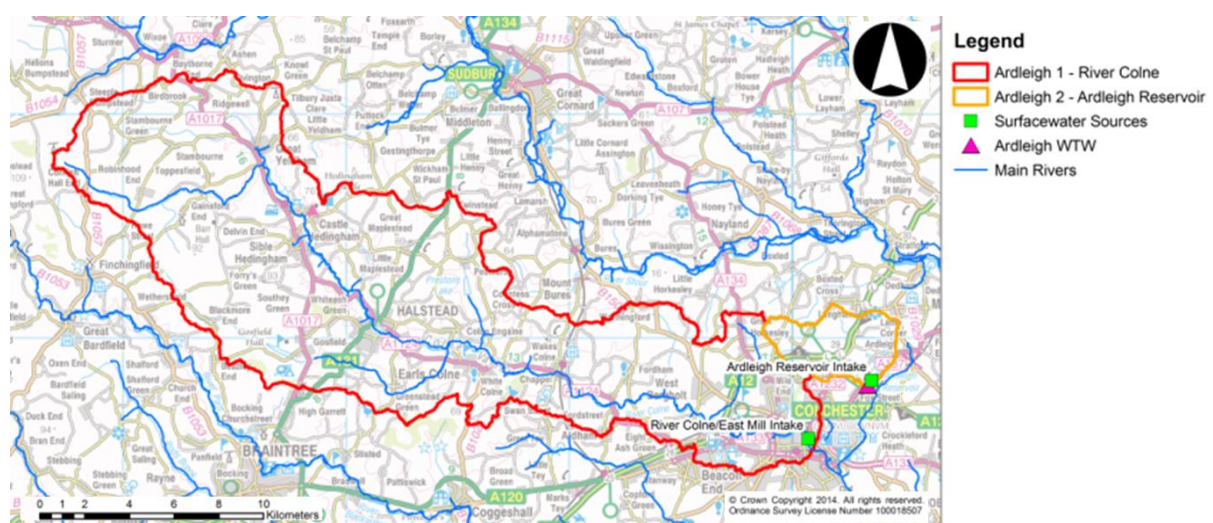


Figure 2: Location of catchments feeding Ardleigh WTW

Metaldehyde usage in the Ardleigh catchments is likely to be widespread as a large proportion of these catchments is under arable land use, and approximately 65% and 40% of arable land is

estimated to be under winter wheat and oilseed rape cropping, in the Colne catchment and reservoir catchments respectively.

Conceptualisation of the catchment indicated that the fastest pathways of metaldehyde transport would occur in the upstream reaches of the River Colne, where soils are clayey and runoff and tile flow are likely to dominate. In addition, the areas close to watercourses are likely to contribute higher amounts of metaldehyde, due to the reduced distance over which metaldehyde degradation is able to occur. The conceptual understanding of the sensitivity of the catchment in terms of metaldehyde transport is illustrated in Figure 3, using the sensitivity mapping process outlined in Section 2.2.1.

