Overview of Catchment Runoff Attenuation Flux Tool (CRAFT)

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Contents

1 Introduction

This report will summarise the current status of the Catchment Runoff Attenuation Flux Tool (CRAFT), a hydrological model developed for simulating water flow, sediments and nutrients. This model was originally developed in 2015 at Newcastle University as a response to the need for a rapid screening tool for catchment mitigation (e.g. Nature Based Solutions (NBS) and Natural Flood Management (NFM)) approaches. At the same time, the model was able to provide a simple method for back-calculating nutrient and sediment loads from catchments with high-resolution monitoring data (usually hourly), leading to its use as a general catchment modelling tool that can be used to assess different scenarios.

The report will also assess the usefulness of the CRAFT for applications in Northern Ireland in more general terms. It will summarise the literature published to date, namely Adams et al. (2020, 2018 and 2016). These papers are introduced in reverse chronological order.

2 Paper 1

The first CRAFT paper summarised here (Adams et al., 2016) was a general overview of the model as applied to the Newby Beck catchment in Cumbria, England in the Demonstration Test Catchments (DTC) project (www.edendtc.org.uk). The paper demonstrates an application to hourly high resolution nutrient and discharge data collected at the Newby Beck outlet over several years. The model was calibrated to the discharge data and was also used to simulate phosphorus (P) and suspended sediments (SS) which required additional calibration. The modelled stores and flow pathways simulated by the CRAFT are shown below in Figure 1.

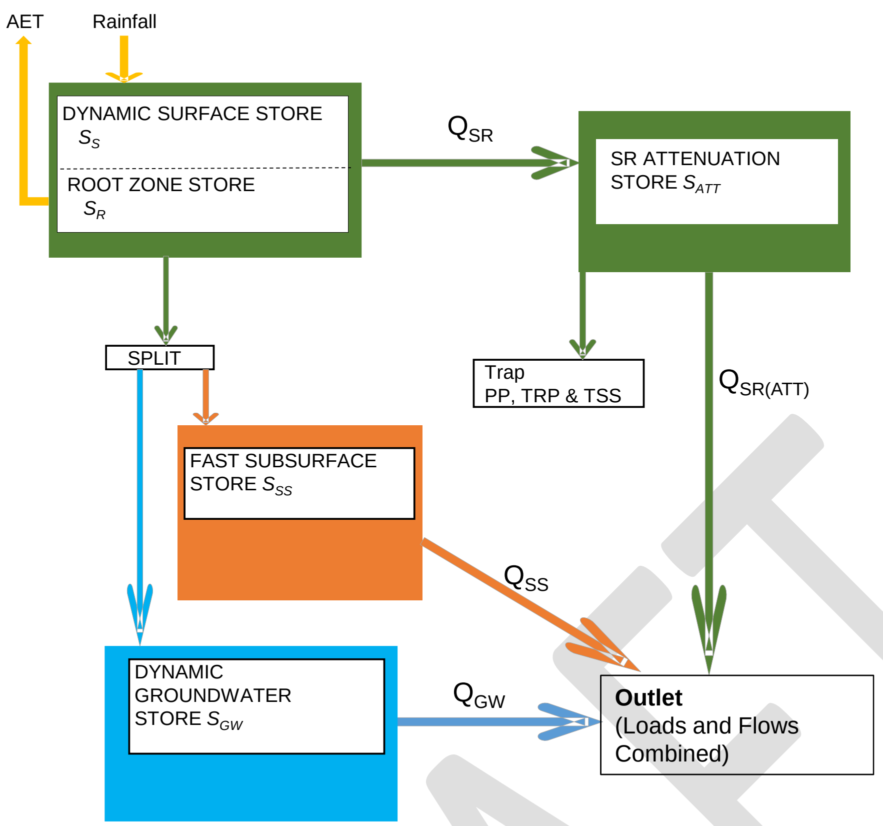


Figure 1 Schematic Diagram of CRAFT Model Stores and Fluxes

Figure 2 overleaf was also taken from this paper, and shows how a runoff event dominated in this case by surface runoff (including overland flow and near-surface runoff through the top soil layers, and also shallow field drains) in this type of catchment will generate rapidly a peak in both SS and TP concentration and load, which in reality (i.e. the response typically shown in the observed data in the Eden DTC catchments) can be either in or out of phase with the peak discharge (flow) Q measured at the catchment outlet. The paper discussed how well the model reproduced the observed discharge and concentration data and the results were deemed to be acceptable.

