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Review

A review of erosion and sediment transport models

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Abstract

Information on sediment and nutrient export from catchments and about related erosive processes is required by catchment managers and decision-makers. Many models exist for the consideration of these processes. However, these models differ greatly in terms of their complexity, their inputs and requirements, the processes they represent and the manner in which these processes are represented, the scale of their intended use and the types of output information they provide. This paper reviews several different erosion and sediment and sediment-associated nutrient transport models with regard to these factors. The review of models is limited to those models with explicit considerations of either the sediment generation or transport process.

Keywords: Water quality; Erosion and sediment transport models; Model selection

Contents

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1. Introduction

Information on soil erosion and its effects on water quality at catchment scales is increasingly sought by catchment stakeholders and managers. This information is required at temporal and spatial scales that reflect the timing and pattern of sediment movement in response to rainfall events. Most of the models that have been developed in the past to provide information on erosion and water quality processes are inappropriate for providing catchment scale, event-based predictions of sediment loads. They can suffer from a range of problems including over-parameterisation, unrealistic input requirements, unsuitability of model assumptions or parameter values to local conditions, and inadequate documentation of model testing and resultant performance.

With the increased computing powers of the last 20 to 30 years, there has been a rapid increase in the exploration of catchment erosion and sediment transport through the use of computer models. This is reflected in the activities of the scientific community, as well as those of catchment managers and other stakeholder groups. The range of model users is extremely diverse in terms of their modelling expertise, the questions they are exploring, the level of detail and scales at which these questions need to be addressed, and the level of interactions between the model users and model developers. Looking initially at government agencies that are responsible for implementing and maintaining land and water management initiatives, many of these agencies have considerable technical and scientific expertise in the development and application of erosion and water quality models. The responsibilities of an agency has in many cases driven the development of catchment scale models capable of being used to explore issues of relevance to the agency in question. Examples of such agencies include the United States Environmental Protection Agency (USEPA) and the Department of Agriculture (USDA). These two agencies have been deeply involved in developing erosion and water quality models for application to catchment scale issues. Similar agencies in other countries have also developed modelling skills with respect to the water quality issues that they face. Other agencies or stakeholder groups, however, may not have this level of modelling expertise and this can largely influence the appropriateness of a given model, if that agency or stakeholder intends to apply the model themselves.

Given that there is such a diverse range of parties that are involved in erosion modelling exercises, and that the objectives of these model users can differ considerably, it is difficult to develop strict criteria for assessing the available models without focussing in on a particular issue, such as the future land management options or management and regulation of in-stream processes. Over time, and between catchments, the agendas of potential model users can change. What is the current hot issue is likely to be superseded at a later date. The key objective of this review is to provide a resource that potential model users can use to guide their catchment scale modelling application, whether their focus be on land surface or in-stream processes. This is achieved by reviewing a number of existing models, the concepts behind these models, and the trade-offs that can influence the performance of the model and the utility of the model in addressing the questions posed by the model user.

1.1. Existing model reviews

Various aspects of the modelling of erosion and sediment generation, transport and deposition processes have been reviewed previously in the literature. The processes of sediment generation, transport and deposition have been well described elsewhere (e.g. Rose, 1993; Haan et al., 1994) and are discussed in this review only to introduce the concepts used in modelling these processes. Bull and Kirkby (1997) traced the development of gully erosion models, from the first stochastic models to the more recent process-based representations of the system. Prosser and Rustomji (2000) reviewed the representations and use of sediment transport capacity relationships in modelling sediment transport in overland flow. The concept of sediment transport capacity is commonly used in modelling sediment movement via overland flow and in channel transport models. The classification system used by Wheater et al. (1993) for describing the process representation of the model (empirical, conceptual and physics-based) is adopted in this paper.

One of the more comprehensive reviews of agricultural non-point source water quality models was undertaken by the Task Committee 'Non-Point Source Water Quality Models: Their Use and Application' and as part of the Southern Region Research Project S-273 'Development and Application of Comprehensive Agricultural Ecosystems Models' (Parsons et al., 2001). This review summarises much of the model evaluation efforts that have occurred over the last decade and has detailed model descriptions and evaluations for 14 agricultural non-point source pollution water quality models that are widely used. The models reviewed were predominantly developed in the North America, although they included some models from Europe.

Other literature deserving specific mention include the works by Beck (1987) and Singh and Singh (2001). Beck (1987) comprehensively reviews the sources of uncertainties in water quality modelling, with a detailed discussion of the problem of parameter indentifiability in models of medium to high complexity. Singh and Singh (2001) provide a detailed discussion of flow routing techniques, particularly the use of hydrologic routing algorithms in routing flows through catchment, channels and reservoirs. Many other authors have contributed to the large body of work evaluating and comparing the many models that exist in the literature. Where appropriate, this work is acknowledged and cited in the text.

