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Review

Modelling of Nutrient Pollution Dynamics in River Basins: A Review with a Perspective of a Distributed Modelling Approach

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Abstract: Nutrient pollution is one of the major issues in water resources management, which has drawn significant investments into the development of many modelling tools to solve pollution problems worldwide. However, the situation remains unchanged, even likely to be exacerbated due to population growth and climate change. Effective measures to alleviate the issues are essential, dependent upon existing modelling tools' capacities. More complex models have been developed with technological advancement, though applications are mainly limited to academic reach. Hence, there is a need for a paradigm shift in policymaking that looks for a reliable modelling approach. This paper aims to assess the capacity of existing modelling tools in the context of process-based modelling and provide a future direction in research. The article has categorically divided models into plot scale to basin-wide applications for evaluation and discussed the pros and cons of conceptual and process-based modelling. The potential benefits of distributed modelling approach have been elaborated with highlights of a newly developed distributed model and its application in catchments in Japan and Australia. The distributed model is more adequate for predicting the realistic details of pollution problems in a changing environment. Future research needs to focus on more process-based modelling.

Keywords: nutrient pollution dynamics; soil erosion; surface runoff; distributed hydrological model; river network

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1. Background

Nutrient pollution affects the surface and groundwater quality predominantly. Nitrogen (*N*) and phosphorus (*P*) are key nutrients that have been responsible for many forms of environmental hazards in aquatic ecosystems affecting the various states of amenities such as fisheries, navigation, water sports, and drinking water supply [1]. The use of chemical fertiliser for crop growing, pasture grazing, and livestock and dairy industry wastes have been responsible for *N* and *P* pollution in waterways [2]. Severe soil erosion is also associated with nutrient pollution in many landscapes [3]. The deforestation and modernisation of human societies are exacerbating the pollution effects. The global nutrient cycle has been altered substantially [1], and the anthropogenically derived atmospheric *N* in the 2000s was ten times higher than that of the 1860s [4–7]. In the United Kingdom, rural pollution contributed 50% of *P* inputs and 71% of *N* loads to surface water in 2002 [1,8]. The toxic algal bloom outbreak has increased in the Murray–Darling basin, the largest basin in Australia, which has vast socioeconomic and environmental impacts [9]. The available trend and evidence of widespread excess nitrate concentration above the World Health Organization (WHO) drinking water guideline in aquifers of many OECD countries indicate worsening groundwater quality [10]. The evidence suggests the need for drastic measures to recover polluted ecosystems, which substantially depend on current-day models' ability in decision support roles.

The consequences of burning fossil fuels are also felt in nutrient pollution. Climate change is likely to intensify the nutrient level in surface water [11]. The climate-driven atmospheric nitrogen deposition has exceeded the critical level in many European ecosystems [12,13]. The situation can be similar in other parts of the world, such as the United States [14]. However, atmospheric deposition may not be a significant source for many ecosystems such as Australia. Poor land management, land-use change (excessive land clearance), and poor stream management have aggravated the situation [15,16].

With the emergence of numerous problems associated with regional-scale land-use management, global climate change, ecosystem functions, and pollutants' fate, the need for integrated environmental modelling (IEM) is increasing [17]. As the concept develops and organises multidisciplinary knowledge, it provides a means to explain, explore, and predict environmental system responses to natural and human-induced stressors [17]. However, many of the existing modelling tools are not suitable to predict the realistic details as necessary, resulting in inaccurate estimation of nutrient budgets globally [18]. The recommendation for further studies from national and international organisations highlighted the need for model developments with future research directions, including priorities for integrated modelling. For example, the European Water Framework Directive (EU WFD) urged the member states of the European Union to quantify and monitor nutrient pollution in their river systems, which necessitated the development of more suitable models such as MONERIS [19]. The Australian government's first five-year plan (1995–2000) National Eutrophication Management Program (NEMP) highlighted the need for process-oriented modelling [20]. Due to the lack of a proper model, the effects of upstream flow process and in-stream mechanism on blue-green algal growth remain unknown for many Australian river systems [21]. The demand for integrated environmental modelling (IEM) has grown in the context of regional-scale land-use management, global climate change impact assessment, valuations of ecosystem services, fate and transport of nanomaterials, and life-cycle analysis [17]. This sees the undertaking of studies on the determination of research directions and priorities for integrated modelling by various organisations around the globe [22–26].