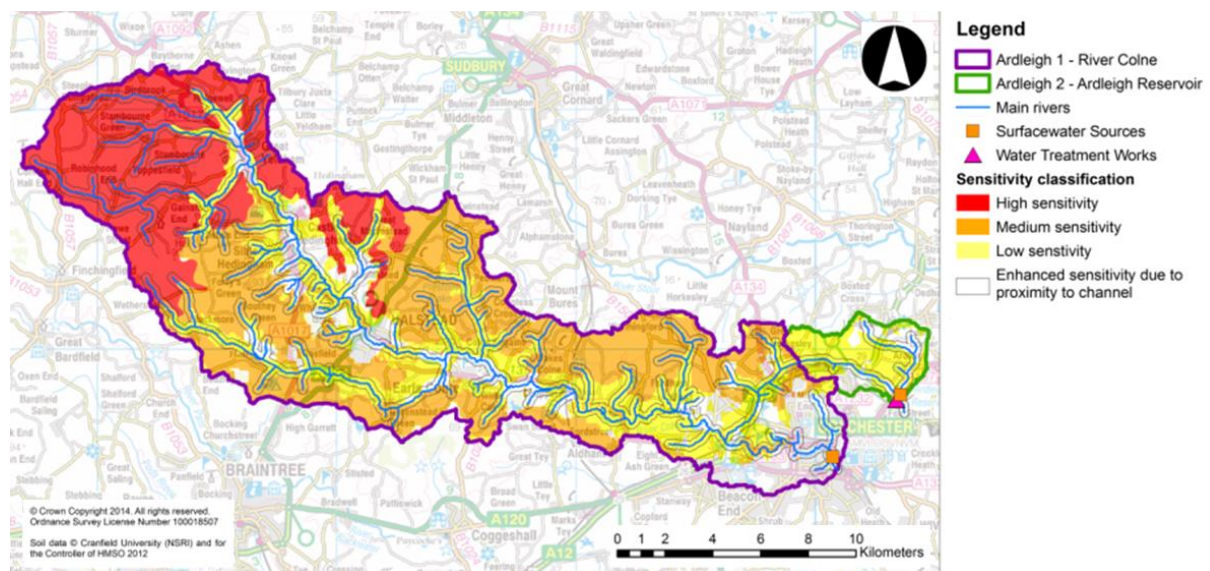


Figure 3: Sensitivity map for metaldehyde transport and contamination in the Ardleigh catchments

5.1.2. Model build

The SWAT model setup for the Ardleigh catchments was carried out as outlined above. Two separate SWAT models were built for the natural reservoir catchment and the River Colne catchment, to improve the efficiency of the model runs. Figure 4 summarises the model setup of the River Colne catchment, showing the delineation of subbasins and calibration points.

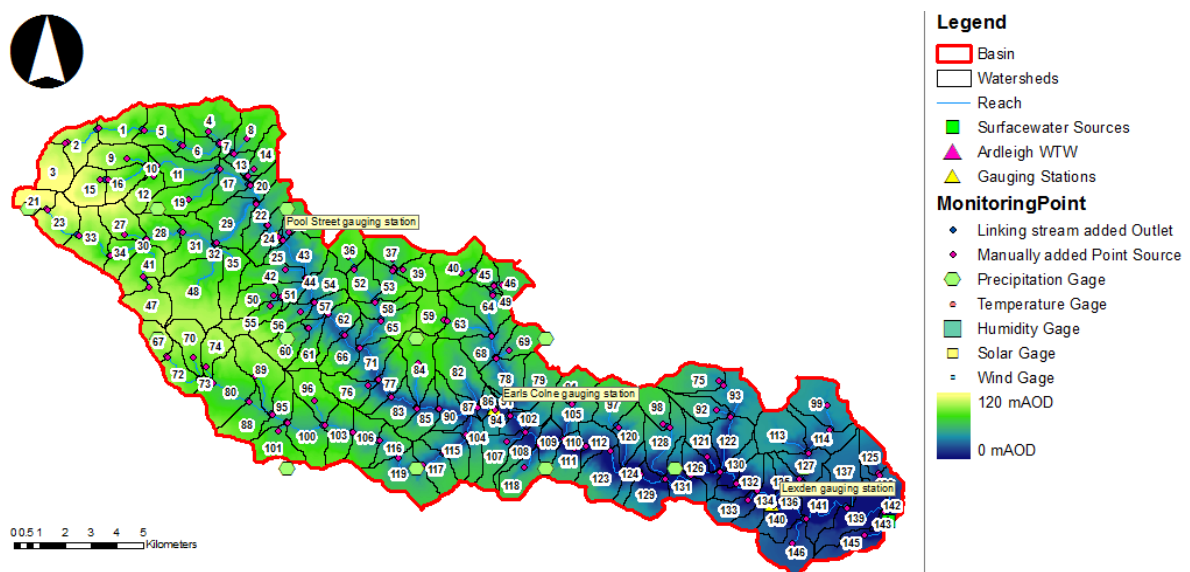


Figure 4: Model setup - River Colne catchment

5.1.3. Model calibration

Overall a good calibration was achieved for the Ardleigh models. The modelled water balance broadly reflects the conceptual understanding of the catchment; simulated surface runoff and tile drainage was highest in the upper reaches of the River Colne catchment, coinciding with the clayey soils. Where more permeable soils dominate, runoff and tile drainage are much less significant. The calibration of flow in the River Colne catchment is good, as shown in Table 2 and Figure 5. However, the model could not replicate the hydrology during a period of exceptionally dry period from October 2011 to the end of the model period.

Table 2: Nash-Sutcliffe values at the Lexden gauging station on the River Colne

Calibration/validation period		Nash-Sutcliffe values at Lexden gauging station	
		Baseflow	Total Flow
Whole modelling period	June 06 – Oct 11	0.49	0.69
Calibration period:	June 06 – May 07	0.57	0.74
Validation period:	June 10 – May 11	0.55	0.77

The hydrology in the Ardleigh Reservoir catchment was compared with an Anglian Water simulated flow series and therefore was treated as an approximation, with no calibration statistics calculated. Calibration of the volume of water in Ardleigh Reservoir was acceptable, although the model underestimated volumes from 2007 to mid-2008.