These reviews are drawn on to provide the reader with an overview of the broad scope of issues that require consideration prior to modelling erosion and sediment movement in catchments. For a detailed analysis of these components, readers are referred to the appropriate references throughout this text.

The intention of this review is to provide an overview of the concepts and models that have been used to simulate aspects of erosion, sediment generation and sediment movement through the landscape at a catchment level. While our focus is on catchment scale approaches, a great deal of work on the simulation of erosion and sediment processes has been undertaken at smaller scales. Much of this work has led to the development of concepts and model algorithms that have been incorporated to some extent into catchment scale modelling approaches. The models reviewed reflect the range of approaches that have been used by the modelling community and catchment managers. The majority of the models reviewed in this paper have been discussed in previous literature. By drawing many of these model descriptions into the one paper, a comparison of the features of these models is fostered. Deficiencies in current approaches can then be identified. In this paper, those aspects of modelling the key processes at the catchment scale that remain problematic are discussed with a view towards targeting future model development to addressing current limitations.

We have narrowed the range of models for review to those that explicitly consider sediment and sediment-associated pollutants. While there is some overlap between the models reviewed by Parsons et al. (2001) and those discussed in this paper, a number of other models with the potential for being used more widely are considered.

This review is not concerned with aspects of water quality beyond those associated with sediment-associated nutrients. Previous reviews of water quality modelling that consider such water quality issues as pH and alkalinity and coliforms include that of Bowie et al. (1985).

1.2. Review structure

The review, from this point on, is structured in the following manner. A brief description of the erosion, sediment transport and deposition processes is given in Section 2. In Section 3, we review the types of erosion and sediment transport models that are available. Models types are distinguished in terms of how the physical processes of sediment detachment, transport and deposition are represented by the model, as well as the spatial and temporal resolution of the model types. Section 4 discusses the modelling of sediment-associated water quality constituents, considering erosion and sediment generation, sediment transport and sediment deposition. This section introduces a number of the concepts commonly incorporated in water quality models and concludes with a brief discussion of the validity of these process representations. Section 5 provides descriptions of a number of available models. The selected models were developed for a wide range of applications, over a range of scales from the plot based models to catchment scale approaches. While the focus of this review primarily considers the catchment scale, existing model applications at these scales have borrowed heavily from smaller scale applications. For completeness, some of the plot scale models that have been implemented at larger scales are described in this section. The models described in Section 5, and summarised in Table 1, are either in-stream models, land surface models or, in some cases, have both land surface and in-stream components. Catchment scale prediction of sediment generation and transport requires consideration of land surface processes and in-stream processes. Thus, examples of models that fit into either, or both, of these categories are

Table 1
Erosion/sediment transport models

Model	Type[a]	Scale	Input/output	Reference
Water quality				
AGNPS	Conceptual	Small catchment	Input requirements: High Output: runoff volume; peak rate, SS, N, P, and COD concentrations	Young et al. (1987)
ANSWERS	Physical	Small catchment	Input requirements: High Output: sediment, nutrients	Beasley et al. (1980)
CREAMS	Physical	field 40–400 ha	Input requirements: High Output: erosion; deposition	Knisel (1980)
EMSS	Conceptual	Catchment	Input requirements: Low Output: runoff, sediment loads, nitrogen loads and phosphorus loads	Vertessey et al. (2001) Watson et al. (2001)
HSPF	Conceptual	Catchment	Input requirements: High Output: runoff, flow rate, sediment load, nutrient concentration	Johanson et al. (1980)
IHACRES-WQ	Empirical/ Conceptual	Catchment	Input requirements: Low Output: runoff, sediment and nutrients	Jakeman et al. (1990, 1994a,b), Dietrich et al. (1999)
IQQM	Conceptual	Catchment	Input requirements: Moderate Output: many pollutants including nutrients, sediments, dissolved oxygen, salt, algae.	DLWC (1995)
LASCAM	Conceptual	Catchment	Input requirements: High Output: runoff, sediment, salt fluxes	Viney and Sivalapan (1999)
SWRRB	Conceptual	Catchment	Input requirements: High Output: streamflow, sediment, nutrient and pesticide yields	USEPA (1994)
Erosion				
GUEST	Physical	Plot	Input: High Output: runoff; sediment concentration	Yu et al. (1997) Rose et al. (1997)
LISEM	Physical	Small catchment	Input: High Output: runoff; sediment yield	Takken et al. (1999) De Roo and Jetten (1999)
PERFECT	Physical	Field	Input: High Output: runoff, erosion, crop yield	Littleboy et al. (1992b)
SEDNET	Empirical/ Conceptual	Catchment	Input requirements: Moderate Output: suspended sediment, relative contributions from overland flow, gully and bank erosion processes	Prosser et al. (2001c)
TOPOG	Physical	Hillslope	Input: HighOutput: water logging, erosion hazard, solute transport	CSIRO Land and Water, TOPOG Homepage; Gutteridge Haskins and Davey (1991)
USLE	Empirical	Hillslope	Input: High Output: erosion	Wischmeier and Smith (1978)
WEPP	Physical	Hillslope/ catchment	Input: High Output: runoff; sediment characteristics; form of sediment loss	Laflen et al. (1991)
In-stream transport				
MIKE-11	Physical	Catchment	Input: High Output: sediment yield, runoff	Hanley et al. (1998)