Many past technical reviews provided future directions in research. In 2003, Borah and Bera [27] comprehensively reviewed 11 nonpoint source models to understand their appropriateness in evaluating watershed management practices. The study identified models for short-term and long-term event simulations. Bennet et al. [28] used environmental models' characterisation techniques to establish an appropriate level of confidence in model performance as they are used in research, management, and decision making. They used numerical, graphical, and qualitative methods for comparison of model performance. Fu et al. [29] reviewed existing catchment-scale water quality models of freshwater, nonurban systems and their ability to support catchment management. Their study identified a significant challenge in separating the impact of climate from land use and management and stressed the need for process-based modelling. In this study, we highlight the needs for process-based modelling from the technical point of view, whereas the previous review by Fu et al. [29] mainly focused on policy needs. Here, we identify models based on categories from source level to basin-wide application and highlight the prospect of process-based modelling compared with others, particularly the capacity in determining the fate of nutrients in higher temporal and spatial resolutions and dealing with climate change applications.

2. The Review of Existing Models

The existing modelling tools are discussed broadly under three categories. The first category describes the plot-scale models, mainly used to determine pollutant loads from agricultural areas. Many of these models are the basis for larger-scale application input, forming the critical foundation for integrated modelling. The river network models are discussed under the second category. Finally, the third category identifies integrated models that combine land surface and in-stream network processes for holistic modelling of the watershed.

The atmospheric deposition of *N* nutrient is one of the sources for nutrient enrichment in many agricultural watersheds in some regions [12,13], and it can be modelled by using tools such as Model of Atmospheric Transport and Deposition of Reacting Nitrogen (MATADORN); long-range element tracer models HARM and TRACE [30,31] are excluded in the review below.

2.1. Nonpoint Source (NPS) Models at the Plot Scale

The early development of nonpoint source models mainly focused on solving pollution problems arising from agricultural land as the issue with the extensive use of chemical fertiliser was growing. Since both *N* and *P* have detrimental effects on ecology, the concern has developed on reducing *N* and *P* loading from agricultural catchments to river systems [32]. The plot-scale NPS models assist in identifying best management practices. However, in most cases, simplistic approaches such as export coefficient or the event mean concentration methods were used and considered acceptable approaches [33]. The Pollutant Load (PLOAD) [34] model is an example of this type of model. Chemicals, Runoff, and Erosion From Agricultural Management Systems (CREAMS) [35] and GLEAMS [36] are similar models but use some physics-based approaches. The process-based approach is found in Soil Nitrogen (SOIL N) and Soil Plant Atmosphere System (DAISY) models. In the SOIL N [37,38] model, the nutrient transformation process is considered conceptually, but the soil transformation process is divided into different layers in a mechanistic way [39,40], which is helpful in the study of the hydro-climatic influence on nutrient release. DAISY [41–43] adopted a more robust approach in describing the soil–plant–atmosphere interaction designed to simulate *N* dynamics in agricultural soils, which is suitable for simulating crop pattern behaviour on the nutrient level. The Root Zone Water Quality Model (RZWQM) [44–48] and Leaching Estimation and Chemistry Model (LEACHM) [40] are some other plot-scale models for the analysis of root zone process and groundwater leaching.

2.2. The River Water Quality Models

The in-stream water quality models are mainly used for determining the fate of pollutants during transport in flowing water. In this kind of modelling, the input is the point discharge at the river upstream or tributary locations. The models output the concentration level of pollutants at different segments of the channel. An example of a widely used stream water quality model is QUAL2K [49] or the improved version QUAL2E [50,51], which simulates state variables at river reaches based on wastewater loading as input for the model. QUAL2K and QUAL2E solve the equations for physical transport and chemical reaction processes of nutrients; however, the steady-state models provide output at a diel time scale only [49].

MIKE11 WQ is a one-dimensional river water quality modelling software that overcomes the limitation of a steady-state model by solving dynamic equations for physical, chemical, and biological processes. The model describes pollutant's interaction with bed load sediment and organisms, including nitrification and denitrification for computing dissolved oxygen (DO), biochemical oxygen demand (BOD), ammonia, and nitrate [52]. The tool adopts Nitrogen Simulation Model DRAINMOD-N to calculate nitrate input from agricultural land with other source inputs for the MIKE11 model [53].

The International Water Association (IWA) River Water Quality Model No. 1 (RWQM1) overcomes the limitations of the BOD-based river water quality models. This model incorporates biomass population growth and respiration processes to deal with the river acclimatisation to changes in pollutant load or environmental conditions and tracks mass continuity by describing the composition of organic material as the mass fraction of organic compounds [54]. In addition, the RWQM1 was a useful simulation tool for CalHidra2.0

to analyse the *N* removal and study different scenarios, including upgrading several wastewater treatment plants (WWTPs) [54].