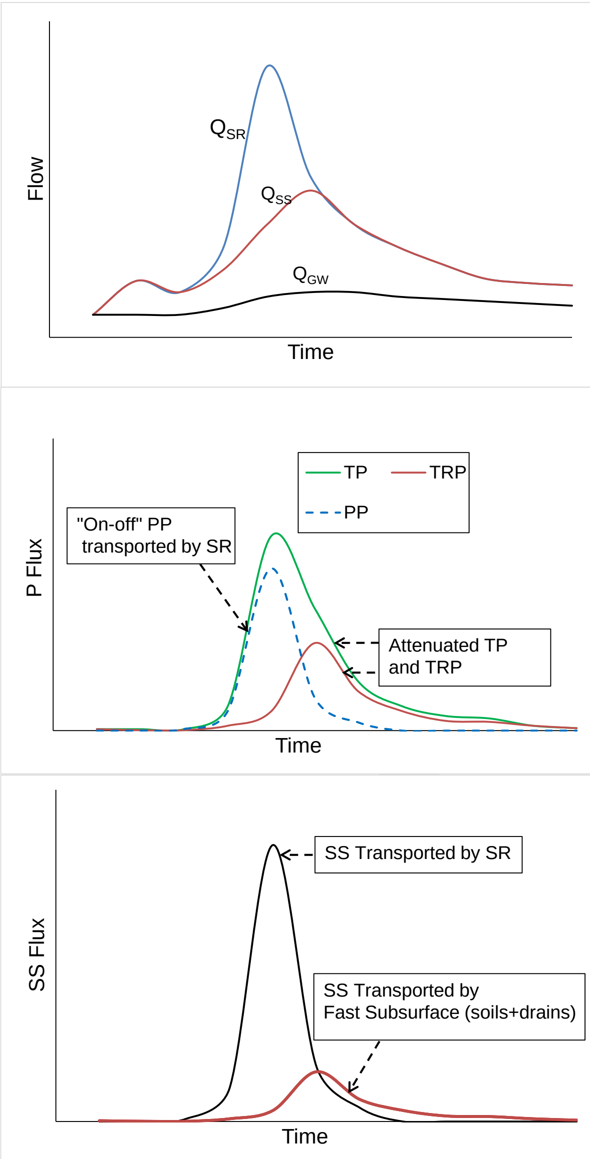


Figure 2 Conceptual diagram of flow and nutrient flux pathways during a typical runoff event: Here SS = Suspended sediment, which also entrains Particulate P (PP) and is transported by surface runoff (Q_{SR}). TRP (total reactive P) is mostly transported by fast subsurface flow (Q_{SS}) with a smaller component transported by slow groundwater flow (Q_{GW}). A small component of SS is transported by the fast subsurface flux pathway.

Following on from Figure 1 showing the different flow pathways in the CRAFT, the role of attenuation (the red chemograph in the middle pane of Fig. 2) can be seen in terms of delaying and flattening the peak in TP compared to the green chemograph representing the un-attenuated TP. The peak in TRP is more delayed in the model as the fast subsurface flow pathway has a discharge coefficient that is calibrated to make the peak Q_{ss} (red curve in the top pane of Fig. 1) arrive later than the peak Q_{SR}. In the middle pane, to avoid cluttering the figure, the TRP chemograph is shown as being the same shape as the attenuated TP chemograph due to the delay.

The CRAFT thus applies an attenuation (lag) to the discharge and associated nutrient fluxes from the Attenuation store shown in Fig 1, this lag is achieved through adjusting a model parameter that attenuates discharge. The ability to trap (i.e. remove) sediment and nutrients from this surface runoff flow pathway is also important as this can be used to simulate removal by mitigation features constructed as part of Nature Based Solutions (NBS). Originally, the model was developed for flooding mitigation (Natural Flood Management), but the ability to trap and remove sediments was added and was explored further in the next paper i.e. Adams et al (2018).