[a] Model classification refers to the over-arching process representation of the model. Model components generally contain a mix of empirical, conceptual and physics-based algorithms.

reviewed. In Section 6, a discussion is provided of the major issues facing erosion and sediment transport modelling: natural complexity, limitations in understanding of key processes, model complexity and accuracy, data availability constraints, model uncertainties, and dependence on water quantity predictions. This discussion is used to identify key components in modelling sediment generation and movement through catchments that require further attention.

2. Erosion and transport processes

The process of erosion can be described in three stages: detachment, transport and deposition. Detachment of sediment from the soil surface was originally considered to be exclusively the result of raindrop impact (e.g. Hudson, 1975), although the importance of overland flow as an erosive agent has now been recognised. Rainfall detachment is caused by the locally intense shear stresses generated at the soil surface by raindrop impact (Loch and Silburn, 1996). Likewise, overland flow causes a shear stress to the soil surface which, if it exceeds the cohesive strength of the soil, termed the critical shear stress, results in sediment detachment. In different situations, the major processes leading to sediment detachment will differ.

There are four main types of erosion processes: sheet, rill, gully and in-stream erosion. Sheet erosion refers to the uniform detachment and removal of soil, or sediment particles from the soil surface by overland flow or raindrop impact evenly distributed across a slope (Hairsine and Rose, 1992a). Together with rill erosion, sheet erosion is often classified as 'overland flow' erosion, detaching sediment from the soil surface profile only. For purposes of simplification, the two processes are often considered together in erosion modelling.

Rill erosion occurs when water moving over the soil surface flows along preferential pathways forming an easily recognisable channel (Rose, 1993). These rills are generally small erosion features, and have been defined by Loch and Silburn (1996) as being 'flow channels that can be obliterated by tillage'. Rill initiation is controlled by the cohesive strength of the soil and the shear forces exerted on the soil. Flow in rills acts as a transporting agent for the removal of sediment downslope from rill and interill sources, although if the shear stress in the rill is high enough the rill flow may also detach significant amounts of soil (Nearing et al., 1994).

Gully erosion, in contrast to rill erosion, describes channels of concentrated flow that are too deep to be obliterated by cultivation (Rose, 1993; Loch and Silburn, 1996). Gully flows differ from sheet and rill flows in that raindrop impact is not an important factor in terms of flow resistance or in sediment particle detachment (Bennett, 1974). Gully development is considered to be controlled by thresholds, as with rills, although these thresholds have been related to slope and catchment area rather than flow erosivities (Loch and Silburn, 1996).

In-stream erosion involves the direct removal of sediment from stream banks (lateral erosion) or the stream bed. Sediment also enters the stream due to slumping of the stream bank resulting from bank erosion undercutting the stream bank. During high flow periods, a large proportion of the sediment that is transported through the stream network can originate from the stream channel. The potential exists to lump stream bank erosion processes with gully erosion for description by considering either as a specific form of the other.

These erosion types do not necessarily occur in isolation from one another. They are influenced by the landscape factors as well as rainfall characteristics. Loch and Silburn (1996) stated that the development of rill and gully erosion requires the concentration of flow and discharges that exceed critical thresholds, and as such will occur as the length of the slope increases. Hence, the dominant erosion process would be expected to follow a downslope sequence of splash–sheet–rill–gully (Loch and Silburn, 1996). As will be discussed in later sections, most erosion models tend to predict erosion for one of these erosion types, or at most a couple. In a catchment scale modelling exercise, this raises the possibility that in certain areas of the catchment the processes considered by the model being used are not truly representative of the processes actually occurring in the catchment.

3. Model types

A wide range of models exists for use in simulating sediment transport and associated pollutant transport. These models differ in terms of complexity, processes considered, and the data required for model calibration and model use. In general there is no 'best' model for all applications. The most appropriate model will depend on the intended use and the characteristics of the catchment being considered. Other factors affecting the choice of a model for an application include:

- Data requirements of the model including the spatial and temporal variation of model inputs and outputs;
- The accuracy and validity of the model including its underlying assumptions;
- The components of the model, reflecting the model capabilities;
- The objectives of the model user(s), including the ease of use of the model, the scales at which model outputs are required and their form (such as concentration vs. load); and
- Hardware requirements of the model.

In general, models fall into three main categories, depending on the physical processes simulated by the model, the model algorithms describing these processes and the data dependence of the model:

- Empirical or statistical/metric;
- Conceptual; and
- Physics based.