2.3. Basin-Scale Integrated Models

The large-scale models aim to integrate land surface and in-stream processes in more detail. The main features in this type of modelling are the amalgamation of components to describe the whole basins. As a result, we found a mix of approaches to describe catchment behaviours in many basin-scale models.

2.3.1. Conceptual Models at Basin Scale

Agricultural Non-point Source Pollution model (AGNPS) [55] is a basin-scale single event-based model estimating pesticide and nutrient runoff from nonpoint sources in the agricultural watershed [56]. The model uses the empirical equation-based method. The AnnAGNPS is an improved version model of AGNPS, developed by the U.S. Department of Agriculture Agricultural Research Service (USDA-ARS) [57–59]. This version is capable of continuous simulation of nonpoint pollutants at a yearly scale [60]. A similar type of model, Areal Non-point Source Watershed Environment Response Simulation (ANSWERS) [61,62], computes movement of water in overland, subsurface, and channel flow phases operating on a cell-to-cell basis [63–65]. However, AGNPS and ANSWERS are single event-based models, and the application is limited to watersheds of about 200 km^2 [66].

Catchment Scale Management of Diffuse Source (CatchMODS) [67] is a semidistributed model that uses the Identification of Unit Hydrographs and Component Flows from Rainfall, Evaporation, and Streamflow (IHACRES) hydrological model [68] for calculating the time-series input of catchment boundary conditions. The sediment component is similar to SedNet model [69]. The model outputs are *TN* and *TP* on an annual basis without considering different species of nutrients due to a lack of process description [67,70].

Modelling Nutrient Emissions in River Systems (MONERIS) [71] is a conceptual model to account for different sources of nutrient emission [72]. The model considers seven pathways of inputs to the river network. The model is applicable for the estimation of annual loads. Monthly simulation is in progress (anonymously).

The stochastic model Spatially Referenced Regressions on Watershed Attributes (SPARROW) is a spatially referenced regression model that examines the landscape characteristics influencing the delivery of *N* and *P* from sources in a watershed to stream channels [73]. The approach in the model to determine the capacity of a watershed to deliver *N* to channels is the use of a 'landscape delivery ratio' (LDR), which is expressed as the fraction of *N* input that completes the overland and subsurface phase of transport to the stream channel. When the landscape delivery ratio is modelled, it is considered as a continuous function of local-scale landscape characteristics. Then, a spatial pattern is estimated that varies as a function of soil and climate characteristics. Subsequent incorporation of regional frameworks, such as physiographic, geologic, or ecological regions, may improve the estimation of landscape delivery ratio that is useful in modelling the effects of relatively broad-scale spatial processes that affect *N* attenuation [73]. The multivariate statistical techniques, such as cluster analysis (CA), principal component analysis (PCA), factor analysis (FA), and discriminant analysis (DA) can help characterise and evaluate surface and freshwater quality and verify temporal and spatial variations caused by natural and anthropogenic factors linked to seasonality [74,75].

The Australian modelling software developer the eWater has developed a suite of modelling packages such as CMSS [76], Environmental Management Support System (EMSS), the catchment modelling framework E2, and Water and Contaminant Analysis and Simulation Tool (WaterCAST) for various applications [70,77,78]. The Catchment Management Support System (CMSS) is an accounting model for nutrient budgeting from different land-use types [79], the EMSS is an event mean concentration and dry weather concentration based simulation model [80,81], and E2 and WaterCAST are improved versions for continuous time series simulations at catchment scale. The Catchment–Stream

Water Quality model CatStream [82,83] is another conceptual and network-based integrated catchment–stream water quality model built on a simplistic export coefficient method. The spatial scale is on a subcatchment basis, and the temporal scale is daily. The model outputs are *TSS*, *TN*, and *TP*. The main limitation of export coefficient-based modelling is the lack of representation of inherent processes, which makes the models unsuitable for predicting changes in hydro-climatic conditions.

2.3.2. Process-Based Models at Basin Scale

The process-based models aim to overcome conceptual modelling limitations by incorporating process descriptions from source generations to pollutant movement in surface and subsurface zones. For example, the Integrated Catchment Model of Nitrogen Dynamics (INCA-N) [30,31] is a process-based semidistributed model that estimates nutrient flux in soil and groundwater zones and tracks movements of both nitrate N and ammonium N in the riverine phase. The Integrated Catchment Model of Phosphorus Dynamics (INCA-P) is a similar type of model for P simulation and has a very complex and detailed description of *P* processes [84,85]. Although INCA-N and INCA-P are physically based models for *N* and *P* in the catchment and riverine phases, the hydrological part is conceptual. Therefore, they may not suit predictions under changing environments.