Assessing Water Quality Simulations

One final key finding of Paper 1 was that the assessment of water quality models needs to be made by a suite of metrics, an approach championed by several authors including Moriasi et al. (2012). The calibration and validation procedure for water quality simulations typically follows on from the calibration of the model for discharge, and a combined metric - based on a visual approach was recommended in Adams et al (2016). Typical performance metrics used include Nash and Sutcliffe efficiencies (more common for discharge than water quality time series), Normalised Root-mean square error (NRMSE) and R-squared measures obtained from a visual goodness-of-fit, usually observed vs. modelled flow or concentration.

At a minimum, and with sparse monitoring data (e.g. weekly or less frequent grab samples) it is recommended that the mean and 90th percentile concentrations (C) are reproduced within an acceptable tolerance of +- 20% by the model. The mass balance error for discharge needs to be within +- 10%, so overall the nutrient load also (viz. C times Q) predicted by the model needs to be within +-20% of the observed load (a Load Error – LE) for the simulations to be acceptable. An observed nutrient load can be calculated from high resolution data (sub-daily Q and C) but for sparser data the methods of Cassidy and Jordan (2011) for example can be used to calculate an ”Observed” load. Gaps in high-resolution nutrient time series need to be filled in either by interpolation (for short gaps of less than a day) or just by factoring up the total calculated load by the number of missing days (i.e. if there are n days of observed data in a calendar year then the annual load is given by 365/n times the calculated load). Some recent literature reviews (e.g. Wellen et al., 2015) have pointed out that water quality models have usually been assessed in terms of reproducing loads not concentrations, probably because reproducing the latter is much harder for models to achieve, especially positive NSE values.

3 Paper 2

The second CRAFT modelling paper (Adams et al., 2018) focusses more on the ability of the CRAFT to simulate the aggregate effect of mitigation features in a catchment. In this case the study was hypothetical because although a series of trial NBS features had been constructed in the Morland mitigation sub-catchment (part of the larger Newby Beck catchment in the Eden simulated in the first paper) the amount of aggregated storage (i.e. flow stored in detention wetlands, swales and ponds during runoff events) added by these features was not considered large enough to be detectable at the catchment outlet. So a series of different scenarios of adding more storage to 10% of the Newby Beck catchment were explored with the model as well as an alternative scenario simulating improved soil management with less runoff.

The key findings were that there was a reduction in TP (of 2 - 5 % of the event mean values) and SS concentrations (of 3 – 6% of the event mean values) modelled at the larger catchment's outlet due to adding attenuation (the flattening of the chemographs and sedigraphs) and also due to removing P and SS through mitigation measures. The discharge hydrographs were attenuated by adding 2000-8000 m^3 of storage to the 1.25 km^2 mitigation sub-catchment.

An important finding here was that the larger storage volume represented a total of 0.64% of the catchment area being flooded if the mean depth of water stored in the feature was 1m. Increasing the amount of aggregate storage to 10% of the mitigation sub-catchment (12.5 ha) would achieve greater benefits in terms of reducing P and SS concentrations at the larger catchment outlet. In Adams et al (2018) CRAFT's usefulness in examining different scenarios to mitigate against diffuse pollution has been demonstrated. The modelling of mitigation options is described in more detail below.

Mitigation Feature Modelling

The CRAFT model is lumped at the catchment (or sub-catchment) scale. The experimental design of the Newby Beck catchment in Cumbria, as part of the EdenDTC, was to split the catchment into a Mitigation and Un-Mitigated (or "Control") pair of sub-catchments. This configuration was designed so that the impacts of the smaller Mitigation sub-catchment could be (hopefully) detected at the catchment outlet. This configuration lent itself to being modelled using the CRAFT as two separate sub-catchments (Adams et al. (2018). The flows and loads from both sub-catchments are combined at the outlet using the method described below. Figure 3 shows a sketch of a typical arrangement with a nested "Mitigation" sub-catchment in green and associated monitoring points. At a minimum two gauges (with co-located water quality monitoring stations) are required to fully monitor and measure the effects of any mitigation features in the green sub-catchment.