The distinction between models is not sharp and therefore can be somewhat subjective. They are likely to contain a mix of modules from each of these categories. For example, while the rainfall-runoff component of a water quality model may be physics-based or conceptual, empirical relationships may be used to model erosion or sediment transport. Models may also be described as hybrids between two of these classes. For example, the IHACRES rainfall-runoff model (Jakeman et al., 1990; Jakeman and Hornberger, 1993) is a hybrid metric-conceptual model. The structure of the model is conceptual in nature, consisting of a number of storages, while the number and configuration of storages used for each catchment is determined using a statistical identification procedure.

3.1. Empirical models

Empirical models are generally the simplest of all three model types. They are based primarily on the analysis of observations and seek to characterise response from these data (Wheater et al., 1993). The computational and data requirements for such models are usually less than for conceptual and physics-based models, often being capable of being supported by coarse measurements. Jakeman et al. (1999) state that 'the feature of this class of models is their high level of spatial and temporal aggregation and their incorporation of a small number of causal variables'. Many empirical models are based on the analysis of catchment data using stochastic techniques, and as such are ideal tools for the analysis of data in catchments (Wheater et al., 1993). Parameter values in empirical models may be obtained by calibration, but are more often transferred from calibration at experimental sites. They are particularly useful as a first step in identifying sources of sediment and nutrient generation.

Empirical models are often criticised for employing unrealistic assumptions about the physics of the catchment system, ignoring the heterogeneity of catchment inputs and characteristics, such as rainfall and soil types, as well as ignoring the inherent non-linearities in the catchment system (Wheater et al., 1993). While these criticisms are valid, insufficient meteorological networks and the spatial heterogeneities of soils, for example, often mean that the more complex and dynamic models are, in this sense, no more superior than empirical models. Such models are generally based on the assumption of stationarity; that is, it is assumed that underlying conditions remain unchanged for the duration of the study period. This assumption limits the potential for such models to be applied for predicting the effects of catchment change. Empirical models also tend not to be event-responsive, ignoring the processes of rainfall-runoff in the catchment being modelled.

Nonetheless, empirical models are frequently used in preference to more complex models as they can be implemented in situations with limited data and parameter inputs, and are particularly useful as a first step in identifying sources of sediment and nutrient generation. Prosser et al. (2001a) noted that, particularly at the regional scale, 'patterns of sediment delivery and sediment residence time remain poorly understood'. Hence, prediction of sediment delivery at these scales is commonly based on empirical methods that are applied uniformly in a region.

3.2. Conceptual models

Conceptual models are typically based on the representation of a catchment as a series of internal storages. They usually incorporate the underlying transfer mechanisms of sediment and runoff generation in their structure, representing flow paths in the catchment as a series of storages, each requiring some characterisation of its dynamic behaviour. Conceptual models tend to include a general description of catchment processes, without including the specific details of process interactions, which would require detailed catchment information (Sorooshian, 1991). This allows these models to provide an indication of the qualitative and quantitative effects of land use changes, without requiring large amounts of spatially and temporally distributed input data.

Traditionally, conceptual models lump representative processes over the scale at which outputs are simulated (Wheater et al., 1993). Recently developed conceptual models have provided outputs in a spatially distributed manner. Alternatively, lumped conceptual models may be applied in a semi-distributed manner by disaggregating a catchment into linked subcatchments to which the model is applied.

Parameter values for conceptual models have typically been obtained through calibration against observed data, such as stream discharge and concentration measurements (Abbott et al., 1986). Due to the requirement that parameter values are determined through calibration against observed data, conceptual models tend to suffer from problems associated with the identifiability of their parameter values (Jakeman and Hornberger, 1993). Most calibration techniques used for conceptual models of medium complexity (say more than six parameters) are capable of finding only local optima at best. This means that there are many possible 'best' parameter sets available. Spear (1995) identified this problem in large simulation models stating that 'there is not a single point in the parameter space associated with good simulations, indeed there generally is not even a well-defined region in the sense of a compact region interior to the prior parameter space'. In general, simpler conceptual models have fewer problems with model identification than more complex models. Thus problems with model identification can be minimised through limiting the number of parameters to be estimated through calibration and possibly identifying additional parameters using a priori knowledge of the system (Kleissen et al., 1990; Wheater et al., 1993). This reduction in problems associated with identifiability through simplification of models may come at the expense of goodness of fit to calibration data. More complex models are more likely to provide a better fit to calibration data, although this does not necessarily extend to providing better predictions of future behaviour, as complex models run the risk of overfitting calibration data (Wheater et al., 1993).

The lack of uniqueness in parameter values for conceptual models means that the parameters in such models have limited physical interpretability (Wheater et al., 1993). However, this problem can also be associated with empirical and physics-based models. Physics-based models in particular are often over-parameterised, whereas empirical models tend naturally to be much simpler in their level of parameterisation (Beven, 1989; Wheater et al., 1993).