The stream order-based model RIVERSTRAHLER [86,87] simulates river eutrophication and in-stream algal production based on the ecological function of the river systems. It links the kinetics of microbiological and chemical processes to their macroscopic appearance at the scale of the whole drainage network [86,88–91].

The Pollutant Flow (PolFlow) model, developed in GIS, adopts a distributed modelling approach that calculates nutrient fluxes, routes nutrients through the river network, and has dynamic functions to account for nutrient transport delay in the soil groundwater [92]. However, the model operates in five-year time steps using spatial function at a spatial resolution of 1 km^2, which may not suit current situations.

The real-time flood forecasting system WATFLOOD [93] is a distributed model that uses group response unit functions to describe the hydrological process. The model estimates runoff, sediment yield, and soluble nutrient concentrations for each land cover class, weighted by area and then routed downstream. However, the model has a limitation in describing the transport process as it does not include a dedicated river component.

The Soil and Water Assessment Tool (SWAT) model [94,95] is an outcome of the USDA Agricultural Research Service (ARS). The origin of SWAT is linked to USDA ARS models, including the CREAMS [96], GLEAMS [36,97], and the Environmental Impact Policy Climate (EPIC) [98]. The EPIC was initially called the Erosion Productivity Impact Calculator [99]. These components were previously combined into a simulator called the Water Resources in Rural Basins (SWRRB) model [100] to assess management impacts on water and sediment movement for ungauged rural basins across the United States. The SWAT has been widely used around the world for its easy access and flexibility [101]. For example, the Ecohydrological Assessment Tool (ECOHAT) combined SWAT with a conceptual rainfall–runoff model Xinanjiang for modelling the Chinese watersheds [102].

The Diffuse Nitrate Modelling Tool (DNMT) [32] is built within the TOPMODEL [103] for simulation of runoff through the permeable area and over the impervious area and the nitrate transport. The *N* transformation process has been modelled using SOILN [38]. However, this model introduced the unit nitrograph (UNG) method, similar to the concept of the unit hydrograph method in hydrology, which is based on a conceptual approach.

The MATSALU model was developed in Estonia for the Matsalu Bay (Baltic Sea) agricultural watershed to assess different management scenarios for eutrophication control of the bay [104,105]. The model consists of four coupled submodels that simulate watershed hydrology, catchment geochemistry, river transport of water and nutrients, and the bay ecosystem. Like SWAT, its watershed components were essentially based on the CREAMS approach. However, since the model was developed for the MATSALU watershed and connected to specific datasets, it is not sufficiently transferable.

The Soil and Water Integrated Model (SWIM) is a watershed model for hydrology and water quality that combines SWAT and MATSLU models and was suggested for N modelling for mesoscale watersheds (100–10,000 km^2) [66].

An integrated surface and subsurface model (ISSM) was applied in the Bonello watershed in Italy; it incorporated a hydrological model (SWAT), groundwater models (MODFLOW and MT3DMS), and an in-stream water quality model (QUAL2E). The tool provides good results in predicting water and nutrient leaching from the surface to the aquifer, groundwater dynamics, aquifer interaction with the stream system, and the surface water and nutrient fluxes at the watershed outlet [106].

The Système Hydrologique Européen Transport (SHETRAN) [107,108] model couples the surface/subsurface three-dimensional water flow, multifraction sediment transport, and multiple reactive solute transport. The leaching and transport of nitrate are modelled using the three-dimensional differential solute transport equations [109,110]. Using SHETRAN-UK, a nitrogen modelling system (NMS) was developed and applied within the 3000 km^2 Tyne basin from 1985 to 1989. The physically based catchment model NMS comprises a field-scale nitrogen model, EPIC. EPIC is an established crop growth and farm management model [111] and provides N input and uptake data to SHETRAN [112].

MIKESHE, a submodel of SHE Système Hydrologique Européen, within the MIKE framework from the Danish Hydraulic Institute (DHI), was combined with DAISY to estimate pesticide leaching to shallow groundwater for physically based simulation of macropore flow process in a spatially distributed manner [113–116]. Similarly, the European Soil Erosion Model EUROSEM [117,118] was combined with MIKESHE for continuous simulation. MIKESHE is a physically based distributed hydrological modelling tool [107,108]. However, the use of MIKESHE may not be applicable where the hydrologic regime is dominated by overland flow [113].

