Estimating future scenarios for farm-watershed nutrient fluxes using dynamic simulation modelling – Can on-farm BMPs really do the job at the watershed scale?

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Abstract

A dynamic model of Phosphorus (P) movement through the Peel-Harvey Watershed in South Western Australia was developed using STELLA© dynamic modelling software. The model was developed to illustrate watershed P flux and to predict future P loss rates under a range of management scenarios. Input parameters were sourced from surveys of local agricultural practices and regional soil testing data. Model P-routing routines were developed from the known interactions between the various watershed P compartments and fluxes between various P stores. P-retention characteristics of a variety of management practices were determined from field trials where available and published values where not. The model simulated a 200 year time frame to reflect 100 years to the present day since initial land development, and forecast 100 years into the future. Although the watershed has an annual P loss target of 70 tonnes per annum (tpa), the measured present day loss is double this amount (140 tpa) and this is projected to rise to 1300 tpa if current land management practices continue. Even if broad-scale BMP implementation occurs, P losses are likely to increase to approximately 200 tpa. This has significant implications for both future land use and subsequent water quality in the watershed.

Introduction

The Peel-Harvey Watershed and agricultural nutrient management

Nutrient losses from land to water have accelerated globally over the last 50 years due to landscape development for agricultural and urban pursuits (Reynolds and Davies 2001). These pursuits bring with them inputs of nutrients, predominantly phosphorus (P) and nitrogen (N), which are used to boost plant production. The subsequent increase in soil nutrient content beyond levels which can be utilized productively may lead to increased losses of nutrients to local and regional waterways and subsequent eutrophication (Nair *et al*. 2004, Behrendt and Boekhold 1994, Sharpley and Smith 1990). In Australia this problem is exacerbated by the fact that many waterways were naturally oligotrophic meaning that excess nutrient inputs impact on the natural aquatic ecosystems more readily and with greater consequence.

The study area for this research is the Peel-Harvey watershed in south Western Australia which has a long history of nuisance and toxic algal blooms. The watershed lies approximately 70km south of Perth, the State Capital, and covers an area of approximately 3072km2. Approximately 190,000 ha of this is the coastal portion of the watershed which has been cleared for land development and which contributes the majority of nutrients into regional waterways. The region experiences a Mediterranean climate, characterised by warm dry summers and cool wet winters (Seddon 1972). About 90% of the region's total annual rainfall occurs between May and September and varies between 700 and 1100mm. Average daily temperatures range from 17ºC to 30ºC in summer and from 6ºC to 17ºC in winter.

Land use in the 190,000ha of the coastal region of the watershed is dominated by agriculture with grazing for beef production the most common agricultural activity (Lavell *et al.* 2004).

Nutrient-transport modelling

Developing an understanding of the complexity of water or nutrient transport through farms and watersheds can be a very difficult and resource-intensive task. To develop a through understanding of nutrient transport on only one farm may involve the establishment of multiple soil and water sampling points and their management over a number of years. The fact that every farm and watershed is different then makes it difficult to justify transfer of results from one monitored site to other sites – even within the same locality. This makes the development of more generic principles which can cross between locations, scales and time difficult but necessary because important land management decisions need to be made at farm and watershed scales. One approach to relate measured data from one point to others, or of applying well understood, if not well measured, principles to a range of locations is through the use of models. These allow us to apply measured relationships or systematic understanding developed in one location or time-frame to others. It is extremely important to note, however, that "As with any tool, the answers they give are dependent on how we apply them, and the quality of these answers is no better than the quality of our understanding of the system" (Butcher *et al.* 1998).

This study was designed to combine measured and surveyed data at the farm and watershed scales with a watershed-scale dynamic model of nutrient fluxes to assess future scenarios for the Peel-Harvey watershed.

Although many conceptual and process-based models describe dynamic natural systems, they are often, in themselves, less dynamic in terms of describing the delays and feedback loops common in the natural environment. System dynamics modelling proposes a solution to this issue.

Figure 1 illustrates the relationship between the model methodology used in this paper and the more conventional model types used more commonly. Although the model is dynamic and utilises the specific benefits of this type of modelling approach, it combines the benefits of both process-based and export-coefficient models as these are the data-types generally encountered in this field and certainly the case in this study.