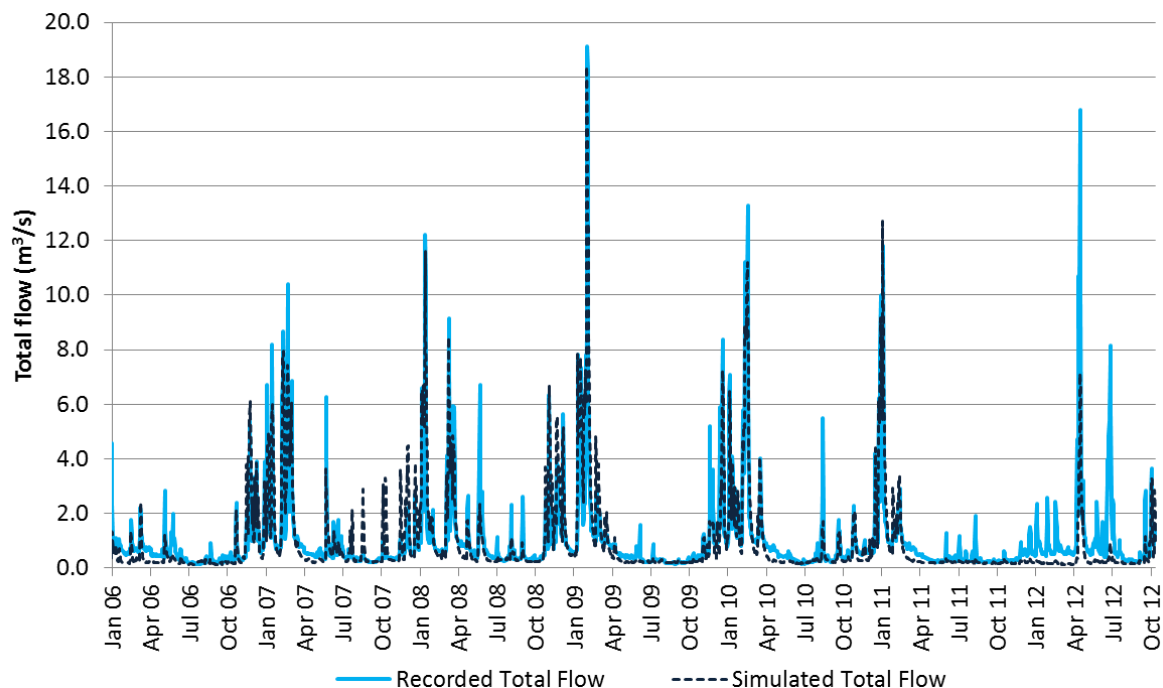


Figure 5: Hydrological calibration at Lexden gauging station on the River Colne

Despite the lack of actual data on application rates and timing, a good water quality calibration for metaldehyde was achieved at the East Mills intake and the natural inflows to the reservoir. Figure 6 shows the calibration of metaldehyde at the East Mills intake. Due to the underestimation of flow at the end of the model period the metaldehyde concentrations are also lower than recorded during 2012. The calibration of metaldehyde in Ardleigh Reservoir (see Figure 7) suffered from underestimation of peaks, despite good calibration of metaldehyde concentrations in the inflows to the reservoir. This can be attributed to the simulation of reservoirs in SWAT as well-mixed waterbodies, which is unrealistic

in the case of Ardleigh Reservoir. This underestimation was accounted for when evaluating the effectiveness of the catchment management scenarios, which was primarily assessed at the intakes to the reservoir to have confidence in concentrations meeting the regulatory limit of 0.1µg/l in the reservoir.