3. Research Gap Analysis over Basin-Scale Modelling

The watershed models provide a useful framework for analysing the anthropogenic and climate effects on the natural environment [66]. Many of these models have been developed, dividing the catchment into homogeneous subareas called hydrologic response units (HRUs). Each HRU consists of parameters for the topographic features, land use, land cover, and soil types. Models such as SWRRB [119], MATSALU [104,105], and SWAT [120] have used the concept of HRU for larger watershed-scale modelling. The size of a watershed is also a factor for the applicability of some models in some instances. It is found that SWRRB can be used in agricultural basins of up to 600–800 km^2, MATSALU was applied in a 3500 km^2 rural basin, and SWAT was applied in watersheds of up to 25,000 km^2 in the United States [66]. Hence, it is apparent that some models are catchment-specific due to limitations in HRU approaches. The main drawback is that the water flows and dissolved and solid-phase concentrations of nutrient compounds are computed from lumped hydrologic and biogeochemical processes at a subarea (HRU), which may not be applicable to larger catchments. As a result, the need for distributed modelling is evident for regional-scale application for water quantity and quality analysis.

In many modelling tools, the nutrient transport via soil erosion process has been ignored, which could be an important source in many watersheds. The WATFLOOD [93,121] model separates soil-bound and soluble nutrient transport processes in the model description, though there are limitations in the transport mechanism that need to be addressed [93]. The SWAT model [95] is not suitable for dynamic sediment modelling [122]. Hence, the linking of hillslope soil erosion process and in-stream sediment transport has been an important research topic in the nutrient modelling context.

ANIMO [123] and DAISY [42,43] are examples of complex mathematical models that could be useful to describe nitrogen biogeochemical process in a detailed manner; however, they are limited to application in soil column movement only at plot-scale levels as they do not include a component for movement or transformation in surface water or groundwater [112]. The integration of this type of plot scale model with a distributed hydrologic model such as MIKESHE or SHETRAN could overcome the limitations. As the computing facilities and GIS functionalities have advanced tremendously, spatially distributed models have been linked with catchment and drainage network systems for continuous time series simulation [124–127]. The fully distributed hydrological model MIKESHE [107,108] has incorporated DAISY, and the similar model SHETRAN incorporated NMS for a physically based description of nutrient dynamics for nitrate simulation. However, their applications were mainly limited to groundwater analysis. The distributed modelling of dominant overland flow process and nutrient export from catchment to the river network system via various pathways are very limited.

Human-induced climate change has far-reaching consequences with negative impacts on the ecosystem from local to global level [11]. Overexploitation of natural resources, population growth, and urbanisation are linked to degraded water quality in surface and ground waters. Climate change will place additional stress on receiving watercourses through alterations to rainfall and temperature and resultant changes in biophysical properties [128]. The uncertainties of how future climate will alter physical, chemical, and biological systems combined with uncertainties of climate models limit our ability to provide robust predictions and identify how best to manage the water environment [129]. Such uncertainties make it difficult to determine future water quality status and set improvement targets to achieve good ecological outcomes [130].

The authors of this paper adopted a process-based approach in nutrient simulation with an aim to improve model predictions, developed within a distributed hydrological modelling framework IISDHM [131–133], and demonstrated how hydro-climate-based parameters were useful to assess the impact of climate change on nutrient pollution and determine the future water quality status [134]. An overview of this modelling is discussed below, and summaries of all models reviewed in this paper are presented in Tables A1–A3 (Appendix A).

4. Applicability of a Distributed Modelling Approach within IISDHM

The Institute of Industrial Sciences Distributed Hydrological Model (IISDHM) is a distributed hydrological model, originally developed at the University of Tokyo, Japan [131–133], that can describe the hydrological process in surface and subsurface zones. Authors Alam and Dutta [134–136] developed the nutrient modelling components within this IISDHM framework. Figure 1 shows the various components of the model.