Beck (1987) noted that conceptual models play an intermediary role between empirical and physics-based models. Whilst they tend to be aggregated they still reflect the hypotheses about the processes governing system behaviour. This is the main feature that distinguishes conceptual models from empirical models. Empirical models make no inferences as to the processes at work, instead relying on observed or stochastic relationships between the causal variables and modelled output.

3.3. Physics-based models

Physics-based models are based on the solution of fundamental physical equations describing streamflow and sediment and associated nutrient generation in a catchment. Standard equations used in such models are the equations of conservation of mass and momentum for flow and the equation of conservation of mass for sediment (e.g. Bennett, 1974).

In theory, the parameters used in physics-based models are measurable and so are 'known'. In practice, the large number of parameters involved and the heterogeneity of important characteristics, particularly in catchments, means that these parameters must often be calibrated against observed data (Beck et al., 1995; Wheater et al., 1993). This creates additional uncertainty in parameter values. Where parameters cannot be measured in the catchment they must be determined through calibration against observed data. Given the large number (possibly hundreds) of parameter values needed to be estimated using such a process, problems with a lack of identifiability of model parameters and non-uniqueness of 'best fit' solutions can be expected (Beck, 1987; Wheater et al., 1993).

Even in situations where parameters can be 'measured', errors in the measurement of important characteristics, and differences between the scale at which model algorithms are applied and the scale at which measurements are made will create additional uncertainty as to the veracity of model outcomes (Bloschl and Sivapalan, 1995).

The derivation of mathematical expressions describing individual processes in physics-based models is subject to numerous assumptions that may not be relevant in many real world situations (Dunin, 1975). In general, the equations governing the processes in physics-based models are derived at the small scale and under very specific physical conditions (Beven, 1989). In practice, these equations are regularly used at much greater scales, and under different physical conditions. The equations are derived for use with continuous spatial and temporal data, yet the data used in practice is often point source data taken to represent an entire grid cell in the catchment. The viability of lumping up small scale physics to the scale of the spatial grid used in many physics-based models is questionable (Beven, 1989). Lane et al. (1995) state that 'model parameters derived in this manner represent nothing more than fitted coefficients distorted beyond any physical significance', while Seyfried and Wilcox (1995) note that 'small scale parameters used for small scale models may lose physical significance at larger scales'. Specifically there is a lack of theoretical justification for assuming that equations apply equally well at the grid scale, at which they are representing the lumped aggregate of heterogeneous subgrid processes. Likewise, there is little information to show whether many of the equations used in the models are valid beyond the small plot scale (Pickup and Marks, 2001).

Error accumulation will need to be controlled in models which transfer output fluxes from one spatial element to the next as input. The finer the spatial scale of a model discretisation the more the errors in such transfers will tend to grow.

3.4. Selecting an appropriate model structure

Each model type serves a purpose, and a particular model type may not categorically be considered more appropriate than others in all situations. Choice of a suitable model structure relies heavily on the function that the model needs to serve.

Within the literature, the preferences of researchers for certain model types over others largely reflect two main viewpoints: emphasis on the processes at work or emphasis on the output. For example, Thorsen et al. (2001) considered that 'the predictive capability of empirical and conceptual models with regards to assessing the impacts of alternative agricultural practices is questionable, due to the semi-empirical nature of the process description'. Yet, other authors argue that simple conceptual models, or empirical models, when used within the developed framework, can be more accurate than models with more complicated structures (e.g. Ferro and Minacapilli, 1995; Letcher et al., 1999). Perrin et al. (2001), considering rainfall-runoff models, noted that 'over-parameterisation can prevent models from reaching their potential performance level in their ability to simulate streamflow'. They note that models with a larger number of parameters generally yield a better fit to observed data during the calibration period than more simple models, although in the verification phase this trend of improved performance is not apparent. Simpler models tend to be more robust, thus providing more stable performances than more complicated models. Overly complicated models with large numbers of processes considered, and associated parameters, run the risk of having a high degree of uncertainty associated with the model inputs which are translated through to the model outputs. These uncertainties may negate the benefit of having a more realistic representation of the processes. The ultimate factor determining a model's value is its simplicity relative to its explanatory power (Steefel and Van Cappellan, 1998). The limit to how parsimonious a model can be made is reached when the model fails to explain observations adequately.

3.4.1. Distributed vs. lumped modelling

Another way to view the range of models is the way in which they represent the area to which the model is applied; that is, whether the model considers processes and parameters to be lumped or distributed. Traditionally, models have treated input parameters as lumped over the area of analysis. With increasing computing power over the last two decades distributed approaches have become more feasible.

Distributed models reflect the spatial variability of processes and outputs in the catchment of analysis. A distributed approach seems particularly applicable to sediment transport modelling. Each source of sediment in a catchment is characterised by its travel time—the time taken for each eroded particle to arrive at the channel network. Ferro and Minacapilli (1995) argue that the dependence of the sediment delivery process on local factors, such as sediment detachment and flow transport travel time, emphasises the need to use a spatially distributed approach for modelling this phenomenon. To apply a spatially distributed strategy at the basin scale requires the choice of both a soil erosion model and a spatial disaggregation criterion for the sediment delivery process. They favoured parametric models to physics-based models given that the latter are data-intensive, and the scale of measurements are generally not at the scale of basin discretisation for most model applications.