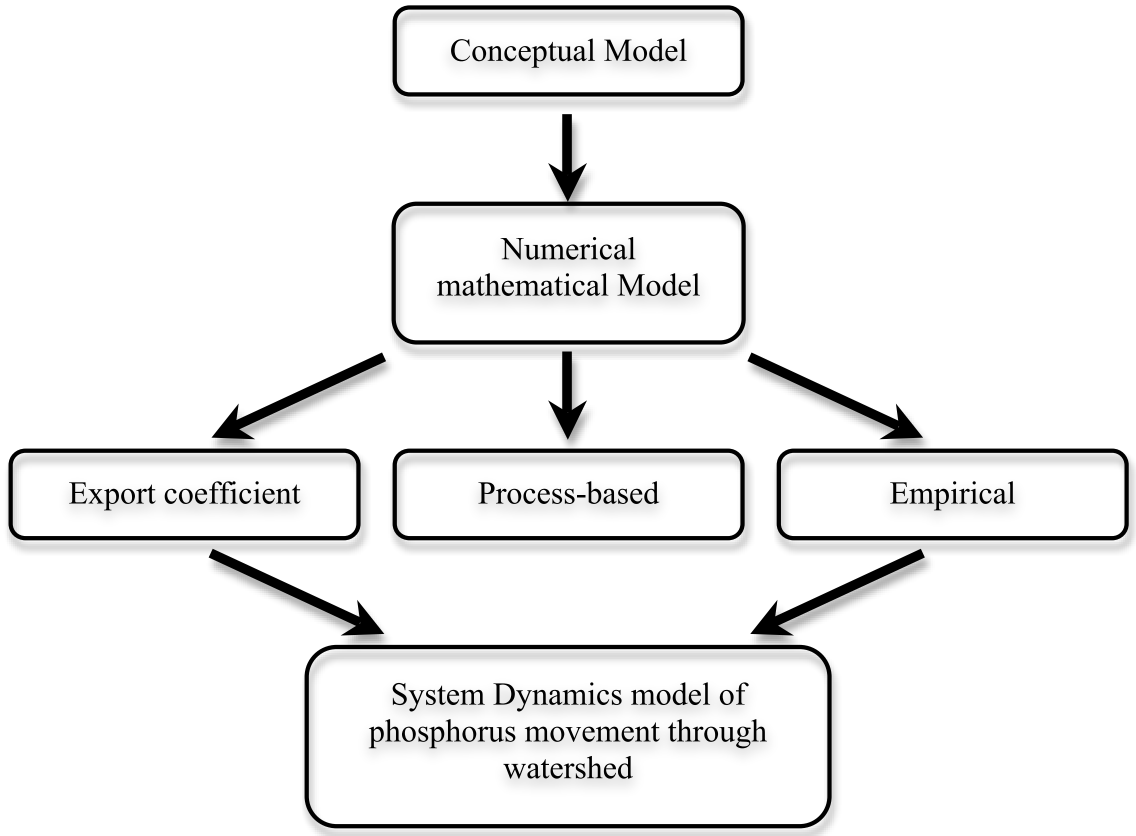


Figure 1: Preferred model methodology

Previous work has been completed on the development of watershed and nutrient-transport models as a means of both relating small-scale management changes to large-scale impacts, and as a way of modelling water and nutrient policy scenarios (Cassell *et al*. 2001, Young *et al*. 1989, Beasley and Huggins 1982, Heidtke and Auer 1993, Poiani and Bedford 1995). However, many of these approaches are complicated, and their widespread use may be restricted by computational complexities, particularly in landscapes that are spatially and temporally heterogeneous.

This paper discusses a simulation model which estimates P transport through major source, sink and flow sectors of the watershed. It attempts to track changes in stores and flows of P over a 200 year time horizon to match watershed development and associated nutrient inputs and outputs to the present day (100 years of development) and project a further 100 years into the future. The model is a lumped, whole-of-watershed model which allows for nutrient storage, assimilation and release from the major components of the watershed environment. It is designed to explore long-term, large-scale changes and is not designed to investigate detailed nutrient transport mechanisms within individual watershed components.

Model Description

Overall model design

The overall, simplified conceptual design of the model is shown in Figure 2. Essentially, the model has four major components: inputs, which direct the flow of P from outside of the model boundary into the model as fertiliser, feed or precipitated P; the soil store of P; the sediment store of P, and; subsequent P lost to the receiving water body.