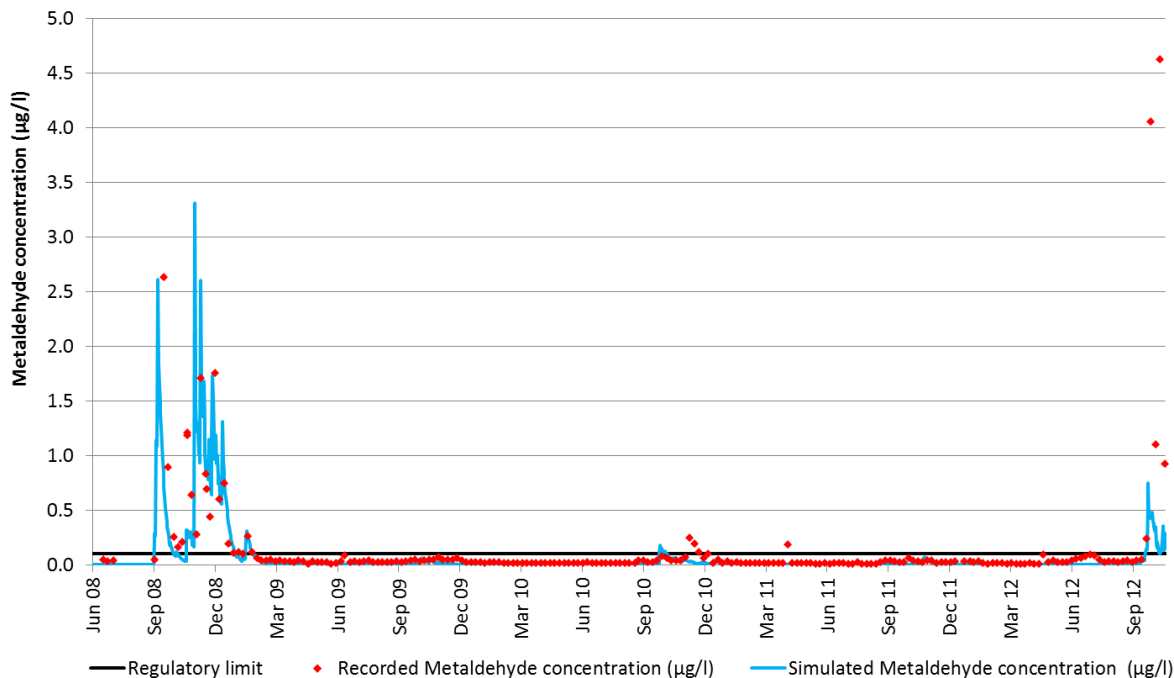


Figure 6: Calibration of metaldehyde concentrations at the East Mills intake

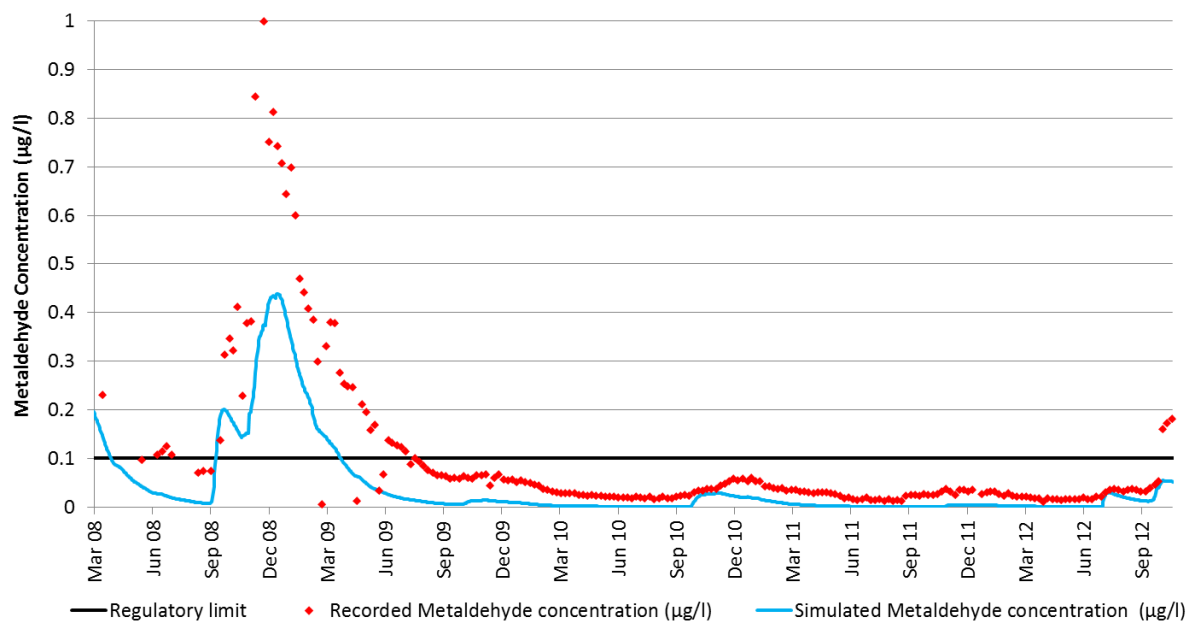


Figure 7: Calibration of metaldehyde concentrations in Ardleigh Reservoir

5.1.4. Catchment management scenario results

Catchment management scenario modelling showed that the pumped River Colne catchment is the dominant source of metaldehyde in Ardleigh Reservoir. This is largely due to the relative size of the larger catchment and its contribution to the total reservoir inflows. In addition, the dominance of low-permeability soils in the Colne catchment results in high surface runoff and drain flow; the most rapid pathways for metaldehyde through the catchment. The significance of metaldehyde contributions from the River Colne catchment suggests that catchment management measures in the natural