Typically, distributed models have involved dividing the area of interest into cells (often rectangular grids) at which basic computations are undertaken, although there are exceptions (e.g. Ferro and Minacapilli, 1995). For distributed models with in-stream components, the outputs for each cell are then routed through the system to produce catchment scale outputs. Distributed models raise a number of issues, including increased data requirements and, perhaps more importantly, effects of cell resolution on model outputs. Input requirements can increase dramatically when each cell requires information. The issue of the effect of cell resolution on model outputs has received some attention for both hydrological modelling (e.g. Zhang and Montgomery, 1994; Quinn et al., 1995; Valeo and Moin, 2000) and sediment generation modelling (e.g. Schoorl et al., 2000).

A compromise between fully distributed methodologies and lumped models are the semi-distributed models that break a catchment down into a group of subcatchments or other biophysical regions over which the model is applied.

Ultimately the choice between lumped or distributed models depends on the desired output of the model and the nature of possible management interactions. Increasingly, resource managers are requiring knowledge of the provenance of the major sources of pollutants or sediments. Distributed models have the potential to assist management in this situation if the data requirements do not inhibit model application. If estimates at the catchment outlet are sufficient, and intervention can be applied spatially uniformly, then lumped models may suffice. Spatially distributed models should include only those parameters and variables for which there exists sufficient information regarding their spatial distribution (Rustomji and Prosser, 2001).

3.4.2. Temporal resolution

A key consideration in determining an appropriate model for application is the timing of the events or processes that the model user wants to predict. Sediment-associated water quality or erosion models tend to have been developed from two opposed viewpoints. Event-based models were developed to look at the response of the modelled area to single storm events. For each event, the model time-step is of the order of minutes to hours. The model algorithms that describe these processes were often developed for application to small plots or grid cells in a catchment. Alternatively, a larger temporal resolution was used and models were applied to explore broad trends over time to changes in rainfall, vegetation or land management. The larger contributions of eroded sediment during storm events are not considered. A third approach was to use a continuous time step, usually daily, that is responsive to, for example, the development and recession of saturated zones or other processes that can be captured at this time step, yet does not capture responses to high intensity and short duration events. As computing power has increased, many of the models originally developed to be applied to a single event (e.g. AGNPS or ANSWERS) have undergone modifications and can now be applied as continuous simulations. Those models that have moved from an event-based to continuous simulation mode often retain the ability to shift between, for example, daily model time-steps to finer temporal resolutions during events.

4. Modelling sediment-associated water quality constituents

Many empirical, conceptual and physics-based erosion and sediment transport models exist, however most of these consider only overland flow erosion. There are, for example, relatively few gully erosion models. To predict sediment movement over the catchment scale, explicit consideration of the processes of erosion and sediment generation, sediment transport and sediment deposition is required.

4.1. Erosion and sediment generation

Sediment generation by water is generally described in two ways in models of on-site or land surface erosion: rainfall splash detachment and entrainment via overland flow. In both cases, particle detachment is caused by the locally intense shear stresses generated at the soil surface (Loch and Silburn, 1996). When the shear stress exceeds the cohesive strength of the soil sediment, detachment results. Once detached, sediments are transported via overland flow as non-cohesive sediment. Most erosion models focus on sediment generation from cohesive sediments via overland flow.

However, in many catchments worldwide, gully erosion has been identified as being a major source of sediment entering the waterways as they usually have high delivery ratios when well connected to streams (e.g. Wasson et al., 1996). Bull and Kirkby (1997) reviewed the modelling of gullying up to the mid-1990s, tracing the transition from stochastic modelling of gullying in the 1970s towards process-based modelling approaches for understanding the theory behind gully initiation in the 1980s. In the last decade, emphasis has been placed on refining these process models and considering the erosional development of catchments and channel networks, differentiating between the dominant transport processes at work. Sidorchuk (1999) identified two main stages in gully development: an initiation period where hydraulic erosion is predominant at the gully bottom and rapid mass movement is occurring; followed by a period where stable sediment transport and sedimentation are the main processes occurring at the gully bottom and gully width is increasing due to lateral erosion and slow mass movement.

To describe this, the author presented a two-stage gully erosion model consisting of a dynamic gully erosion model to describe the unstable gully initiation period followed by a static model of the stable period.