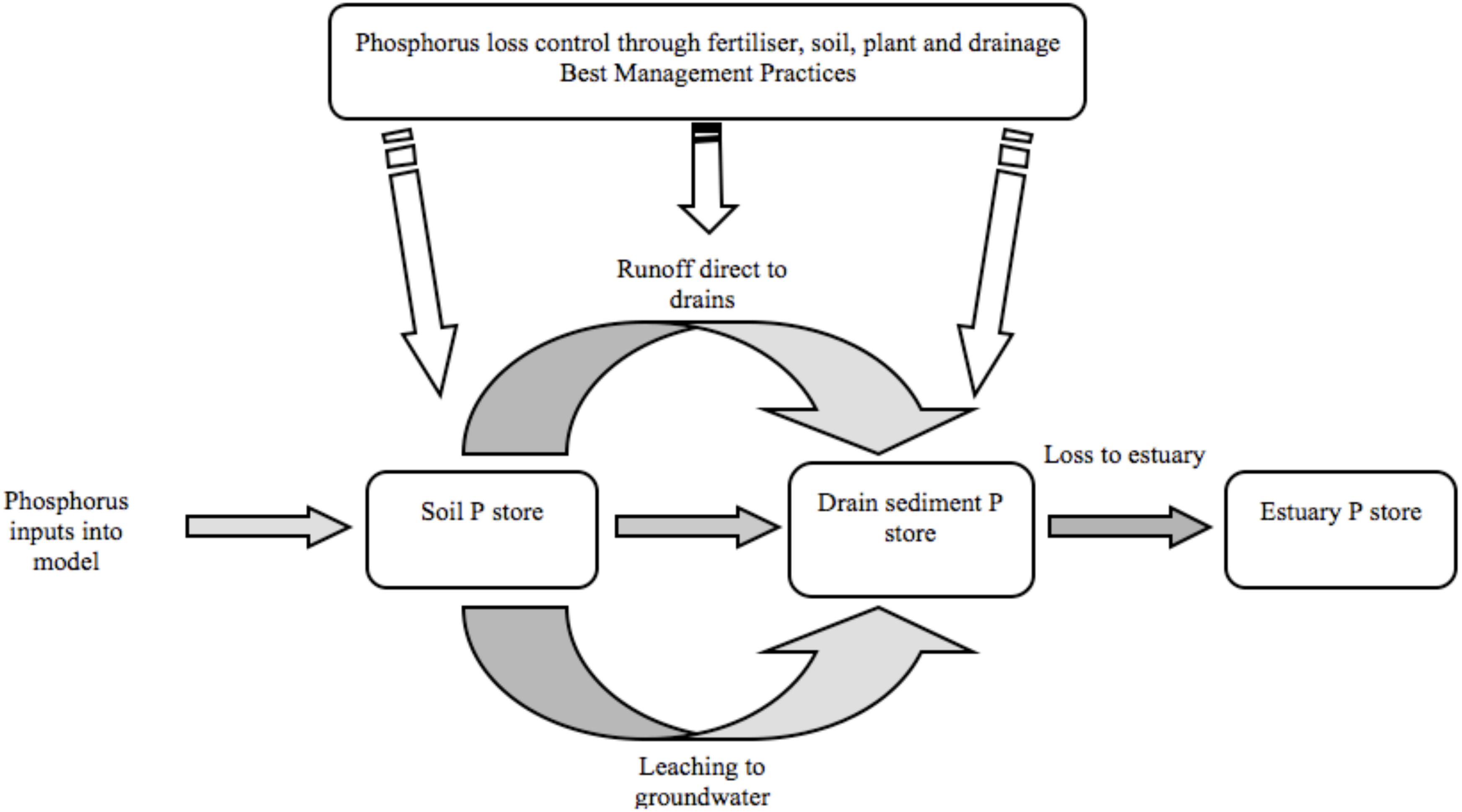


Figure 2: Conceptual P transfer model

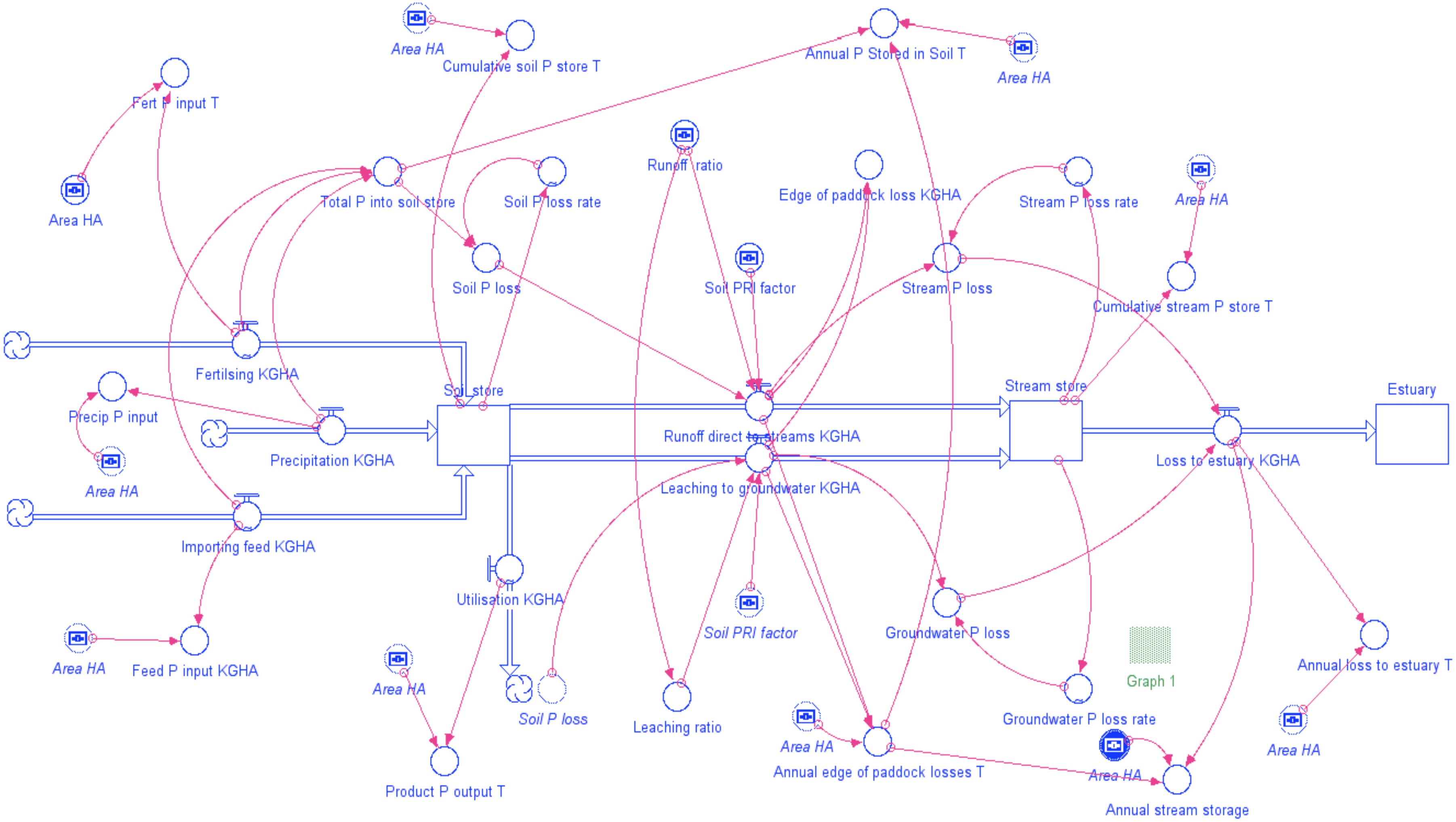


Figure 3: Simplified STELLA© P transfer model

Between each of these P stocks are flows that govern the rate at which P is transferred through the model. These are, in turn, controlled by a series of converters and controllers which are variable through time and which can be highly complex. Finally, overlain on the model are a series of P-mitigation strategies which have been employed in the past in this region to manage P loss.