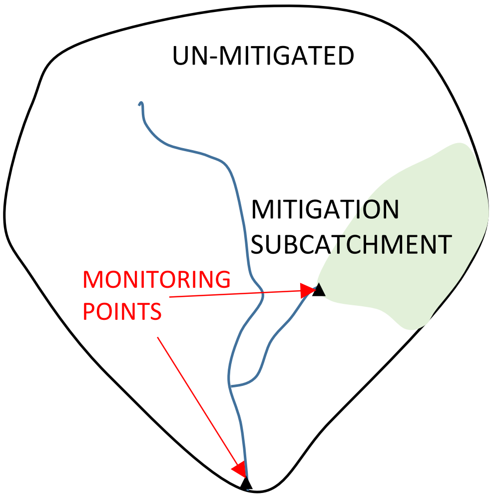


Figure 3. Sketch of Mitigation sub-catchment (Green) nested within the un-mitigated area, showing minimum monitoring network required to identify impact of mitigation features.

The fluxes and flows from the two sub-catchments can be combined at the catchment outlet into a single timeseries of flow and flux (or concentration). Attenuation can be added to the surface runoff pathway (see Fig. 1) in order to represent the aggregate storage in the measures, adding attenuation delays and flattens the peak discharge along this flow pathway and also the corresponding peak P load. The impact at the catchment outlet (downstream point) is obviously less pronounced since the runoff and nutrient loads from the white portion of the catchment in Fig. 3 have not been attenuated and no nutrient loads have been removed by mitigation features. The reader is referred to Adams et al. (2018) for more detail on the processes modelled by the CRAFT.

4 Paper 3

The third paper reviewed here is Adams et al. (2020) which was also based on the EdenDTC catchments. However, the smaller Pow Burn catchment was modelled in addition to Newby Beck. Pow Burn had quite different agricultural practices (more intensive farming including piggeries) and also different soils and geology to Newby Beck. This paper is partly an analysis of observed nutrient and chemical data in the two catchments during runoff events but makes use of the CRAFT's ability to model three individual flow pathways (Fig. 1) in the catchments to carry out "Event Forensics" where the model was used to identify the likely pathways during events for P. This information could be useful when designing mitigation measures to target these flow pathways in the two catchments which need to be tailored for local conditions in order to be most effective at trapping and removing sediments and nutrients.

5 Case Study on Oona Catchment (From AFBI Science 2021)

A simpler example of the mitigation modelling approach where features are assumed to be constructed across the entire catchment with the impact detected at a single monitoring point was presented in the 2021 AFBI Science Impacts publication in the

Oona catchment (https://www.afbini.gov.uk/publications/afbi-science-impacts-2021-publication) and is summarised below.

The CRAFT (Catchment Runoff Assessment Flux Tool) was used in this study on the Oona subcatchment of the Blackwater to explore phosphorus (P) dynamics (temporal variations in concentration and annual export) under the existing land use in the Oona (Baseline). The Baseline results indicated that the P concentration required for “Good” WFD status was only achieved for 39% of the time in the Oona, over the period 2005-2015 which was the time period that the model was calibrated on. It was then estimated from the relationship between modelled concentrations and loads that a reduction of more than 60% in the SRP load was required to meet “Good” status in the catchment (see notes below).

Subsequently, two mitigation scenarios were investigated using the CRAFT: (i) mitigating SRP in fast near-subsurface flow (by reducing the concentration of SRP through the $C_{SRP(SS)}$ parameter in Scenario 1), and (ii) targeting sediment P losses in surface runoff by trapping 60% of particulate P in this flow pathway in Scenario 2. These Scenarios were applied across the entire 94 km^2 catchment rather than splitting the catchment into mitigation and non-mitigated sub-catchments.