Another potential source of sediment is from the channel itself (or in-stream erosion). Haan et al. (1994) identified that dynamic models of channel change require a number of components: streamflow routing, sediment load calculations, changes in channel width and depth, and accounting for changes to curvature effect. The authors noted that the models that result from the relationships between these components are very complex as input parameters (particularly bed roughness, bank and bed erodibility parameters and those relating to sediment transport relationships) are not known with a great deal of certainty. An alternative to such models are the more simple in-stream erosion models that do not consider changes to channel form. An Australian developed model in this class is the Solute Transport with Advection, Resuspension and Settling (STARS; see Dietrich et al., 1999) model for in-stream transport of suspended sediment. STARS is a one-dimensional model of advective transport between two gauging stations or nodes given flow at both nodes. The model simulates processes, such as particle settling, deposition and resuspension of sediment, as well as lateral sources of sediment from bank erosion and sediment inputs associated with local rainfall.

4.2. Sediment transport

4.2.1. Flow routing

The majority of the models reviewed later in this document incorporate both flow and pollutant routing processes. A number of routing algorithms have been presented in the literature. Argent et al. (2000) identified five main classifications for flow routing from simple lag models that consider only time delays to complex three-dimensional representations of the routing processes. The processes considered in the more complicated representations of the routing process may include consideration of shear stress, turbulent flow and in some cases stratification (Argent et al., 2000).

Depending on the systems being modelled, flow routing can be classed as catchment routing, channel routing or reservoir routing (Singh and Singh, 2001). Catchment routing refers to the transformation of precipitation or other basin inputs to the outflow from the basin. Channel routing calculates the outflow from a stream for which inflow and channel characteristics are known or assumed.

Based on the manner in which flow processes are represented by the routing algorithms, the routing of water through rivers and reservoirs can be further categorised as hydrologic, hydraulic and semi-hydraulic. Hydrologic routing models often employ spatially lumped forms of the continuity equation. Forms of the continuity equation have commonly been incorporated with models containing flow routing components (e.g. Haan et al., 1994). Hydraulic routing methods are based on the conservation of momentum and mass. Such techniques include the variations of the St Venants equation that are commonly incorporated into many water quality models (e.g. Mike-11, see Section 5.12). Hydraulic methods tend to require a more detailed description of the physical properties of the system than hydrologic techniques. Their higher demands for computing power, as well as the quantity and quality of the data inputs required to drive them, potentially limit the practical applicability of hydraulic models (Singh and Singh, 2001). Semi-hydraulic models are a compromise between hydrologic and hydraulic methods.

The transport of sediment includes further considerations, namely relating to the hydraulic component of sediment transport relationships.

4.2.2. Overland flow sediment transport

Many algorithms that describe sediment transport processes have been incorporated in physics-based erosion models. Three commonly used algorithms are the steady state sediment flux equation (e.g. Hairsine and Rose, 1992b), the fundamental energy transport equation

(Engelhund and Hansen, 1968) and the steady state continuity equation for rill and interill detachment and/or deposition. These algorithms are described in Table 2.

These algorithms are largely based on the concept of sediment transport capacity, to varying degrees of complexity. Most of the sediment transport capacity relationships were initially derived for alluvial rivers and have been adapted for use in shallow overland flows. The concept of sediment transport capacity of overland flow has been widely applied to the modelling of erosion, being incorporated in models, such as ANSWERS, WEPP, LISEM and GUEST (Prosser and Rustomji, 2000). The sediment transport capacity per unit width of a slope, q_s, can be simply modelled by

$$qs = k_1 q^{\beta} S^{\gamma} \tag{1}$$

where q is discharge per unit width, S is the local energy gradient, and k_1, β, and γ are theoretically derived constants. Treating q as a function of upslope contributing area per unit width, allows q_s to be evaluated according to upslope contributing area and local land-surface gradient. Prosser and Rustomji (2000) noted that modellers have chosen a range of values for β and γ in the sediment transport capacity equation, raising the question of how particular choices were made and the sensitivity of any prediction of sediment transport to the value of β and γ. Rustomji and Prosser (2001) analysed the sensitivity of modelled patterns of potential sediment delivery, from hillslopes to valley floors, to various parameterisations of both hillslope hydrology and the sediment transport capacity equation. They concluded that if the aim of a modelling application is to predict actual loads or specify differences between regions, then results will be sensitive to the choice of the sediment transport capacity

Table 2
Some commonly used algorithms for sediment transport in physics-based erosion models