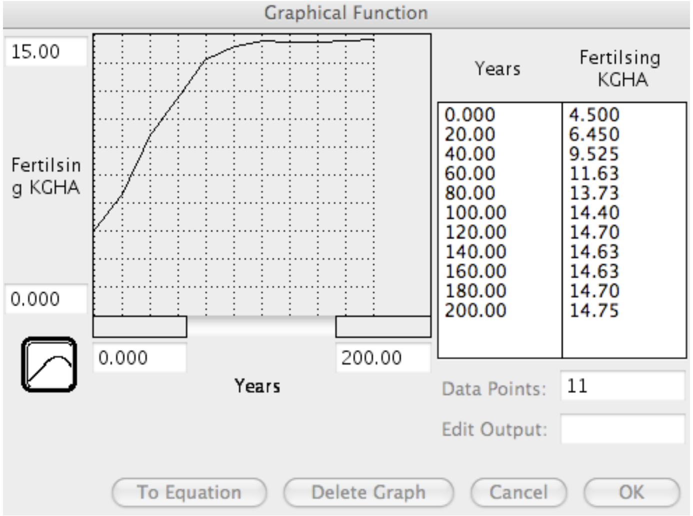
The structure of the actual model in detail as programmed into STELLA© but without BMP detail is illustrated in Figure 3 (BMP details are discussed later and the more complex form of the model including BMP details is attached as Appendix 1).

Detailed model description and initial parameterisation

Phosphorus inputs (flows)

Phosphorus input into the soil store occurs via three pathways: Precipitation, fertilising and importation of feed.

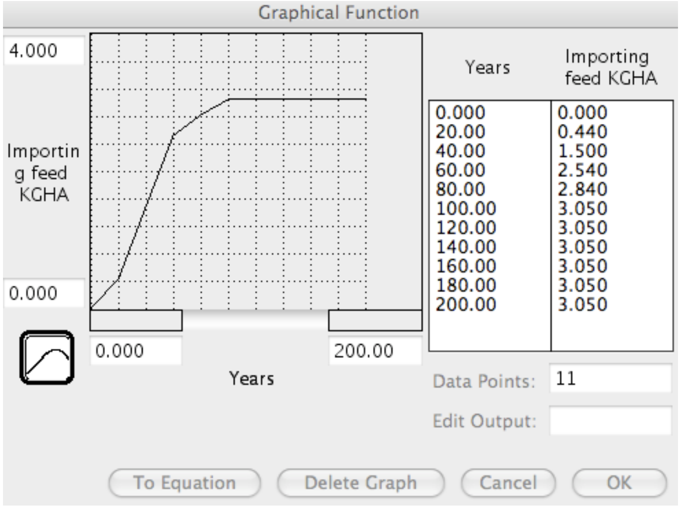
Precipitated P inputs are set at 0.09 kg ha^{-1}yr^{-1} (adapted from Chen *et al*. 1985 and McLaughlin *et al*. 1992) while P inputs from fertiliser and feed are varied through time to reflect agricultural development in this region. Fertiliser P inputs are varied as shown in Figure 4 and feed inputs as shown in Figure 5.



Years	Fertilsing KGHA
0.000	4.500
20.00	6.450
40.00	9.525
60.00	11.63
80.00	13.73
100.00	14.40
120.00	14.70
140.00	14.63
160.00	14.63
180.00	14.70
200.00	14.75

Data Points: 11

Figure 4: Model fertilser P inputs over time



Years	Importing feed KGHA
0.000	0.000
20.00	0.440
40.00	1.500
60.00	2.540
80.00	2.840
100.00	3.050
120.00	3.050
140.00	3.050
160.00	3.050
180.00	3.050
200.00	3.050

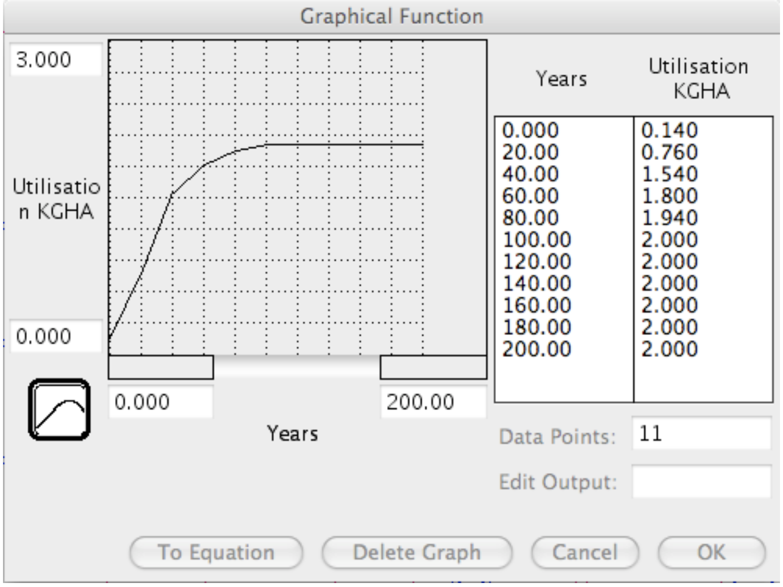
Data Points: 11

Figure 5: Model feed P inputs over time

Soil P store (stock)

This stock describes the net accumulation of P in the soil component of the watershed. It is the sum of the inputs as described above minus the sum of the losses from soil via productive use of P and loss via overland runoff and vertical leaching.

P utilization (flow)



Years	Utilisation KGHA
0.000	0.140
20.00	0.760
40.00	1.540
60.00	1.800
80.00	1.940
100.00	2.000
120.00	2.000
140.00	2.000
160.00	2.000
180.00	2.000
200.00	2.000

Data Points: 11

Edit Output:

Figure 6: Model productive P utilisation over time

This parameter is described by a temporally-varying function in a similar manner to the inputs of P from fertilser and feed (Figure 6). It is assumed that there was a very low initial loss of P from the watershed which increased until the surveyed, present-day levels of 2.00 kg $ha^{-1}yr^{-1}$.