reservoir catchment have a less significant impact on metaldehyde concentrations in Ardleigh Reservoir. Therefore interventions focused in the pumped River Colne catchment would be most effective.

To successfully reduce metaldehyde concentrations to below the regulatory limit of $0.1\mu\text{g/l}$ in Ardleigh Reservoir, catchment management measures are likely to be required over all arable land in the River Colne catchment, and some in the natural pumped catchment. However, it may not be necessary to completely remove metaldehyde applications over this entire area. The model indicates that metaldehyde should be replaced with an alternative product on low-permeability, artificially drained soils, where the risk of metaldehyde transport to watercourses is high (through surface runoff and drain flow), and that on all other arable land metaldehyde applications should be reduced to a maximum of 60g/ha . The areas impact that this scenario has on metaldehyde concentrations at the East Mills intake and in Ardleigh Reservoir are shown in Figure 8.

Metaldehyde concentrations in some reservoirs, including Ardleigh, could be controlled using abstraction management, which was not investigated as part of this project. If there are sufficient resources from the natural catchment to maintain water levels in a reservoir, the pumped transfer could be stopped during periods of elevated metaldehyde concentrations. The use of abstraction management would require careful management to avoid disruption to water supply and is currently being investigated by Anglian Water.

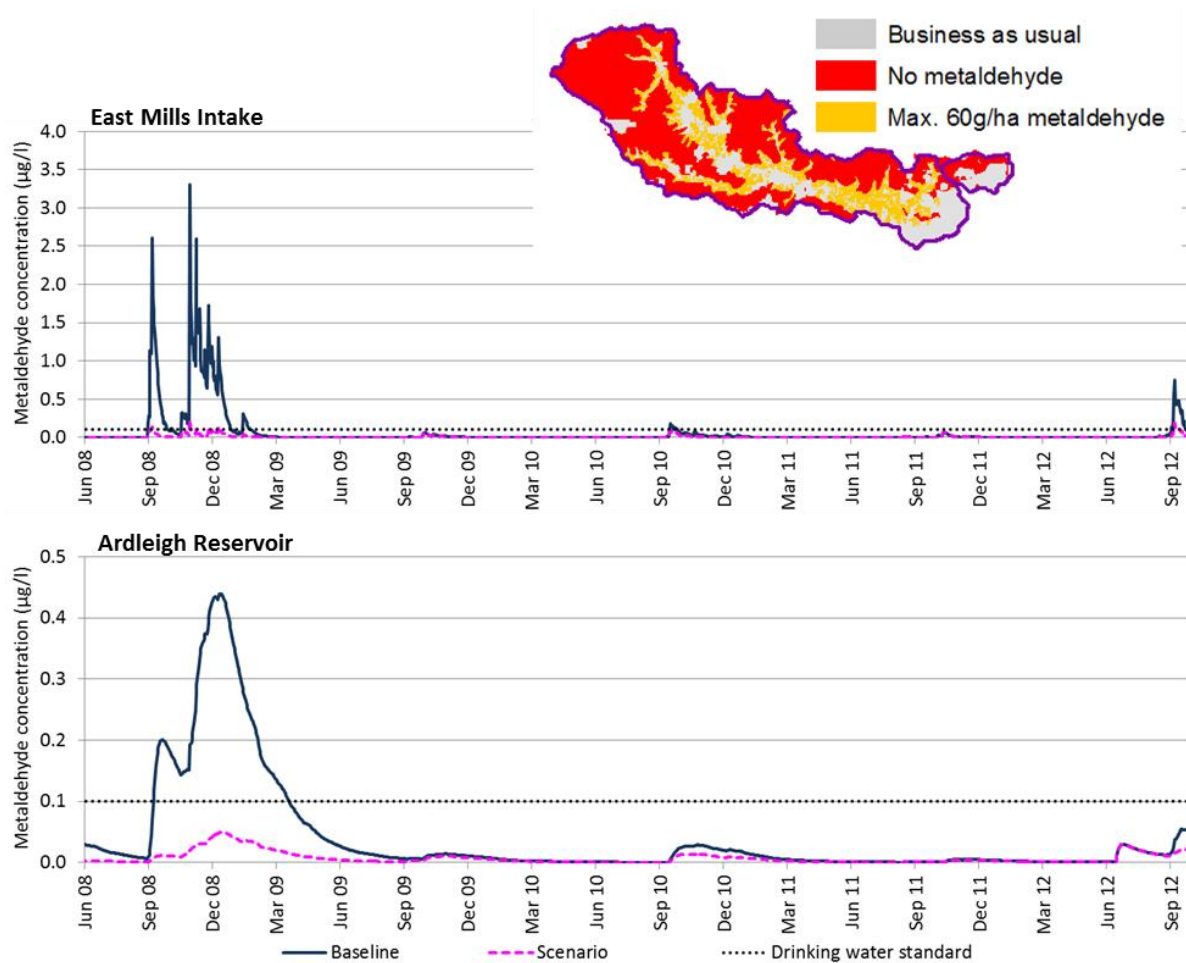


Figure 8: Results of most effective scenario for Ardleigh WTW

5.2. Elsham Water Treatment Works

5.2.1. Catchment overview