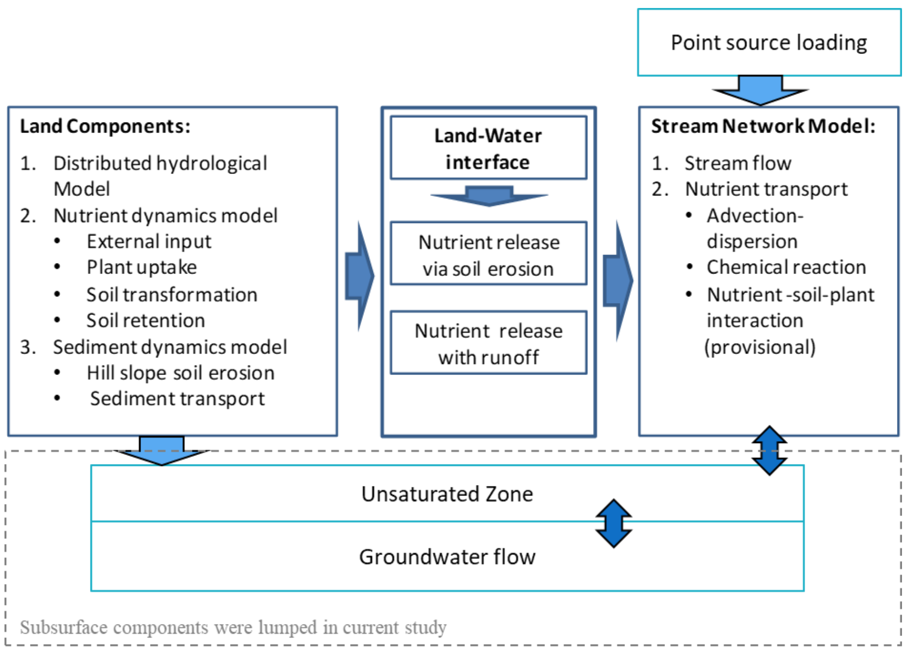

Figure 1. Integrated modelling framework for nutrient dynamics and transport.

The model was tested and verified in two case studies in Japan and Australia (Figure 2), which are hydro-climatologically of distinct characteristics, being situated in different hemispheres. The size of the catchment of the Saru River of Japan is about 1350 km^2. Although the catchment is predominantly a forested ecosystem, huge amounts of sediment and nutrient loads are carried away during heavy floods.

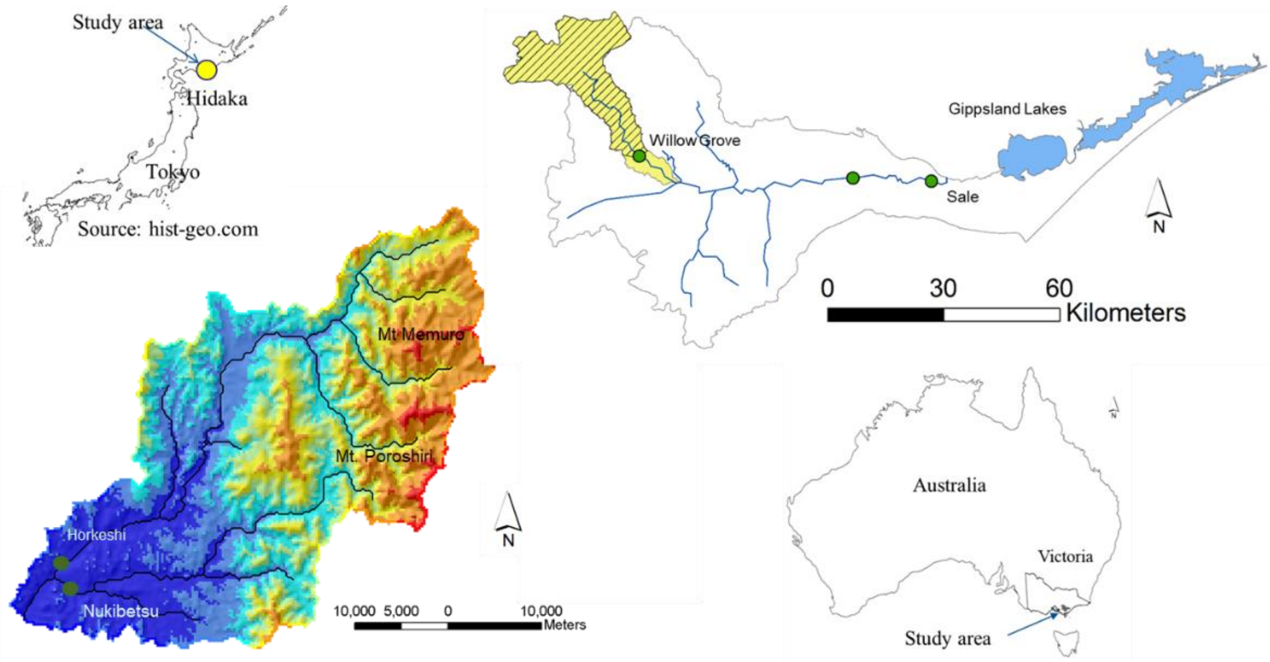

Figure 2. Location maps showing case study areas (the Saru River, Japan (left) and the Latrobe River, Australia (right).

As data were available from a high-intensity data collection campaign, the applicability of the model for flash flood events could be tested in the Saru River. The observed data show strong correlations between flow and nutrient level for this river, as shown in Figure 3, which was predicted well with hourly interval output.