Runoff direct to streams (flow)

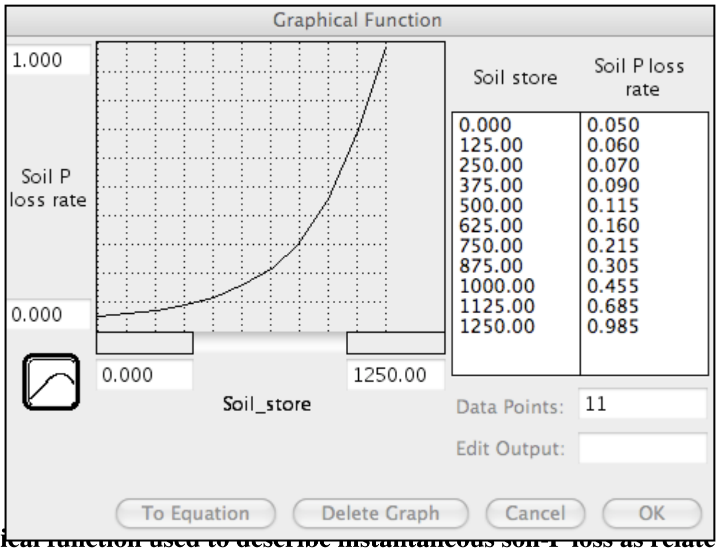
The algorithm used to calculate the loss of P via overland flow direct to the regional drainage network (but not including BMP modification) is a function of a number of inter-related parameters:

$$\text{P loss}_{\text{Runoff}} = \text{P loss}_{\text{Soil}} * \text{soil PRI factor} * (\text{runoff ratio}/100)$$

The net P lost as runoff is the "Soil P loss" modified by the function describing soil P-retention capacity "Soil PRI factor" and the function describing the soil drainage pathway ("Runoff ratio": proportional runoff or leaching).

The "soil P loss" factor is itself a function of the total P in the soil store and the consequent rate at which P is lost from the soil. The "Soil P loss rate" is a variable function which is described in Figure 7.

As the net soil P store increases from 0 kg ha^{-1} to a maximum value of 1250 kg ha^{-1}, then the soil P loss rate increases from a very low value (high ability to retain P) to 1 (zero ability to retain P).



Soil store	Soil P loss rate
0.000	0.050
125.00	0.060
250.00	0.070
375.00	0.090
500.00	0.115
625.00	0.160
750.00	0.215
875.00	0.305
1000.00	0.455
1125.00	0.685
1250.00	0.985

Data Points: 11

Edit Output:

Figure 7: Graphical function used to describe instantaneous soil-P loss as related to P in the soil store

Expressed textually, the net result of the amalgamation of these functions is that the rate at which P is lost from soil as runoff direct to the stream network is controlled by: the amount of P in the soil at any given time; the consequent ability of that soil to hold more P applied to it at that time; the inherent P-retention capacity of the soil, and; the drainage characteristics of the soil.

Leaching to groundwater (flow)

The algorithm used to calculate the loss of P via vertical leaching (which still subsequently reaches the regional drainage network but via sub-surface flow) is a function of the same parameters described above for P lost as runoff direct to streams, but modified by the leaching ratio which is 1-runoff ratio.

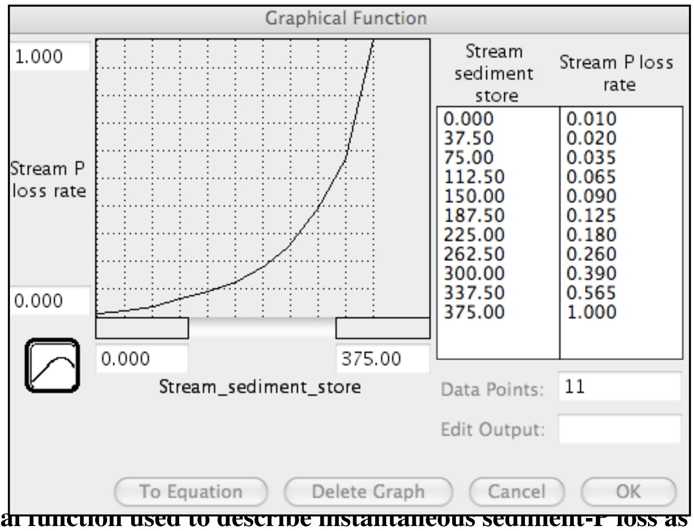
Although the algorithms for runoff P loss and leach P loss are identical, they are calculated separately as different P-loss modifying BMPs act on the two different P-loss pathways.

Stream sediment store (stock)

The streams represent the off-farm drainage system, and the destination of P loss from edge-of-field at the farm-scale but prior to receipt by a receiving waterbody. This stock describes the net accumulation of P in the stream sediment component of the watershed. It is the sum of the inputs from runoff and leaching minus the losses from sediment to the final receiving waterbody.

Loss to Estuary (flow)

This is calculated in a similar manner to that undertaken for “Runoff direct to streams” and “Leaching to groundwater”. The net P lost to the estuary is the sum of “Stream P loss” and “Groundwater P loss” modified by the functions describing the rate at which P is lost from sediment: “Stream P loss rate” and; “Groundwater P loss rate”. Both of these are variable functions described in Figure 8.