Elsham WTW is fed by the River Ancholme catchment in Lincolnshire. Due to the heavy demands placed on the River Ancholme by agriculture and industry, two neighbouring catchments, the River Trent and River Witham, are used to support flow in the Ancholme through a system of pumped transfers. The catchments and the system of transfers are shown in Figure 9. Therefore, the potential area that could contribute metaldehyde to the River Ancholme is very large, covering a total area of 1173km².

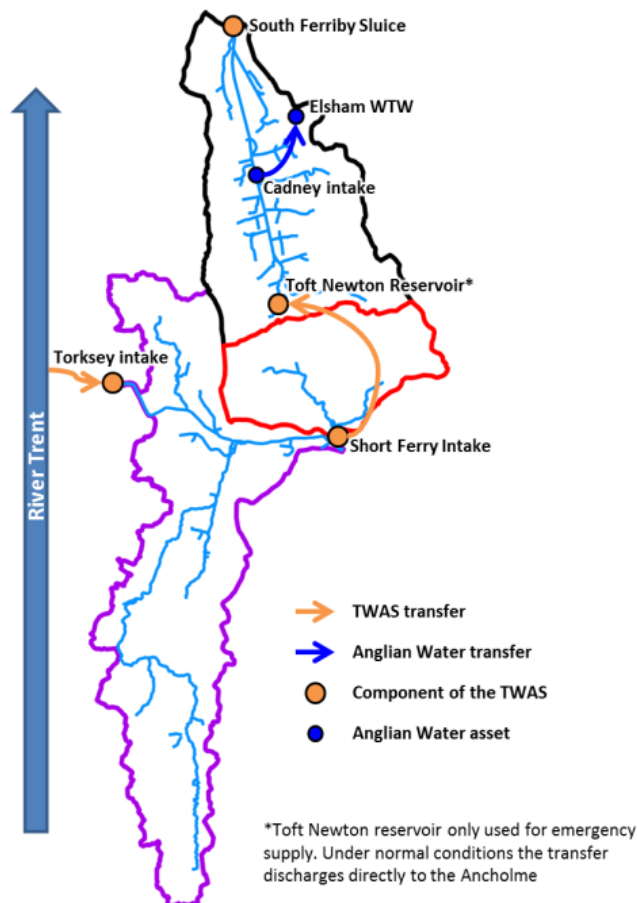


Figure 9: Diagram of transfers between the catchments feeding Elsham WTW

5.2.2. Model setup and calibration

The Elsham catchment model was built following the same process as the Ardleigh model. However, there were some factors specific to the Elsham catchments that introduced additional challenges to the modelling process.

The landscape of the Elsham catchments is very flat and low-lying. Large areas of the catchments are managed by Internal Drainage Boards (IDBs) which control the hydrology by pumped drainage. The land is drained to a network of drainage channels which are pumped to the main rivers. In these drained areas, the watercourses carrying water from the upland areas are typically higher than the drains (and the drained land). This artificial drainage impacts on the hydrology by pumping water to the main channels that would otherwise pond and saturate the flat arable land. The drainage system is also used to retain water in dry periods so that the arable land does not dry out. To address this, the boundaries of the IDB controlled catchments were incorporated into the delineation of subbasins

during model setup. Flow was routed between these subbasins to replicate movement of water through the system as closely as possible.

