HOW DO YOU BUILD A LAKE MACQUARIE ECOLOGICAL RESPONSE MODEL

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Abstract

Building an Ecological Response Model (ERM) seems straight forward. Combine the water quality and ecology reaction (WQ) models with a hydrodynamic (HD) based transport dispersion model, and a range of boundary values and run it. However there are a number of constraints that get in the way, a major one being that we generally do not have the computer resources that will actually run this model much faster than real time. So what can be done to create a model that allows multiple 40 year runs but still covers most of the main processes that are needed for a successful ERM. Firstly the WQ side of the model is generally run on a daily time step, whilst the hydrodynamics a time step in the order of minutes – some form of temporal aggregation is required between the two. The WQ model is a larger scale box model, designed to delineate the major physical and ecological characteristics. The HD model is generally much finer scaled, designed to delineate the major drivers and features of the flow. Again aggregation is required.

Based on OEH's recent experience in constructing the Lake Macquarie ERM, I will discuss these and other aspects of assembling a functional ERM.

The objective

Ecological Response Models are a means of quantifying the impacts of land use, water use and waste water discharge in estuary waterways. These impacts generally arise from planning decisions associated with catchment development, industrial and agricultural water and discharge uses amongst others. The ERM then provides a means to prioritise and possibly modify planning decisions based on their impact. ERMs attempt to simulate the interactions between waterway constituents (salinity, temperature, sediments and nutrients) and their relationship with aquatic plants and animals. These links are two way, and can be highly inter-dependent.

Ecological processes can be viewed as a recycling process involving nutrient moving between different forms which can be particulate or dissolved or bound in sediments or living organisms. Nutrients bound in sediments are not necessarily locked away, and under specific conditions can be released back into the water column. In relation to living organisms in the water column, cycles of growth, bloom and death also provide longer period cycles of nutrient uptake and release. These characteristics mean that ecological responses must be modelled over years or even decades to simulate these uptake and release mechanisms.

However the inter-reaction of nutrients is not the whole story. Waterway physical characteristics determine the movement and dispersion of nutrients and sediments and living organisms within the water column.

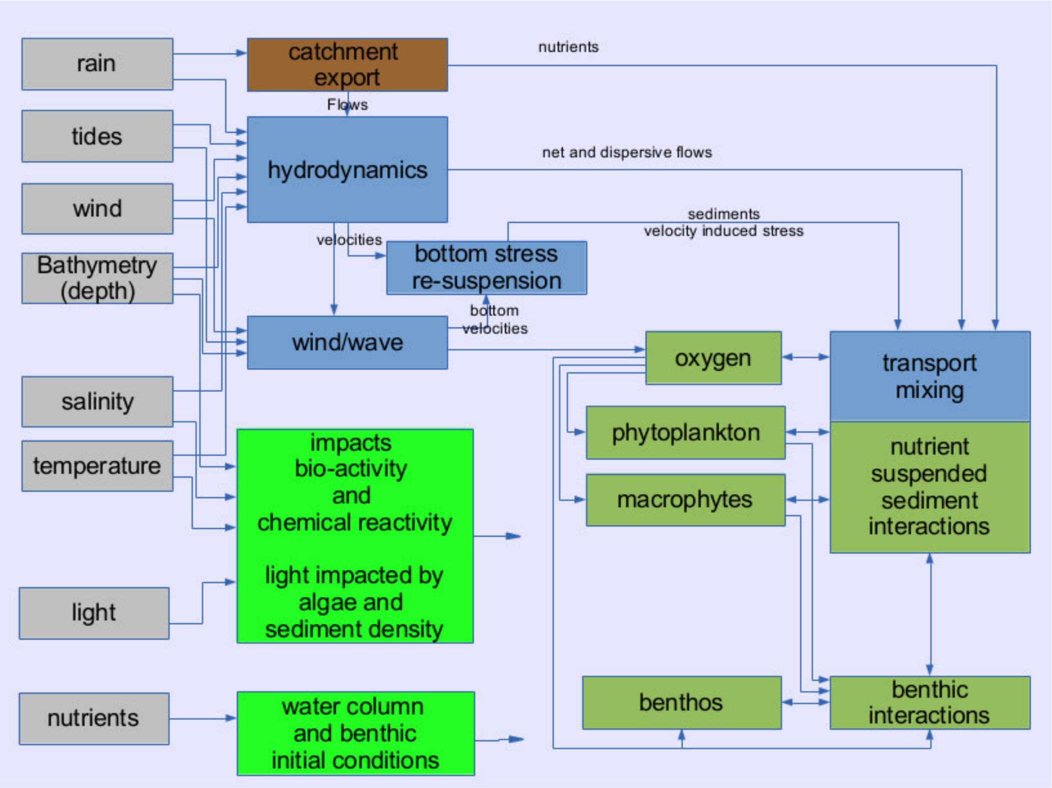

Figure 1- ERM main components and interactions

The main components

The overall approach can be broken up into three main groups

- Catchment Runoff including water flows and nutrient and other loads
- Hydrodynamics that determine the movement and mixing of water column constituents
- Ecology processes that define the transformation and transfer of nutrients between air, water, sediment and living organisms.

Figure 1 shows the main relationship between these components.

Each of these process groups requires specific data to monitor day to day behaviour, some of which is common between the groups. Probably the most complex process to measure and model is the transfer of nutrients between the water column and sediments and living organisms. These transfer functions are generally simplified equations that fit detailed observations both in the field and laboratory, sometimes controlled by other components in the surrounding environment that act similar to catalysts. These models can use theoretical experimental based relationships that are fine tuned to local conditions.

The calibration of the ecological processes depends heavily on data sets of water column concentrations. The major processes, which are the transfers between different forms of the same or different constituent, generally cannot be readily measured. As a consequence, much is inferred from observed concentrations.

The major features of the ecological response model

Generally an ERM is a temporal and spatial model. Waterways can rarely be considered as an isolated homogeneous system. There are both time and spatial differences. Temporal variations occur due to rainfall, meteorological events and the time evolution due to nutrient interactions. Spatial variations occur due to those same meteorological events, but also to location of tributaries and catchment landuse and the bathymetry and sediment variations around and within the waterway.