Data Points: 11

Stream sediment store	Stream P loss rate
0.000	0.010
37.50	0.020
75.00	0.035
112.50	0.065
150.00	0.090
187.50	0.125
225.00	0.180
262.50	0.260
300.00	0.390
337.50	0.565
375.00	1.000

Figure 8: Graphical function used to describe instantaneous sediment-P loss as related to P in the sediment store

Estuary (stock)

Although defined as "Estuary" in this model, this stock represents the ultimate point of the watershed to which all of the "streams" exit. Phosphorus in water flowing from the streams to the receiving waterbody will undergo one or more of assimilation, sorption, desorption or productive use whilst in the streams. This is identified as "Stream loss" in the model and is regulated by "Stream loss rate" (a graphical function, itself varying as in-stream P varies) and by the incoming P losses. This function then leaves a final amount of P to flow into the final receiving waterbody.

Model initiation

Table 1 shows the major model components shown in Figure 3 and their initial values unmodified by BMPs.

Table 1: Summary of major model components

Key	Model component	Model function	Initial value	Subsequent values
a	Fertilising	Flow	1.00 Kg $ha^{-1}yr^{-1}$	Graphical function
b	Precipitation	Flow	0.09 Kg $ha^{-1}yr^{-1}$	Graphical function
c	Importing feed	Flow	0.00 Kg $ha^{-1}yr^{-1}$	Graphical function
d	Utilisation	Flow	0.00 Kg $ha^{-1}yr^{-1}$	Graphical function
e	Soil store	Stock	300 Kg ha^{-1}	$\sum((a+b+c)-(d+k+m))_t$
f	Total P into soil store	Converter	NA	a+b+c
g	Soil P loss rate	Converter	150	Graphical function
h	Soil P loss	Converter	NA	f*g
i	Soil PRI factor	Converter	0.5	Slider (input variable)
j	Runoff ratio	Converter	30	Slider (input variable)
k	Runoff direct to streams	Flow	NA	h*i*(j/100)
l	Leaching ratio	Converter	70	100-j
m	Leaching to groundwater	Flow	NA	h*i*(l/100)

Key	Model component	Model function	Initial value	Subsequent values
n	Stream sediment store	Stock	0	$\sum ((k+m)-s)_t$
o	Stream P loss rate	Converter	180	Graphical function
p	Stream P loss	Converter	NA	k*o
q	Groundwater P loss rate	Converter	0	Graphical function
r	Groundwater P loss	Converter	NA	m*q
s	Loss to estuary	Flow	NA	o+r
t	Estuary	Stock	0	$\sum s_t$

Model Validation

As has been stated previously, the time-frame over which this model has been developed to run is a 200 year period commencing 100 years ago at approximately the time of European settlement of this region, and then 100 years into the future from the present day. Such a lengthy time frame was selected because: watershed-scale response to more localized management of soil and water resources is known to take long periods to become apparent (Meals *et al*., 2010), and; the 100 year point in the model (present day) provides an accurate model validation point as water quality monitoring data is available to verify the load entering the "Estuary" component of the model. This is a validation to observed data approach or historical behaviour test approach (Ford 2010).

Model calibration and validation was completed by initially loading the model P input parameters and native soil and sediment P content and assimilation attributes with data obtained from sampling of native (unfertilized) soils and with known natural watershed nutrient input and output rates. The model was then run for an initial 100 year period which aligns with the period of agricultural development for this watershed.

Results

Base run

In order to initially verify the overall efficacy of the model it was loaded with test data of which the key data sources were the data obtained during the Peel-Harvey Coastal Catchments Initiative (CCI) Projects (Lavell *et al.* 2004, Weaver *et al.* 2004, Neville *et al.* 2004, Keipert *et al.* 2008) and regional soil P and P retention test results (Weaver and Wong 2011).

The CCI survey data was used to determine the present-day inputs of P into, and outputs from the watershed (Figure 9). This indicated that there is an annual "P surplus" of 2070 tonnes, or 80%, of the applied P, every year which is not being used productively. Soil P and P-retention test results indicate that approximately 1200 tonnes is stored by the watershed soils every year (but this capacity is declining) resulting in 870 tonnes a year being lost to streams and groundwater. Stream P storage accounts for a large proportion of these losses (again, declining) resulting in a net loss of 140 tonnes of P to the estuary annually.

The consequent, present-day nutrient loss rate to the estuary was modelled to be 138 tPpa (Figure 10) which compares well with the value of 140 tPpa obtained from long-term water quality monitoring (EPA 2008). This represents a validation point for estuary P export as well as for watershed-compartment P content and loss rates.