The system of transfers between the three catchments supplying Elsham WTW was simulated in the SWAT model. To do this, daily abstraction or discharge data at each of the transfer locations was required. However, at the discharge point at Toft Newton in the headwaters of the River Ancholme, only monthly data was available so a daily average taken from the monthly total discharge was used. However, this resulted in large discrepancies in daily recorded flows downstream of the discharge point. Therefore, at the calibration point downstream of the discharge modelled flows could only be matched to the recorded data by visual comparison.

The downstream end of the River Ancholme, where the Cadney intake that feeds Elsham WTW is located, is subject to tidal intrusion. Therefore, a tidal sluice is used to ensure a residual flow to tide, and any sea water that leaks through the sea doors at high tide can be diverted into an adjacent drain. At high tide the closure of the sluice causes flow to back up in the lower Ancholme, which can result in flow reversal at the Cadney intake. SWAT uses daily average values and a daily time-step; it is therefore unable to replicate tidal cycles (approx. 12.4 hours duration) and their influence on streamflows. Although it is not possible to replicate the detail of this downstream boundary condition in the SWAT model, over a 24 hour period the average flow direction will be towards the sea, and this will be replicated by SWAT. However, the influence of the area of the catchment located downstream of the Cadney intake is uncertain and it cannot be ruled out as a source of metaldehyde at the intake using the results from this study.

Despite these complications a good calibration of flow in the River Ancholme and in the other catchments feeding Elsham WTW was achieved, either through the full calibration process described above, or using visual comparison of modelled versus recorded data. The calibration of metaldehyde concentrations at the Cadney intake and in Cadney Carrs Reservoir was also good, suggesting that Cadney Carrs is a fairly well mixed reservoir and is simulated well by SWAT.

5.2.3. Catchment management scenario results

The results of the catchment management scenario modelling show that the transfers from the Rivers Trent and Witham are unlikely to cause high metaldehyde concentrations at Elsham WTW, due to the timing of the transfers, which operate principally in dry periods when metaldehyde usage is low and transport pathways are limited. Therefore, the River Ancholme was identified as the key area in which to target catchment management solutions.

The Ancholme catchment upstream of the Cadney intake should be prioritised for catchment management measures, as most metaldehyde is likely to reach the intake from these areas. However, the whole Ancholme catchment should be considered when planning interventions due to the flow reversals that occur in the Ancholme, as limitations in the modelling mean the possibility that metaldehyde may reach the intake from downstream reaches cannot be ruled out. Catchment management measures will be most effective if metaldehyde is replaced with an alternative product on:

- Heavy, drained soils, where the risk of rapid metaldehyde transport to watercourses is high (through surface runoff and drain flow); and
- Any other areas within 500m of watercourses, where the distance and time for attenuation and degradation of metaldehyde to occur before reaching the stream is limited.

The impact that this scenario has on metaldehyde concentrations at the Cadney intake and in Cadney Carrs Reservoir are shown in Figure 10.