As the main observational data for nutrients are concentrations, the hydrodynamic induced dispersion is very important, along with the direct transport by velocity. Even though nutrients once transferred into the sediment remain effectively spatially locked away, once released back into the water column they are moved around by the hydrodynamics. This means that any spatial and temporal variation in nutrients and their effect on living organisms is directly linked to the hydrodynamic processes.

In the ERM the sediment interaction essentially provides a long term storage system which slowly inter-reacts with the water column nutrients. Because of this it is necessary to know the nutrient makeup of the sediments and expected water column concentrations, to provide good starting conditions for ecology modelling. In the case of the hydrodynamics modelling, the model will quickly adjust to the provided boundaries and poor starting conditions can be readily corrected, ignoring the 'warm up' period.

Because of this, the hydrodynamics need to simulate the major flow structures that move water around the system. In the case of Lake Macquarie, the processes needed to be included were tidal and wind driven flow, density effects due to both saline and fresh boundaries and heated cooling water from power stations. Density effects also arise from heating and cooling due to solar radiation, air temperature and wind influences.

Combining the components

In most cases the major process groups can considered as dependent in one direction – meaning that for example that the catchment flows and loads influence the hydrodynamics and the ecology processes but generally not the reverse. One situation where the influence is two way is the case of in-stream vegetation, which is modelled in the ecology processes. The feedback mechanism is that vegetation density changes due to ecological factors can affect the flow resistance in the hydrodynamics. If feedback is not required then the catchment and hydrodynamics can be run early, with result files stored. This allows numerous runs of just the ecology component during calibration without the cost of re-running the hydrodynamics. If 'what-if' scenarios do not change the catchment flows significantly then these can be run by adjusting just the catchment loads without a re-run of the hydrodynamics.

Each of the major components has specific characteristics that can be used to advantage when optimising the use of the modules.

The catchment model

The catchment modelling can be defined independently of the hydrodynamic requirements. The main consideration is the spatial breakup into sub-catchments, which is generally defined by the physical constraints of the geography of the system. Sub-catchments may be included to isolate past and future landuse changes resulting in different catchment load delivered to the waterway. To simulate the temporal load variations and to produce exceedence characteristics of catchment influences, the full study period must be run.

To use catchment models, each sub-catchment needs parameters that define the runoff behaviour (including flow and associated nutrient and sediment loads) given specific rainfall events. These parameters depend on the landuse, geology and terrain physical structure such as slope, and imperviousness and physical length and shape. In building catchment models generally generic parameters are used based on previous data for specific catchment traits. Specific catchment data to define the behaviour are difficult to collect and in most cases historical data does not exist. The flow component requires either direct flow measurements or flow related to water level measurement. Flow was not measured directly but through velocity and related flow area measurements, which can be obtained as time series. Location of flow measurement sites can also be difficult to locate, requiring special conditions to ensure a good dataset. Nutrients and sediment loads generally need to be physically collected and processed offsite. This makes long term time-series collections not feasible, and even short term event sampling becomes expensive.

The hydrodynamics Model

The hydrodynamics should be considered to be supplying the underlying physical processes, responsible for the basic movement of the catchment loads and ecology resultant constituents. The hydrodynamic model also supplies the local depths and water levels. The hydrodynamic model's grid resolution and density is defined by the flow structures that need to be represented. These constraints are project dependent and any existing data will define those requirements. Included in this assessment are the number and location of major catchment tributaries, the physical shape and the physical drivers of the system, In the case of Lake Macquarie, it is also important to include the power station cooling water systems. Even if the temperature density effects are ignored, power stations generate significant flow patterns. Figure 2 shows all major drivers for Lake Macquarie.

In hydrodynamic models it is relatively easy to calculate flow rates and water levels, however calculating velocities that match reality is more difficult. Mixing processes, at the smallest scales is a direct result of the instantaneous velocities moving packets of water around in the water body. However, when we measure or model velocities, it is impossible to resolve all the temporal and spatial variations of the velocity – the results are a combination of temporal and spatial averages. In these cases the dispersion concept is used as a correction to the mixing processes to account for these unknown variations. This means as models and measurements become coarser the dispersion process becomes more important to represent the spatial movement of water body constituents. The dispersion processes are usually included by using dispersion coefficients in conjunction with concentration gradients. However there is no general available theoretical formula to calculate the required coefficient. In practice the coefficient can vary by 100x or 1000x depending on many factors. A good example of this process is the aggregation of tidal velocities over a 1 day period - the net flow is close to zero, yet the mixing provided over that period is equal to the tidal prism (which is exchanged both ways between adjacent cells).

By using high detailed, fine grid, models there is less reliance on the evaluation of dispersion coefficients because detailed spatial and temporal velocity variability can be simulated.