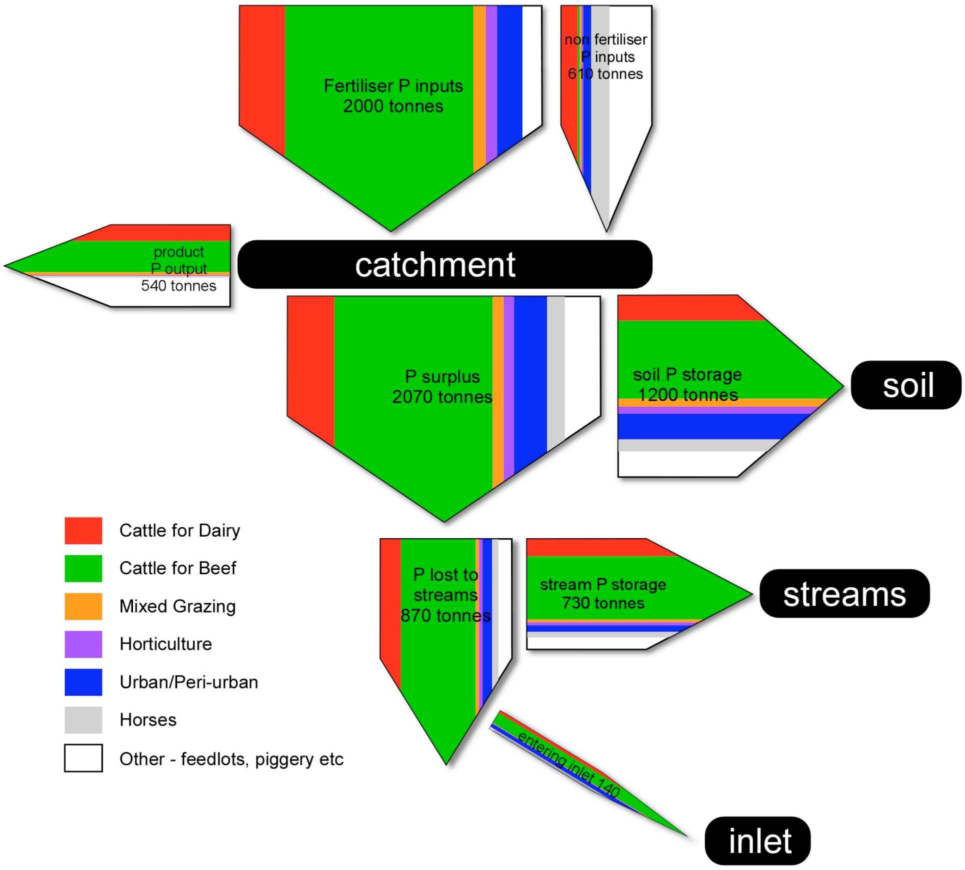


Figure 9: Phosphorus input, transformation, storage and loss for the Peel-Harvey Watershed (After Keipert *et al*. 2008)

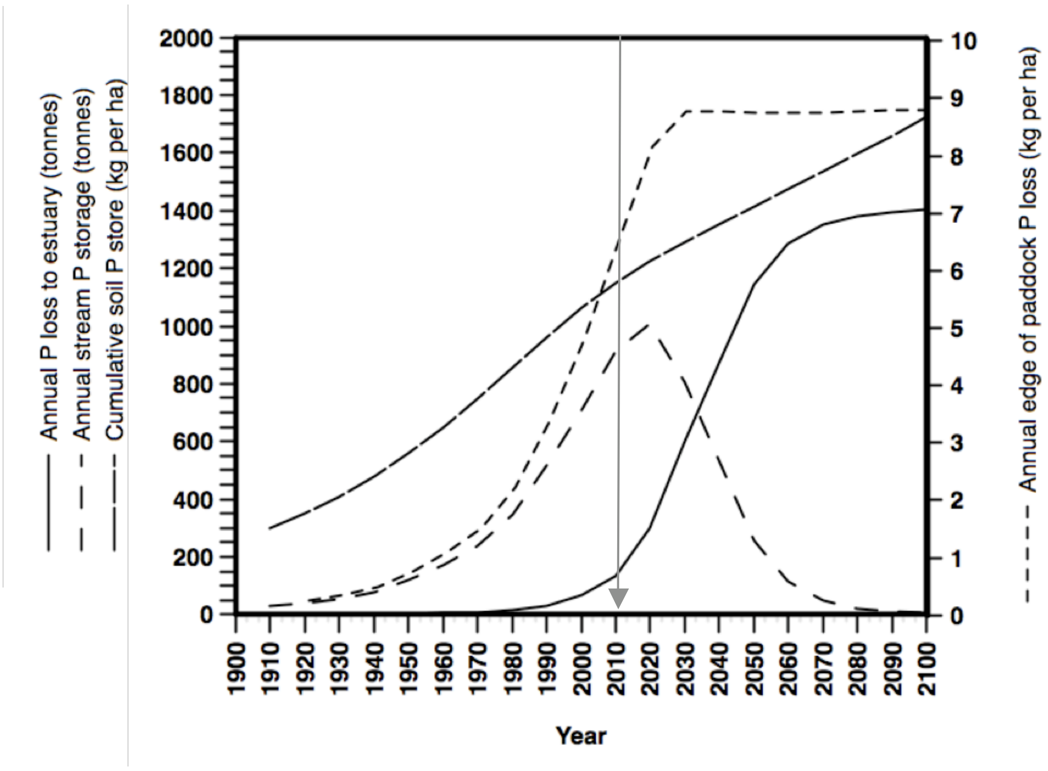


Figure 10: P losses and storages for watershed compartments over a 200 year simulation

Best Management Practice implementation scenarios

BMP effectiveness and application

The figures in Appendix 1 illustrate the STELLA© model following division into discrete sectors which are more manageable in programming terms. A summary of the effects of the various BMP sectors in terms of mitigating the P loss through the model is also shown below in Table 2.

Table 2: Potential P-loss reductions through use of P-management BMPs

Best Management Practice	Proposed maximum P-loss reduction potential	Location within model and P-transport system
Planting of perennial pasture species	10%	P runoff from soil
Re-planting of riparian vegetation	10%	P runoff from soil
Stock exclusion from waterways	30%	P runoff from soil
Use of P-retentive soil amendments	40%	P leaching through soil
Use of low-solubility P fertilizers	30%	P leaching through soil
"Best practice" fertiliser management – appropriate fertiliser only applied to soils requiring additional P and at the correct rates and times	10%	P input through fertiliser

The absolute effectiveness of these BMPs is not certain as reported values for their effectiveness are variable, as is their effectiveness under different land use and hydrological conditions. However, there is a significant amount of locally-derived information for BMP effectiveness in the Peel-Harvey region (Regeneration Technology Pty Ltd 2006, McKergow *et al*. 2002, Cronin 1998, Steele *et al*. 2009, Department of Agriculture and Food WA 2008, Steele 2006, Summers 2004).