The results (Fig 4) show that Scenario 1 was most effective, reducing SRP export by more than 57% and achieved “Good” status in the Oona Water catchment for 95% of the period (red curve labelled “Scen 1” in lower left pane) compared to the baseline which only achieved “Good” status for 39% of the period (black curve). A small reduction in the $C_{SRP(GW)}$ parameter was also required to achieve this, in reality this may reflect the need to reduce background sources of P in the catchment (e.g. Septic tank discharges). Scenario 2 was less effective mainly because the surface runoff flow pathway transported less SRP than the fast subsurface flow pathway, so that even imposing quite a large removal efficiency (60%) was not enough to achieve the overall target reduction. The concentration-duration results from the model for Scenario 2 are not shown on the bottom left pane since there is little discernible difference between them and the baseline (black curve).

However, a combination of Scenarios 1 and 2 would achieve the best environmental outcome in the catchment and provide more flexibility to land mangers on the sorts of mitigation measures they could adopt in practice.

Notes

The SRP export (load/area) that achieves “Good” status will vary slightly between catchments due to differences in runoff etc., but is generally assumed to be around 0.2 kg P/ha/year based on the value of export coefficients that have been calculated for non-agricultural land in Northern Ireland by various studies.

The UKTAG method involving elevation and alkalinity was used to calculate the WFD target concentrations assuming the Oona is an “Upland” site, the lower *reaches of the Oona may be classified as "Lowland" with a slightly more generous "Good" target (69 µg P/L) due to their elevation.*

6 Recommendations and Limitations of the CRAFT and new Developments

The following section will present some suggestions for applying the CRAFT model to NI catchments. The model has already been used on the INTERREG CatchmentCARE project and one case study of mitigation in the Oona Catchment as outlined in section 5 above. The reader is also referred to a more in-depth report on the CRAFT prepared for CatchmentCARE, referred to as the "CRAFT Modelling Review". This report describes two new developments of the "standard" CRAFT which have the additional ability to simulate: 1) a "tree" of branched sub-catchments where interventions and scenarios may be targeted in one area of the larger catchment (MULTICRAFT) and assessed at its outlet; and 2) a version of the CRAFT called DynCRAFT which uses time-varying concentrations for soluble reactive P, particulate P and nitrate-N. This version uses processes modelled by the TOPCAT-NP model from which CRAFT was developed. To avoid confusion the following discussion relates to the standard CRAFT described by the three papers above. Some of the issues raised are being addressed by the new developments.

Benefits of the CRAFT and recommendations for use in NI

- Using a model such as CRAFT generates a timeseries of daily or hourly concentration values that can elucidate the catchment's response during high as well as low flows, i.e. across the entire flow regime which is useful when investigating and possibly setting water quality framework targets at a sub-catchment scale.
- For the water quality simulations a very strong (R-squared close to 1) relationship was found in the Blackwater Catchment between the two flow pathway SRP concentration parameters and the observed SRP data which will assist modelling catchments with scarce observed data. If the catchment has data indicating its Water Framework Directive status in terms of SRP, then the modeller can use the observed status of "Poor", "Good" etc. to assign values to some of the parameters.
- High resolution monitoring data can provide insights into P dynamics particularly during events and can be used to identify processes such as the mobilisation of near-channel sources of P during storm events (Cassidy and Jordan, 2011). These data will be beneficial both to model testing and catchment analysis once these datasets become more widely available from current projects in NI (e.g. NAP and NAP/EFS).
- An ongoing development version of the model (DynCRAFT) has scope to add nutrients (N and P) at different times of the year to represent fertiliser or slurry applications. In general further testing of the Nitrogen (nitrate) component of CRAFT is required in NI.