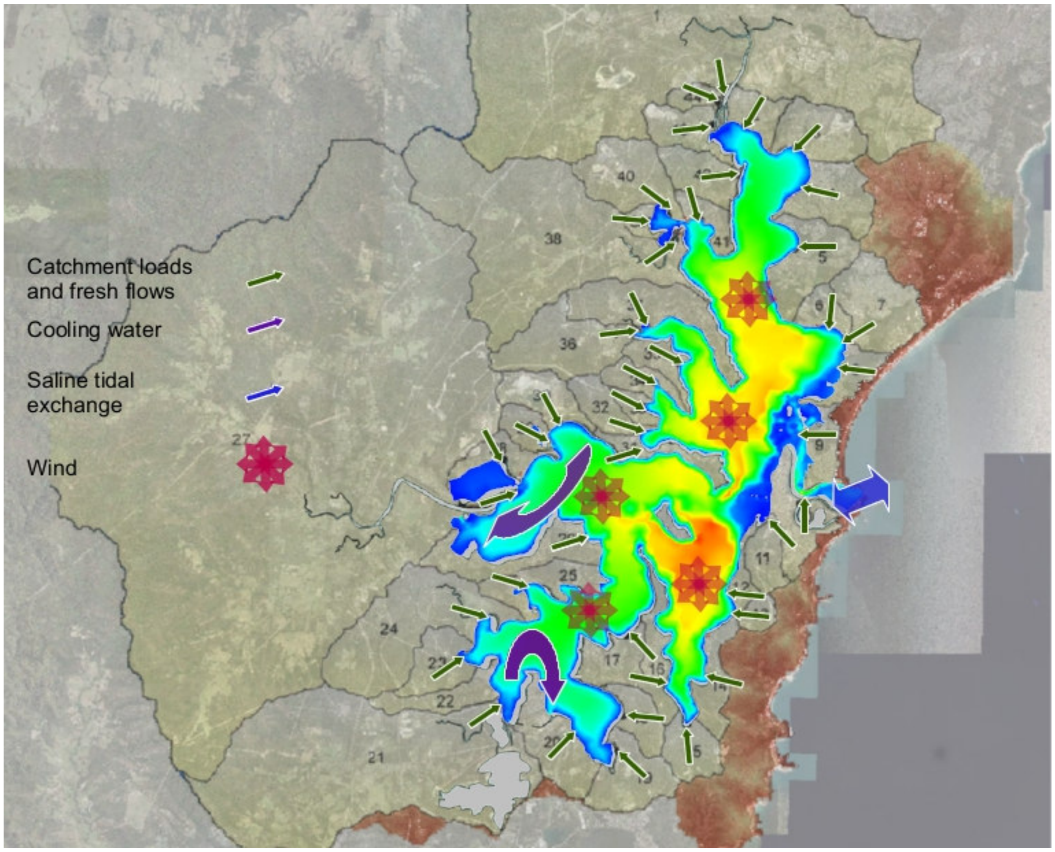

Figure 2 - Lake Macquarie major drivers

Hydrodynamic models are run using a time stepping method, however physical and numerical constraints limit the maximum time step allowed (for accuracy and stability). This results in forced decreases in timestep size as spatial grid sizes decrease. In ERMs that need to run for years or decades, other methods of simulating the flow behaviour over model period is needed.

The simplest approach for modelling the temporal behaviour of flows is to model the full study period. However as these models improve in spatial detail, computational run times can become infeasible. The sledge hammer approach then reduces the maximum simulation period, and/or reduces the model spatial detail.

Another approach is based on recognising major temporal characteristics of the system. In most systems it is possible to break the system up into various characteristic 'seasons', for example wet, dry and average (or typical). In Australia the breakup can also be characterised by event and typical conditions. By carefully constructing hydrodynamic runs of each of these type of flows at hybrid longterm flow scenario can be constructed. The event simulations may involve a number of disparate events that cover the expected exceedence characteristics of the system. A way of viewing this approach is that there is an underlying typical conditions that provide a global transport and dispersive environment that is interspersed with larger scale events. The loads from the larger scale events are transported into and through the waterway over the event period and then over the proceeding period (up to the next 'event') those loads are transported, mixed, and exchanged with the ocean using the typical conditions. In building these hybrid systems, extreme care must be taken to ensure mass continuity is maintained across the whole system. Minor events can not be ignored and those that are not directly modelled in the events modelling are still represented by using a simple mass balanced distributed flow from the tributaries to the ocean and combined with the modelled typical conditions. These minor events are typically less than a day in length, and the tidal and wind mixing dominates quickly.

This latter approach was applied for Lake Macquarie. A typical year of tidal and wind driven events was devised and run. Modelled catchment flows were analysed and the largest 100 events were then run through the hydrodynamic model. The event runs were constructed such that each event spanned a period where conditions had returned to typical tidal behaviour by the end of that period. Events could be single or multiple days and the ranking of the top 100 was based on the total flow over the event period. The approach is summarised in Figure 6. This approach applied to the hydrodynamic modelling resulted in typical year simulations taking approximately 1.5 days to run, and the 100 events modelling (which was equivalent to a 3 year simulation) taking nearly 5 days. An equivalent full run period simulation would have taken 60 days, which was logistically not possible. Besides the time limitations, there would be major issues associated with handling the size of the result files. A single 60 day run is not impossible to do, but given my experience in this area, one run will never be enough and the capability of being able to rerun cases is necessary.

The ecology model

The ecology model needs the loads from the catchment model, and the transport and dispersion from the hydrodynamic model. What are the characteristics required for this model? It should be spatial and temporal, but at what scales?

With the current understanding of ecology processes, the models are generally defined on a daily time step, which matches the major drivers of the ecological processes, sunlight and temperature. The process equations used in the models do not have the resolution to model the minute by minute, hour by hour behaviour of the system. Even if the process equations could work at those time scales, the data sets at those time scales do not exist. If running at a daily time step, catchment models can also run that resolution, with little impact on the flows and loads generated. However estimates of velocities will be underestimated as input to the hydrodynamics when the catchments are 'flashy'. The underlying hydrodynamics can aggregate flow results into daily values for these models.

The spatial resolution can be at the same scale as the hydrodynamic model. These can be referred to as Common Grid models. Many of these models take a simplistic approach and run both the hydrodynamic and the ecology models at the same time. This generally means huge computational resources are needed. To speed things up – grid resolution is cut, losing the accuracy of the dispersive flow results from the hydrodynamic model. Given that high detail spatial datasets of ecology at these scales do not exist (predominantly due to cost factors) and are both time consuming and expensive to collect, they are concentrated over spatial scales that are designed to pick up the range of spatial variability, and not spatial detail. Also due to the nature of ecological variables and the physical processes that transport and disperse them, the values vary little over larger spatial scales. On that basis it appears sensible to build ecology model grids that match observed ecological spatial characteristics.

The next level of coarsening the ecological grid can be referred to as Grid Aggregated models. The ecology model grid is directly related to the hydrodynamic grid but the grid is created that combines a fixed number of hydrodynamic cells together for each ecological cell. For example one ecological grid cell combines 4, 9 or 16 hydrodynamic grid cells, effectively coarsening the ecological grid size by 2, 3 and 4 times (in a 2

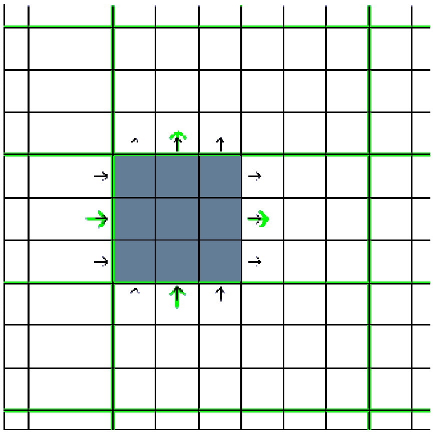

Figure 3 - Aggregated Flows

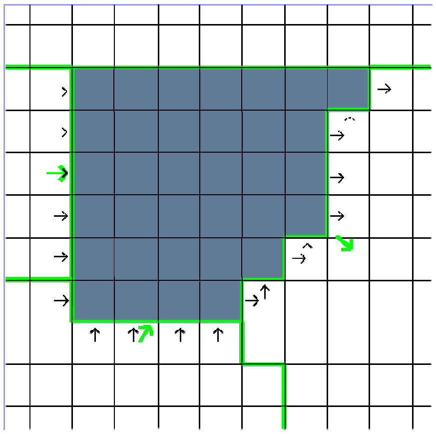

Figure 4 - Boxed Flows

dimensional perspective). These types of grid are designed to effectively coarsen the grid for computational performance but only at the ecology model level. However these grids are generally still much finer than the real spatial ecology variability. This method is schematised in Figure 3.