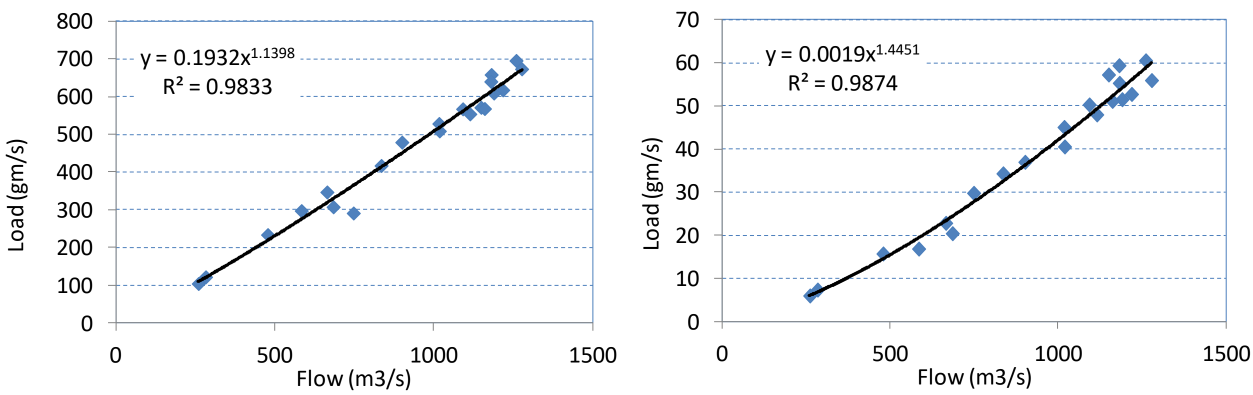

Figure 3. Correlation of NO_3-N (left) and PO_4-P (right) loadings with flow in the Saru River.

The model adopted hydro-climate-based parameters and soil moisture index, which was useful to simulate seasonal nutrient transport behaviours for the Latrobe River in Australia. Figure 4 shows the seasonal pattern of NO_3-N level and the correlation with the flow that was used for model validation.

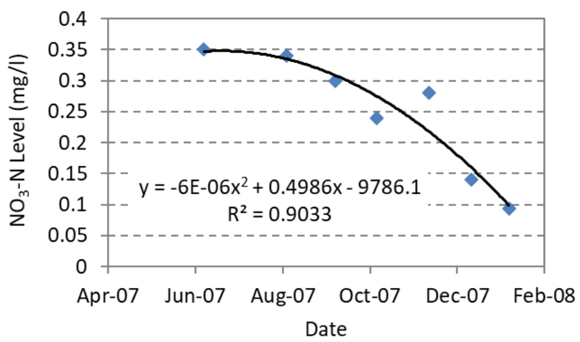

Figure 4. Seasonal pattern in NO_3-N level and the correlation with the flow in the upper catchment of the Latrobe River.

5. Conclusions

A comprehensive review of the existing nutrient modelling tools has been presented in this paper. The discussion has covered various types of models, including plot-scale models, river water quality models, and basin-scale integrated models. It is observed that the conceptual approach using the export coefficient method or event mean concentration method is a widely used approach in determining nutrient release from different land uses. These methods are best suited for assessing best management practices by accounting for annual loadings of *TN* and *TP* from agricultural lands. However, this type of modelling is unsuitable for predicting dynamic behaviour due to changes in catchment processes. The process-based models overcome the limitations, though their application has been very limited to agricultural lands, where they have mostly been used to determine the nutrient level for plant growth interaction or groundwater modelling. The implementation at a larger scale is relatively scarce because of the inability to describe the proper nutrient export mechanism. Future research should focus on integrating catchment and river transport modelling that enables the determination of catchment export, the residence or movement of nutrients in various pathways, and the role of sediment in nutrient budgeting at downstream waters. This study shows an application of a distributed modelling approach that was useful to predict nutrient pollution at a detailed level under a changing environment. This type of modelling will be helpful to determine the future water quality status and adopt management options for integrated planning.

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Conflicts of Interest: The authors declare no conflict of interest. The research was not part of any projects related to authors' current affiliated organisations.

Appendix A

Table A1. The summary of plot-scale models.

Name of Model	Type	Land Surface Process	Ground Water Process	Temporal Scale	Output	Reference
PLOAD	Conceptual	Export coefficient	-	Annual	*TN* and *TP*	[34]
LEACHM	Process based	Soil and crop model	Unsaturated zone model	Variable time	*N* and *P*	[40,137]
SOILN/SOILNDB	Process based	Soil and crop model	Lumped	Annual	*N*	[17,38,109,138]
EPIC	Process based	Soil and crop model	-	Annual	*N* and *P*	[123]
ANIMO	Process based	Soil layer model	Leaching	Variable time step	*N* species	[99,123]
CREAMS/GLEAMS	Physics	Soil and crop	Root zone	Event based	*N* and *P*	[35,36,96,97]
RZWQM	Process based	Soil and crop model	Lumped	Subdaily	NO_3-*N*	[46]
DAISY	Process based	Soil and crop model	Leaching	Variable time	NO_3-*N*	[41–43]

Table A2. The summary of river water quality models.