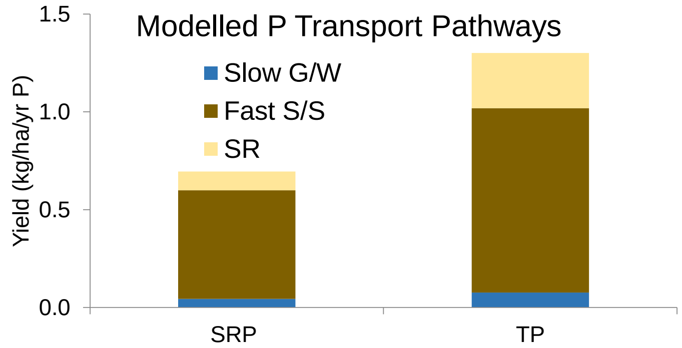
- The standard version of the model can also provide a useful means of inverse modelling the catchment, that is back calculating the concentrations from the fluxes measured at the outlet and assigning values to flow pathways, although there is considerable uncertainty in this form of modelling that needs to be communicated effectively back to stakeholders.
- The mitigation scenarios carried out in the Oona subcatchment used the standard CRAFT, but the concentrations in the flow pathways had to be adjusted manually to represent mitigation effects. The resulting P exports however do give an insight into the scale of load reductions that would be required to meet “Good” WFD status for P which will be useful for regulatory agencies.
- The CRAFT model framework allows the “Mitigation sub-catchment” approach to be used where the sub-catchment is divided into two representative sub-catchments, “Mitigated” and “Un-Mitigated”, see Fig. 3. In the “Mitigation” sub-catchment the user can evaluate different scenarios of NBS, or how changing soil properties to improve infiltration will reduce surface runoff.

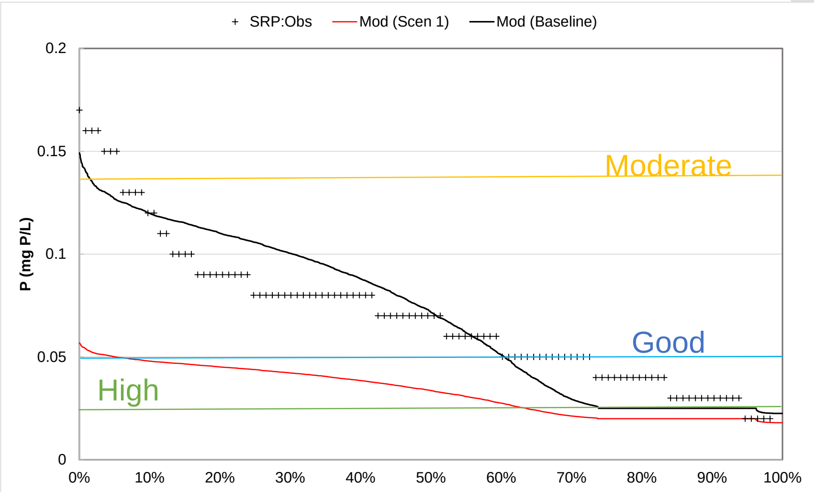
Limitations and Drawbacks

- CRAFT requires calibrating against observed timeseries of discharge and concentration. If the concentration data is sparse (e.g. monthly frequency) or discontinuous (i.e. more than 25% of the record is missing) then the model can realistically only reproduce the mean of the data and could offer little improvement in terms of predicting P loads above using statistical load estimation methods (e.g. Cassidy and Jordan, 2011).
- CRAFT is therefore not directly applicable to ungauged catchments unless they are similar to nearby gauged catchments with calibrated CRAFT parameters. In NI, the relatively homogeneous land use, climate and soils should enable ungauged catchments to be simulated using a multiple catchment version (under development), subject to limitations and uncertainty associated with model predictions. The SLAM model results (*Adams and Doody, 2021*) from the CatchmentCARE project can be used to estimate an annual mean TP concentration for a subcatchment, for two flow pathways (near surface and groundwater) which could guide the model calibration.
- CRAFT does not currently have a component that can directly translate agricultural inputs (e.g. fertiliser N and P) into model parameter values in the way that SWAT or INCA-NP can. Nor can the concentrations in the flow pathways vary in space or in time (except the PP and TRP concentrations in surface runoff). The DynCRAFT version of the model (under development) addresses the second of these shortcomings.
- Further work including a combination of monitoring and hydraulic modelling is required to assess the impact of mitigation measures at the sub-catchment level. The current representation in CRAFT is quite basic and only attenuates the surface runoff flow pathway during storm events. For mitigation measures to be successfully adopted in Northern Irish catchments it will probably be