Finally a Box Model approach divides the spatial domain up based on known features of the system. These features can by physical (planform, bathymetry, sediment types and flow patterns), and known distributions of ecological variables (eg seagrass distribution being one example) using directly collected data or remote sensing methods. It is not necessary to only use existing data to determine this. Building the hydrodynamic model before assembling the ecology model is also useful, to effectively add to the data set. Model results allow flow patterns and tributary 'zones of influence' to be spatially delineated based on flow velocities and tracer transport dispersion characteristics. Use as much data as you can to help determine the needed ecology model grid. The boxes are not determined by the underlying hydrodynamic grid but by the processes being modelled. It is quite possible that small shallow ICOLLs can be accurately modelled by a single box Box Model. This is schematised in Figure 4.

In both the Grid Aggregated and Box models, the inter-cell flows can be calculated from the finer resolution hydrodynamic models. Even though the grid has been coarsened to a very high degree, the high resolution hydrodynamic model results aggregated over the time and spatial grids of the ecology model can generate accurate inter-cell transport and good estimates of the inter-cell dispersive flows.

The ecology model must be run continuously through the whole study period. The study period needs to be long in order to simulate the natural temporal distribution of flow and load events and the inter-event distribution of the ecology constituents throughout the waterway, and the longer term exchange processes with the ocean. Optimisation of these processes similar to the hydrodynamics hybrid approach is not possible.

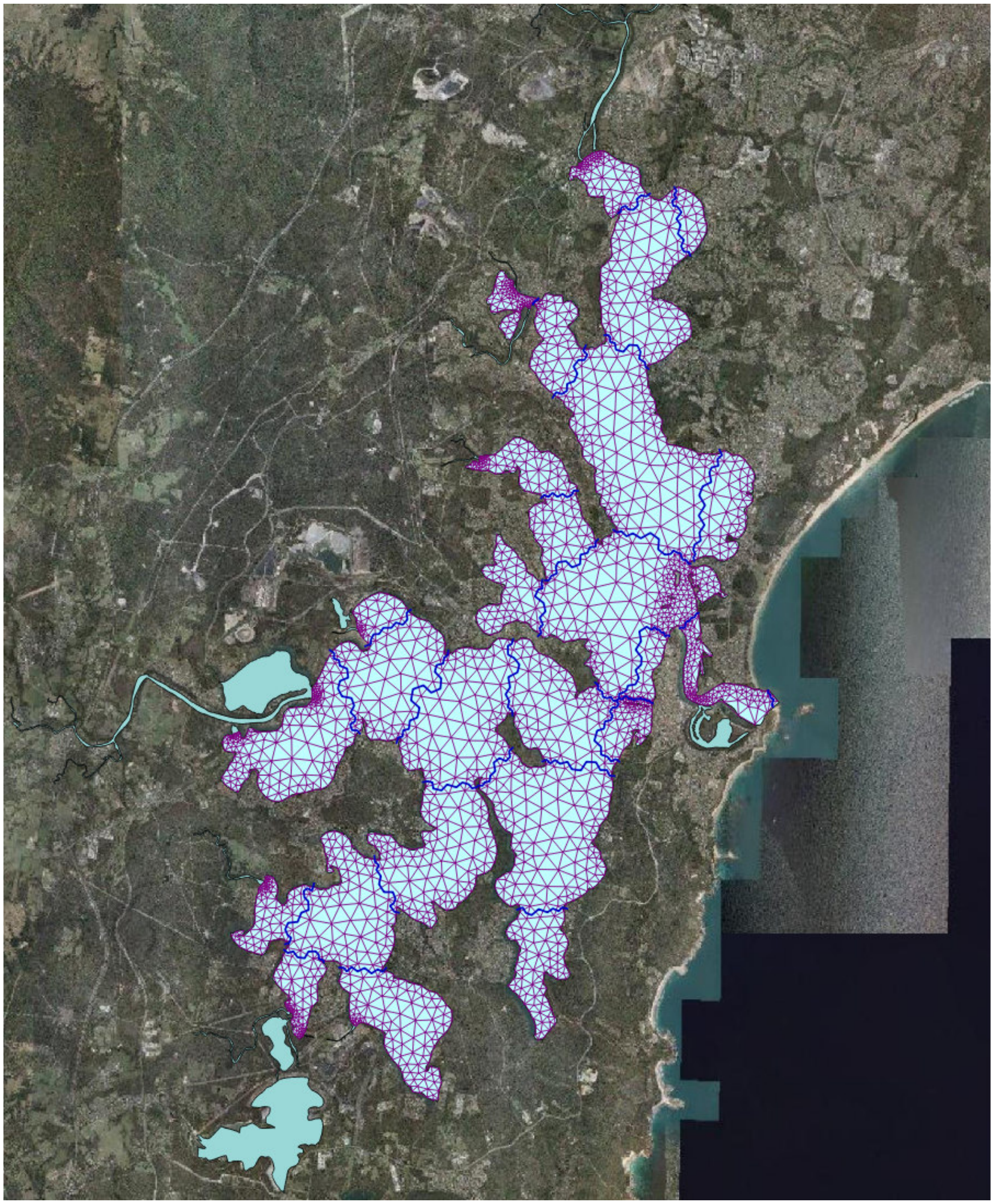

Figure 5 - Final Lake Macquarie hydrodynamic grid and ecology boxes

The Lake Macquarie approach

The solution is to run hydrodynamics at as high a detail as is necessary and practical, but run the ecology at daily time steps. The hydrodynamic modelling results provide the transport between the ecology boxes, but also the detailed spatial and temporal results from the hydrodynamics provides the detailed velocity variations that define dispersive flux values, when aggregating velocities to the coarser grid.