Individual BMPs are applied to those particular components of the model to which they specifically apply (Table 2). For example, the proposed P-loss mitigation effect of the use of best practice fertiliser management actually reduces the amount of P being applied to farmland and, therefore in modelling terms, acts directly on P inputs. Conversely, management of riparian zones acts predominantly on P runoff over the soil surface. This is an important factor as multiple BMP actions on P as it moves through the model / system act in series, with BMPs applied earlier in the system effectively multiplying the effectiveness of those applied later.

Results of simulations

No-change scenario

When the initial model base run is allowed to run the course of the full 200 year simulation (Figure 10 and Table 3) releases of P from the soil store reach their maxima in approximately 70 years from now and will not reduce from this value. That is, the soil P "storage" components of the watershed are already "leaking" P, and their ability to buffer will be almost exhausted in 70 more years if current practices continue. Concomitant with the reduction in soil P storage capacity, is a maximization of the capacity of the watershed streams to store P in around 20 years time. From this point onwards, an amount of P approaching the entire present day P farm budget surplus will be released into the regional waterways.

BMP-implementation scenarios

The effectiveness of the implementation of BMPs generally increases the earlier in the P-transport pathway that they are applied. The implementation of comprehensive fertiliser-management practices which act at the very start of the P-transport pathway and effectively reduces actual P imports into the watershed, has the potential to produce a net P loss into the estuary of approximately 291 tonnes per annum (tpa) after 50 years and 541 tpa after 100 years. Conversely, BMP actions implemented later in the P-transport pathway, such as the use of perennial pastures and stock exclusion from waterways, have a much lower effectiveness. Perennial pastures allow net P-losses of 1146 tpa and 1301 tpa at 50 years and 100 years respectively, and stock exclusion allows net P losses of 1039 tpa and 1217 tpa at the 50 and 100 year points. Neither of these results differ significantly from the expected P-losses under the "no change" scenario.

Implementation of all BMPs, which effectively attempts to improve on all areas of inefficiency in the farm to watershed P-transport system, can potentially lead to net P losses to the estuary of 184 tpa and 345 tpa at the 50 and 100 year points respectively.

Even this scenario does not reduce P losses from current day levels and certainly does not reach the target P-loss rates of 70 tpa.

Table 3: : Phosphorus export to estuary following BMP implementation strategies

Scenario	P export to estuary (tonnes)	
	50 years from present	**100 years from present**
Current P export 140 tonnes per annum Target P export 70 tonnes per annum		
No change in management	1200	1342
Planting of perennial pasture species to 50% of appropriate land	1173	1322
Planting of perennial pasture species to 100% of appropriate land	1146	1301
Stock exclusion from all watershed waterways	1039	1217
Improved management of riparian vegetation to all watershed waterways (complete stock exclusion and vegetated buffer).	1039	1217

Scenario	**P export to estuary (tonnes)**	
	50 years from present	**100 years from present**
All “biological” BMPs – stock exclusions, riparian management and use of perennial pastures	1001	1187
Use of P-retentive soil amendments applied to all sandy soils at 10 tonnes ha^{-1}	833	1051
Use of P-retentive soil amendments applied to all sandy soils at 20 tonnes ha^{-1}	465	745
Low-solubility P fertiliser	833	1051
“Best Practice” fertiliser management	707	958
All “chemical” BMPs – low-solubility fertilizers, “best” fertiliser management and soil amendmnent with P-retentive materials.	291	541
All BMPs adopted	184	345

Discussion and conclusions

If nutrient input rates into the Peel-Harvey watershed continue at current levels then this, combined with the expected reduction in buffering capacity of the soils and streams, will have major environmental implications for a watershed and associated waterways which are already under severe stress. Not only will the target P-loss rate of 70 tpa not be achieved, but over the course of the next 100 years, P losses will increase by a factor of more than 9 times the current rate (from 140 tpa to approximately 1300 tpa). Broad-scale, comprehensive implementation of BMPs which address all components of the P-transport pathway can, at best, produce annual P losses of 184 tonnes and 345 tonnes at the 50 and 100 year points respectively.

The importance of the location of P-management strategies along the P-transport pathway has also been shown. Maximum BMP-effectiveness is achieved by the application of BMPs both at the earliest possible point in the P-transport pathway and/or at the most critical point in the watershed. Those BMPs which most reduce P imports into the watershed (best-practice fertiliser management) and which attempt to address the most critical issues in terms of P loss (the use of P-retentive soil amendments which target extremely poorly P-retentive soils) are most effective at reducing P loss. Implementation of a series of BMPs, each of which addresses the P-losses which were not attenuated by the previous BMP in the pathway maximize potential P retention.

However, there are still a number of large uncertainties both in the model as used in this study and in the watershed system itself. Phosphorus transport processes are almost entirely hydrologically driven. Whilst the current model inherently contains some hydrological information through the use of P-balance data as an input source, it does not cater for spatial or temporal variations in hydrological regime. It is not known, for example, what happens in terms of P loss in dry versus wet years, or what would potentially happen to P stored in the soils and sediments of the watershed if a wet year occurs after a long series of dry years (as is currently the case). The forms of P stores in the terrestrial and hydrological components of the watershed (and subsequently the model), and how these vary temporally are also poorly understood, as is the rate of P "utilization" within soils and drainage systems by biota other than that used in agricultural production.

Modelling indicates that nutrient levels in the estuary and waterways will increase significantly over the next 50 to 70 years unless major efforts are made to reduce losses at source. It is unlikely that symptomatic interventions at downstream points will be able to successfully manage nutrient accumulation rates in the future without major re-design of agricultural systems or re-engineering of soil and drainage systems if the present agricultural paradigm remains.

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