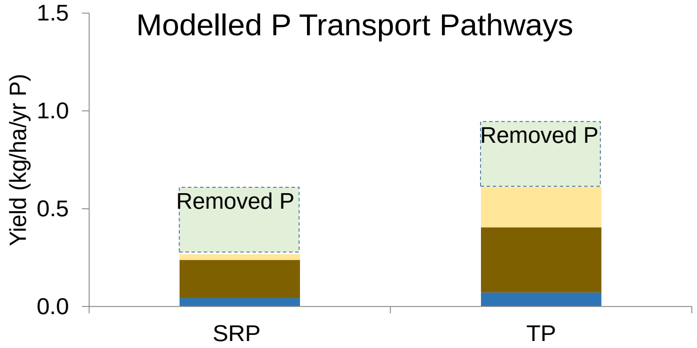
necessary to also target attenuation and nutrient trapping in the fast subsurface flow pathway in addition to the surface runoff flow pathway otherwise the required load reductions may not be achieved.

"Baseline" Modelled P Yields (by Flow Pathway)
"SR" = Surface Runoff, "S/S" = Subsurface, "G/W" = Groundwater





Scenario 1: Removal of SRP in fast subsurface flow (e.g. drainflow) and groundwater.
Required removal = 0.43 kg P/ha/year, meets WFD target



Scenario 2: Removal of P in surface runoff (60% trapped)
TP reduced by 0.2 kg P/ha/year overall. WFD target not met

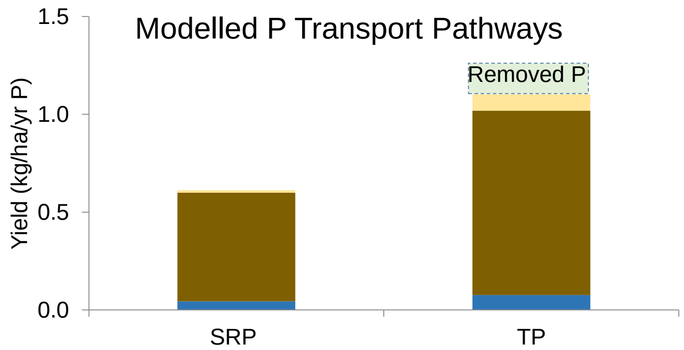


Figure 4 (modified from the AFBI Science 2021 Article) showing the results of two CRAFT Mitigation Scenarios applied to the Oona catchment. The lower left pane shows concentration-duration relationships using observed monthly SRP data (black crosses).

Summary

This report has summarised the existing literature on the development and application of the CRAFT and has found that the model could be applied to Northern Irish catchments. Some test simulations including a case study on the Oona sub-catchment of the Blackwater have already been carried out to date. There are a series of limitations that need to be taken into consideration, however to some extent any water quality model that will be selected for catchment simulations will have certain drawbacks. The main advantage of the CRAFT is that it can simulate mitigation options to reduce nutrient and sediment loadings. The main disadvantage of the model is that a front-end that can directly transform agricultural loadings to nutrient loads is currently not available.

References

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Moriasi, D. N., Wilson, B. N., Douglas-Mankin, K. R., Arnold, J. G., & Gowda, P. H. (2012) “Hydrologic and water quality models: Use, calibration, and validation”. *Transactions of the ASABE*, 55(4),: 1241-1247.

Wellen, C., et al. (2015) "Evaluation of the Current State of Distributed Watershed Nutrient Water Quality Modeling." *Environ. Sci. Tech.* **49**: 3278-3290.

Links to download the three CRAFT papers are below:

Adams et al. (2018) (Open Access) https://www.mdpi.com/2073-4441/10/9/1227

Adams et al. (2020) (Open Access) https://www.mdpi.com/2073-4441/12/4/1081

Adams et al. (2016) can be downloaded here: https://www.sciencedirect.com/science/article/pii/S0048969716300468 *or from https://www.academia.edu/22616974/Simulating_high_frequency_water_quality_monitoring_data_using_a_catchment_runoff_attenuation_flux_tool_CRAFT*