The latter approach allows ecology cells to be defined based on a mixture of homogeneity of physical, ecological, hydrodynamic characteristics and even spatial spread of available datasets. A major part of the model development process is the rationalisation of the number of box cells to represent the spatial variations expected of the processes or parameters. For example for Lake Macquarie it was useful to develop separate box cells for shallower seagrass areas, the deeper basin areas in a lake, the heads of the many embayments, and identified alternate flow paths, resulting in a 26 box ecology model shown in Figure 5.

Aggregating cells in the ecology model also allows for the fact that the inter-reactive nature of the ecology model may require substantially more computational resources per cell then the hydrodynamics models, even on daily time stepping.

The data headache

Putting together model runs for 40 year simulations is difficult. At the current time, many required variables are not necessarily available for the period. And when available, the quality of the values especially in the earlier part of the period can be low. The model builders need to apply a lot of objective choice on how to handle this problem.

In the case of Lake Macquarie the data sets required for the ERM are listed below

- lake tidal data, flow and levels
- ocean water level, water temperature and salinity
- lake and catchment rainfall, spatial distributions and values
- power station cooling water flows and temperatures
- lake water quality, including nutrients, chlorophyll, oxygen, salinity, temperature
- catchment sources water flow and quality
- wind speed and direction
- lake climate data including solar radiation, humidity, temperature
- seagrass locations and depths
- detailed lake and channels bathymetry

The list does not indicate the detail required for some of the items. In applying the available data, after filtering for missing and low quality data is generally not continuous. Extreme care needs to be taken to assemble what needs to closely resemble a continuous recurring record.

In the Lake Macquarie case, the major mixing driver for the lake is wind. There were just two long term sites close to the lake, and data capture intervals at those sites varied over the time period required. In the early part data intervals were long (12, 6 and 3 hourly due to manual readings) and improved in the last decade to 15 minutes or smaller (with automatic weather stations). None of of the sites provided a continuous data record. The final choice of running a 'typical year' helped solve this data variability problem, with the last ten years providing a good dataset to extract typical conditions data from.

However there was still a problem assigning wind data to the recorded catchment

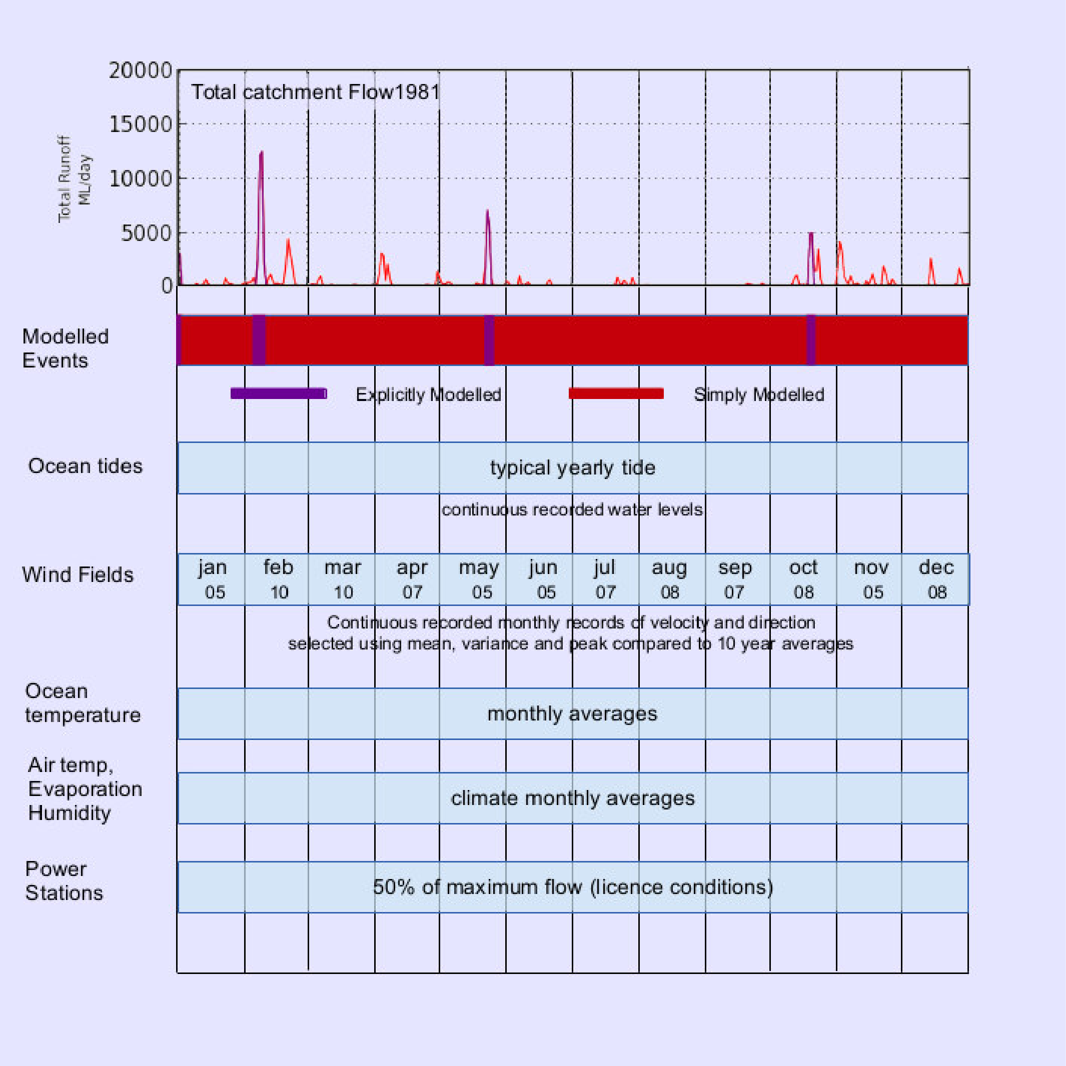

Figure 6 - Merging of data to drive the hydrodynamic model using 1981 as an example of catchment input

events, especially those before 2000. In this case, priority was set to actual data from the time of the event at the minimum of 3 hourly data from a preferred site, else data from other appropriate sites and if that still failed, extract the wind data from the 'typical year' for the same days of the year, that is use seasonally expected wind conditions. If longer reliable records are available it may be possible to find a typical year, but this case wind records were analysed on a monthly basis, and statistical comparisons between years was made for each month. Based on these comparisons a real months record close to average behaviour for that month was chosen as that typical months wind record.