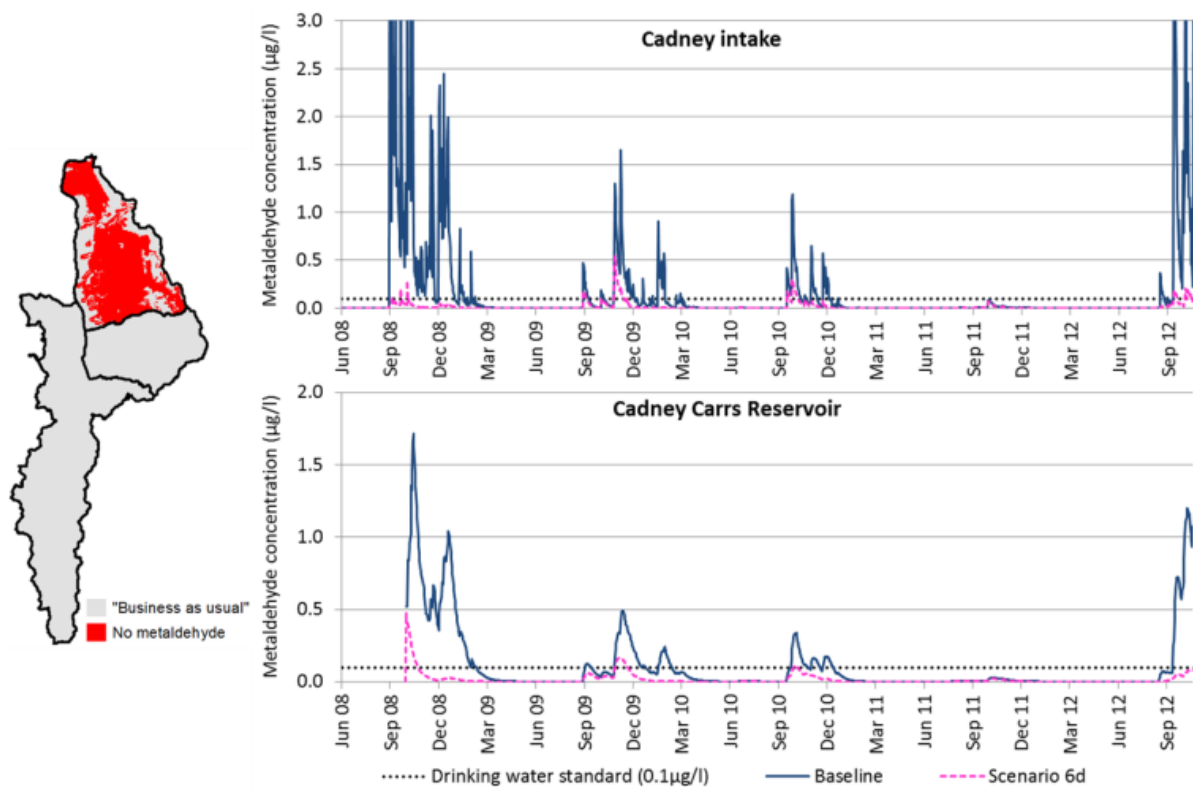


Figure 10: Results of most effective scenario for Elsham WTW

These target areas together cover about 305km² arable land of which 189km² is estimated to be under wheat and oilseed rape cropping. If the area downstream of the Cadney intake is excluded, the target areas cover about 215km² arable land of which 133km² is estimated to be wheat and oilseed rape. However as stated above, the possibility that metaldehyde reaches the intake from downstream reaches could not be excluded using the model.

6. Conclusions

The catchment modelling carried out for this project indicates that land management practices have the potential to reduce metaldehyde concentrations to below the regulatory limit of 0.1µg/l at surface water sources in the Anglian Region. The most effective areas for application of catchment management varied between the different catchments. For Ardleigh WTW, applying measures across the large pumped catchment that provides the majority of the water to the WTW was necessary to reduce metaldehyde concentrations to below the regulatory limit. However, at Elsham WTW, targeting the catchment that feeds the intake to the reservoir is most effective, with the larger supporting catchments having a much smaller impact. The nature of the catchment soils is also important; catchment management is likely to be more effective if the catchment consists of a large proportion of heavy, impermeable soils.

It is likely that to reduce concentrations at the sources to below the regulatory limit, substitution of metaldehyde with an alternative product will be required on large proportions of the contributing catchments identified above (over 80%), covering extensive areas. The practicality of implementing catchment management over such large areas has not been investigated, but limiting metaldehyde

application over areas of arable land of this size presents a challenge. Therefore, further investigation into the costs and feasibility of restricting use of such an important pesticide is required.

There is some uncertainty related to the likelihood of achieving concentrations below 0.1µg/l at the intakes to the WTWs due to limitations in the modelling, such as the limitations of SWAT to simulate of metaldehyde concentration in large reservoirs. Therefore other measures, such as raising awareness of drinking water quality concerns and best practice pesticide management, should also be promoted across the Anglian region to increase the likelihood of achieving the regulatory standard.

The catchment modelling outlined in the paper has allowed Anglian Water to better understand the link between land management and contamination of surface water in drinking water catchments. The model outputs were used to inform Anglian Water's Business Plan for investment in AMP6 (2015-2020), and could pave the way to reducing energy and carbon-intensive treatment, saving cost and better protecting the environment in both the short- and long-term. Some specific actions are already underway, including the employment of agronomy trained catchment advisers, who will engage with farmers to provide advice and education and carry out additional catchment monitoring. Anglian Water has also started to investigate the use of remote sensing data to provide more accurate land cover and crop data for their catchments. This data will be used in SWAT models of the catchments that feed reservoirs naturally, where metaldehyde contamination can't be controlled by other means.

Overall, this project has produced robust and technically defensible simulations of contaminant concentrations at the water treatment works under current and potential future conditions (such as changes in agricultural practices and potential land use changes). Work is ongoing to update, refine and improve the catchment models for use as a planning and operational tool into the future.

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