Name of Model	Type	Land Surface Process	In-Stream Process	Ground Water Process	Spatial Scale	Temporal Scale	Output	Reference
QUAL2K/ QUAL2E	Process based	Time series input	Network model	-	River reach	Diel time scale	*N* and *P* species	[49–51]
MIKE 11	Process based	Time series input	Network model	-	Node and link	Variable time step	*N* and *P* species	[139]
RWQM1; CalHidra 2.0	Process based	Exist	Exist	-	Node and link	Not available	*N* and *P*	[54]
INCA-N	Process based	Semidistributed	Reach based	Semidistributed	River reach	Weekly	NO_3-*N* level	[30,31]
INCA-P	Process based	Semidistributed	Reach based	Semidistributed	River reach	Daily	Organic and inorganic *P* levels	[85]
RIVERSTRAHHLER	Process based	-	River network model	-	River reach	Variable time	Nitrate, phosphates, and silica	[86]

Table A3. The summary of integrated basin-scale models.

Name of Model	Type	Land Surface Process	In-Stream Process	Ground Water Process	Spatial Scale	Temporal Scale	Output	Reference
CatStream	Conceptual	Subcatchment	River network	-	Subcatchment based	Daily	*TSS*, *TN*, and *TP*	[82,83]
AGNPS	Physics	Rate based	-	-	Grid based—can be used up to 200 km^2 size watershed	Single event	*N* and *P*	[55]
ANSWERS	Physically based	Sediment and runoff based	Exist	Exist	Hydrologic response unit (HRU) (200 km^2)	Single event	*N* and *P*	[61,62]
CatchMODS	Conceptual	Time series by IHACRES	Network model	Leaching estimates	Subcatchment based	Annual	*TN* and *TP* loads	[67]

Table A3. *Cont.*

Name of Model	Type	Land Surface Process	In-Stream Process	Ground Water Process	Spatial Scale	Temporal Scale	Output	Reference
CMSS	Conceptual	Export coefficient	-	-	Subcatchment based	Daily	*TN* and *TP* loads	[76]
EMSS	Conceptual	Event mean concentration	-	-	Subcatchment based	Daily	*TN* and *TP* loads	[70]
E2	Conceptual	Event mean concentration	-	-	Subcatchment based	Daily	*TN* and *TP* loads	[77]
SWRRB	Physics based	CREAMS	-	GLEAMS	Basin scale (600–800 km^2)	Single event		[119]
PolFlow	Conceptual	Lumped	Lumped	Lumped	1 km grid	5 year	*TN* and *TP* loads	[92]
MONERIS	Conceptual	Rate based emission from different sources	-	Lumped as a source	1 km grid	Annual	*TN* and *TP* emission	[71]
SPARROW	Regression model	Landscape delivery ratio	Network model	Lumped	River reach with catchment input	Annual	*TN*	[73]
DNMT	Process based	SOILN model	Unit Nitrograph (UNG) method for transport to waterways	Lumped with soil nutrient process model (SOILN)	Subcatchment based	Multiple steps	NO_3-N	[32]
SWAT	Process based	Lumped soil and aquifer process	QUAL2E	Lumped with surface process	Semidistributed variable storage routing method	Variable steps	*N*	[94,95,140]
MATSALU	Same as SWAT				Elementary Areas of Pollution (EAP) based	Daily	*N*	[105]
SWIM	Same as SWAT				Mesoscale watershed	Daily	*N*	[66]
ISSM	Process based	SWAT	QUAL2E	MODFLOW-MT3DMS	-	Daily	*N* and *P*	[106]
WATFLOOD	Process based	Group response unit (GRU) approach; CREAM and AGNPS approach	-	Lumped to estimate leaching using extraction coefficient	Grid based	Hourly	*N* and *P*	[93,121]
TNT2	Process based	Soil–ground water and surface interaction	-	Exist	Grid based	Variable steps	*N*	[140]
SHETRAN	Process based	EPIC model	Exist	Exist	Grid based	Variable steps	NO_3-N	[107,108,110]
MIKESHE/DAISY	Process based	DAISY	-	Solute transport process	Grid based	Variable steps	NO_3-N	[13,41–43,107,108]
IISDHM	Process based	Flow capacity based	Dynamic	Lumped	Grid based	Run in 1 s time step with hourly interval output	*N* and *P* species	[131–136]

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