Tide level records are quite reliable and longterm enough to allow the choice of a typical year for tidal behaviour. In this case the chosen year needed have relatively minor (or no) ocean events so only tidal exchange will be imposed. Care was taken to also find a tidal signal that was similar for beginning and end of the year record. A small error would be incurred due to tidal phasing over the yearly cycle could be minimised by careful choice of start and end dates.

Some data did not exist or was impossible to obtain in the required forms, and typical or average behaviour patterns were needed to be substituted. Variables treated in this way include ocean temperature and salinity, power station cooling water flows and temperatures. A summary of the data merge is shown in Figure 6.

Sequencing the data

Some data variables need to use real sequences of data to fully simulate the physical processes that drive the model. It is easy to see that tidal water levels and flow data fits this criteria but it is also important for other more obscure variables.

For Lake Macquarie wind is such a dataset. Wind events on the lake can influence surface flows within short periods of time, and movement and mixing of the lake water depends greatly on wind. Filtering this dataset to obtain mean or average conditions over long periods does not provide a realistic dataset. The water movement behaviour is driven by the time series' sequence. For example the fact that a strong north westerly wind can turn to south westerly and then finally to a strong southerly is important in developing the lake flow patterns over time. These flow patterns can be local and also on lake wide scales. 9am and 3pm average wind speeds and directions are essentially useless when trying to model the mixing characteristics of a wind driven water body. In producing the 'typical year' behaviour, the 10 years of good wind data for Lake Macquarie was analysed over monthly segments, and a typical month (based on mean, median, standard deviation and skewness statistics) for each of the calendar months was chosen out of the 10 years. These disparate months were then stitched together to form the 'typical year'. What is important is that this method maintains the seasonal variations and the hour to hour changes of the wind speed and direction.

Applying the model to Lake Macquarie

Some ERM and Hydrodynamic model uses and examples from the Lake Macquarie study are given.

ERM behaviour

Figure 5 shows the ERM run over the very wet period during the late 80s and early 90s and the effect on the sediment Organic Matter (OM) and to some extent the phytoplankton and Dissolved Inorganic Nitrogen (DIN) are shown. DIN gets assimilated very quickly which is in line with our field data. The spatial plots show the mean concentrations for each box over the model run. The Total Nitrogen (TN) plot provides a proxy for the influence of catchment OM, while DIN shows the influence of 1) uptake by sediments in shallow bays, 2) regeneration in deep basins, and 3) phytoplankton assimilation.

Figure 6 shows the average spatial distribution of the major nutrients from a 15 year simulation. These figures show that DIN distributions are determined by proximity to catchment inputs, uptake by phytoplankton and benthic plants (shallow areas) and regeneration (deeper areas). Phytoplankton is determined by DIN availability, light and water residence times. The TN plot shows the potential for enrichment around the lake, highlighting the sensitivity of the poorly flushed bays.

Risk Assessment

The hydrodynamic model can be used to highlight embayments that are at higher risk of ecological impact. Applying simplified scenarios, the spatial flushing characteristics of each of the catchment tributaries' inputs can be quantified. The method used was to run the hydrodynamics model under tide and wind with a catchment tracer (set at a value of 1.0) for the largest daily flow (based on 40 years of catchment modelling) for each catchment for 24 hours and then monitor the time behaviour of the tracer over the next week or two. The spatial tracer concentrations at the end of the initial tracer injection at 24 hours and 48 hours are plotted, along with point tracer concentration over the following period. Figure 7 and Figure 8 show an example of the results and highlight expected risk areas.

Acknowledgements

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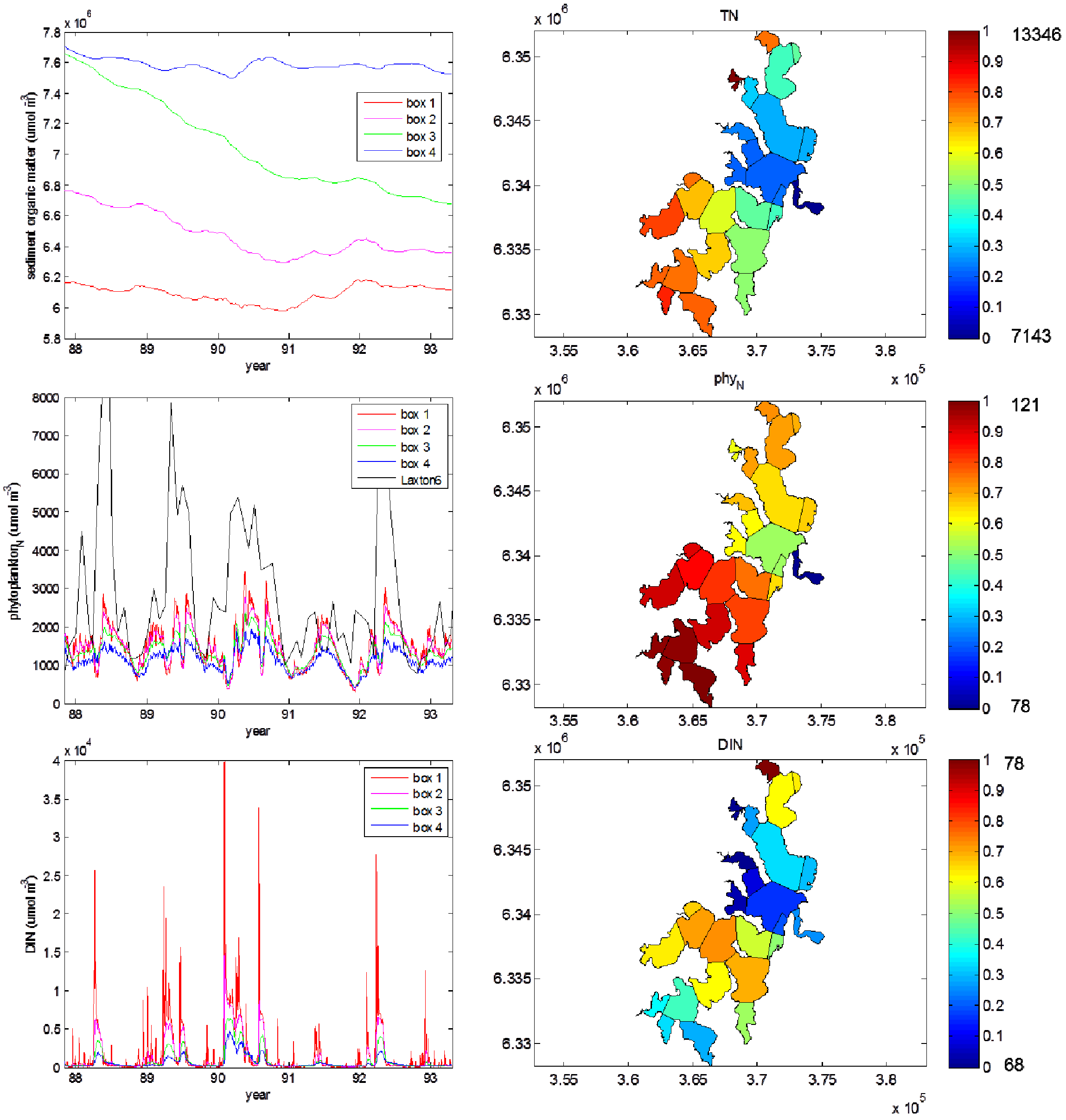


Figure 5 - ERM Model results from 1988 to 1993 showing the influence of wet versus dry conditions on nutrient recycling for sediment organic matter, phytoplankton and dissolved inorganic nitrogen.

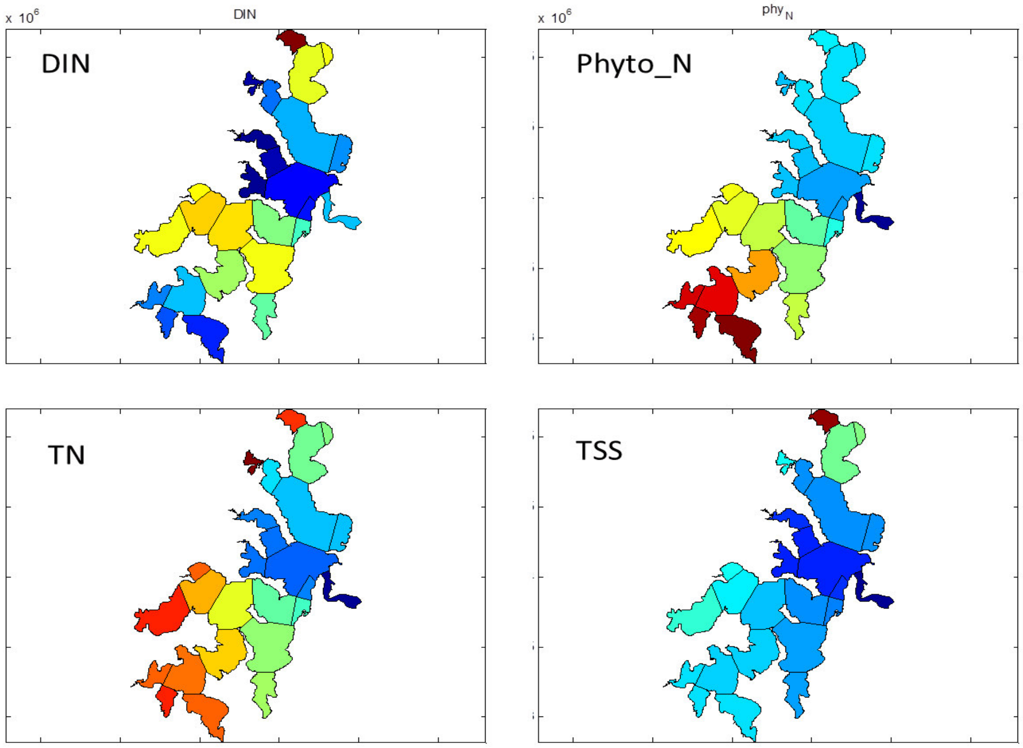
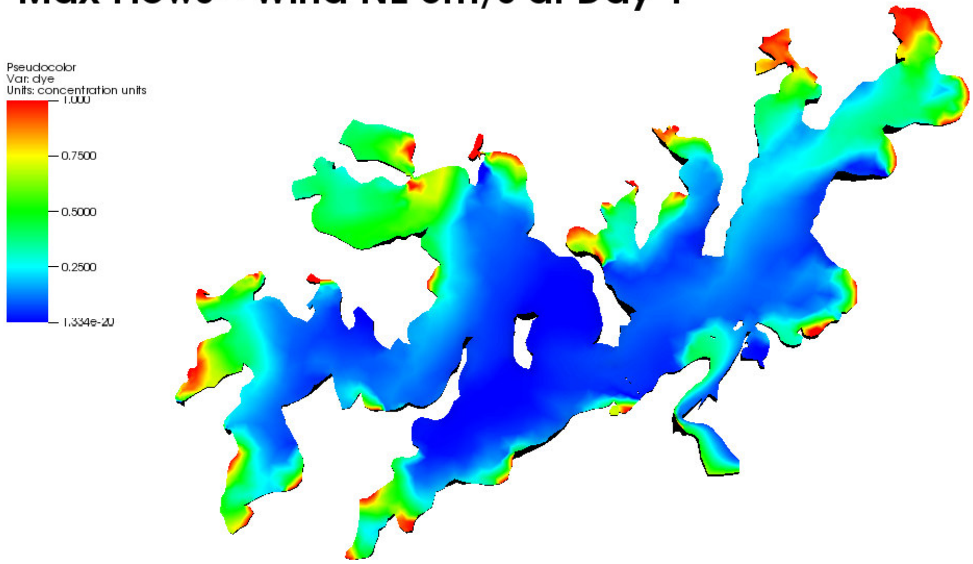


Figure 6 - Spatial average of major nutrients over 15 years of simulation where red is maximum and blue is minimum.

Max Flows - Wind NE 5m/s at Day 1



Max Flows - Wind NE 5m/s at Day 2

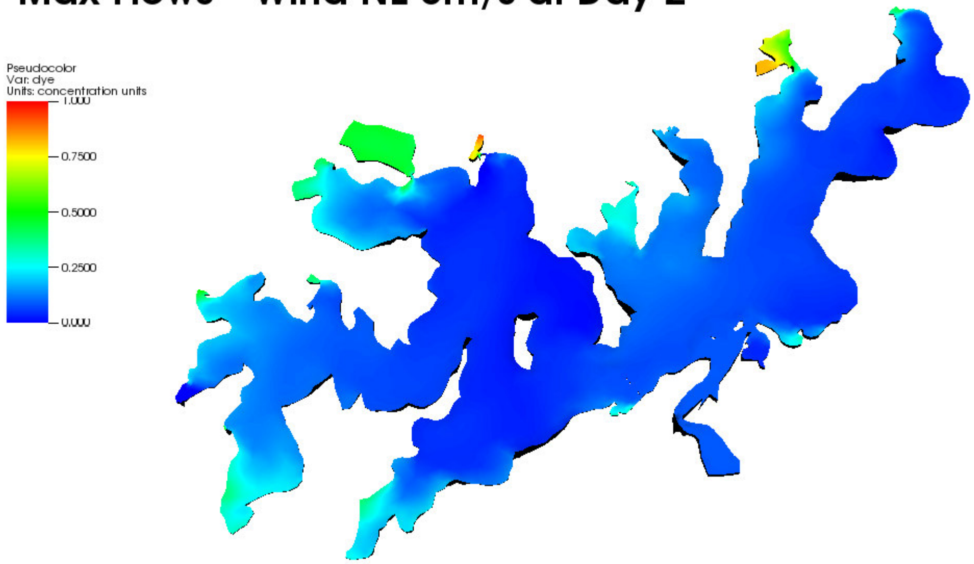


Figure 7 - Risk assessment - tracer mixing under 24 hour maximum flow and 5m/s northeasterly wind at the end of the tracer injection and 24 hours after that – note higher risk areas are evident after 2 days.

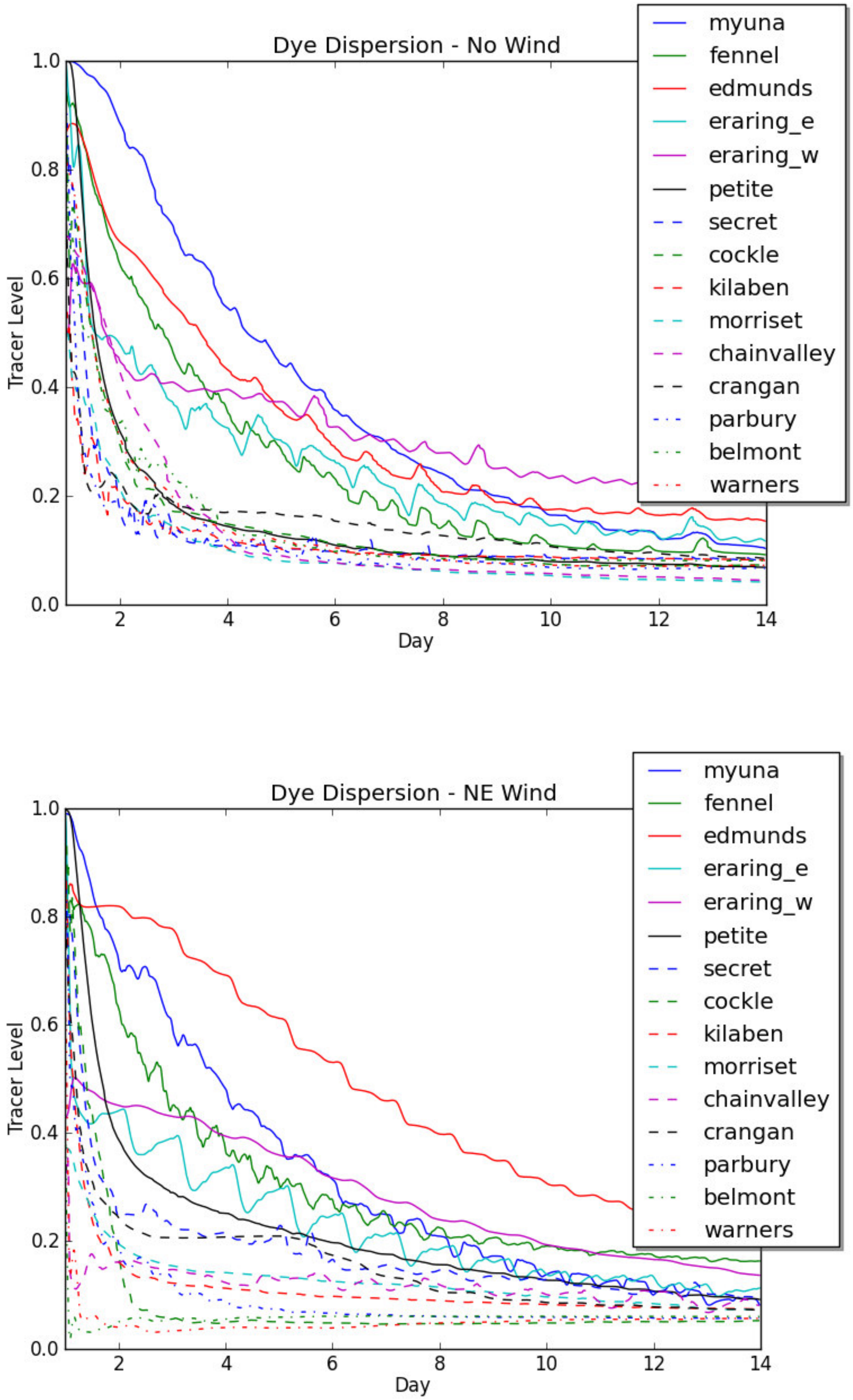


Figure 8 - Risk assessment - time behaviour over 2 weeks of tracer concentration for no wind (top) and 5m/s NE wind (bottom).