Name	Algorithm	Example model
Foster's equations	Steady state continuity equation for rill and interill detachment and/or deposition $$\frac{dqs}{dx} = Dr + Di$$ where $\frac{dq_s}{dx}$ is the sediment rate per unit width of rill channel, D_r and D_i are the rill and interill net detachment or deposition rate, respectively	WEPP NSERL (1995) CREAMS
Engelhund and Hansen (1968)	Fundamental energy transport equation for transport and deposition of sediments along a movable bed $$qT = 0.04\frac{(Sh)^{3/2}}{(s-1)^2 d50 g^{1/2}} v^2 = 0.04\left(\frac{2g}{f}\right) 1/6 \frac{(Sq)^{5/3}}{(s-1)^2 d50 g^{1/2}}$$ q_T is the amount of transported sediment ($m^3\ m^{-1}\ s^{-1}$), S is the energy slope, s is the ratio of the specific weight or density of sediment to water, v is flow velocity ($m\ s^{-1}$), h is water depth (m), F is the roughness coefficient, d_{50} is the median grain diameter (m), q is runoff ($m^3\ m^{-1}\ s^{-1}$) and g is acceleration due to gravity.	TOPOG http://www.clw.csiro.au/topog/user/
Rose	Steady state sediment flux equation, (1) in the absence of rills, and (2) when rills are present. $$\frac{dc}{dq} = \frac{(1-H)}{qQ}\left[aP + \frac{F(\Omega-\Omega o)}{J}\right] - \frac{c}{q}$$ c is the equilibrium sediment concentration, q is the volumetric flux of water per unit width of plot, Q is the runoff rate per unit area, P is measured rainfall rate, a is a rainfall related erodibility parameter, F is a constant relating to the fraction of the excess streamflow power effective in re-entrainment of sediments $$\frac{dc}{dG} = \frac{N}{GQ}\left[\{(1-Hr)Wx + Ws\}\left\{aP + \frac{F(\Omega-\Omega o)}{J}\right\} + a*Wu + qsli\right] - \frac{c}{G}$$ N is the number of rills per unit width of erosion plot, G is the discharge rate, H_r is the effective surface on which a deposited layer can form, q_{sli} is a lateral sediment flux to the rill from the interill area, W_x is the rill width, W_s represents the vertical component of the wetted perimeter, and $a*W_u$ denotes the sediment contribution by rainfall detachment at a potentially maximum rate from the unshielded potion of the rill sidewall.	GUEST Misra and Rose (1996) Ciesiolka et al. (1995) Rose et al. (1997) Hairsine and Rose (1991) Hairsine and Rose (1992a) Rose (1993)

relationship. Current knowledge of sediment transport capacity is sufficient to predict only the broad spatial patterns of sediment transport in large catchments (Prosser et al., 2001a).

4.2.3. In-stream sediment transport

The concept of sediment transport capacity is largely used to describe sediment transport in channel networks, as well as in overland flow. Many equations have been developed to describe bed-load transport. Commonly employed in the models reviewed in Section 5 are, amongst others, the Meyer-Peter and Muller (1948); Einstein (1950) and Bagnold (1977) equations.

4.3. Deposition

Much of the sediment that is transported, either in overland flows or in the stream network, is deposited prior to reaching the stream (in the case of overland flow) or deposited in the stream network prior to reaching the catchment outlet. To reflect this, deposition processes require explicit consideration in a catchment model.

4.3.1. Deposition in land surface models

In catchment models where land surface sediment processes are linked to the channel network, these linkages are usually achieved in two main ways. These relate to the contribution of eroded particles from land surface sources to the stream network. Many of the simpler empirical or conceptual models do not explicitly model deposition processes occurring in overland flow. Instead, a prescribed (or calibrated) sediment delivery ratio is used to define the amount of eroded soil or sediment that moves into the channel network. Alternatively, deposition occurring in overland flow may be explicitly modelled, as is routine in the physics-based erosion models. The approaches in Table 2 all consider sediment deposition as part of the sediment transport process.

4.3.2. In-stream deposition

In-stream deposition is routinely incorporated in models of channel evolution and development. The representation of deposition processes is similar in many ways to the treatment of deposition processes in overland flows. Sediment transport and deposition processes are often simulated simultaneously using the sediment transport capacity concept described earlier.

4.4. Validity of concepts commonly incorporated in erosion models

Huang et al. (1999) compared three process-based erosion model concepts under conditions where processes of detachment, transport and deposition are occurring concurrently. These concepts relate to land surface models, not in-stream models. The model concepts considered were the Meyer and Wischmeier 'rate-limiting' model (Meyer and Wischmeier, 1969), the Foster-Meyer model (Foster and Meyer, 1972; Foster and Meyer, 1975; Laflen et al., 1991), and the Rose concept (Hairsine and Rose, 1991; Hairsine and Rose, 1992a; Hairsine and Rose, 1992b; Rose, 1993). Using a dual-box system to quantify erosion process scenarios from deposition-dominated to transport-dominated regimes, it was found that the Rose model, which considers detachment transport and deposition processes simultaneously (although separate from one another), best described the experimental findings. The dual-box system consisted of a 1.8 m long feeder box connected to a 5 m long test box in such a way that runoff from the feeder box can be fed to the upper end of the test box. Despite there being a large body of work on developing concepts of the erosion process, there is still an incomplete understanding of the inter-relationships between the various processes at work. Further work is needed to confirm that the concepts incorporated in many erosion models are indeed valid. Unfortunately, ensuring that these inter-relationships between processes are explicitly considered in the model structure is likely to lead to more complicated models that are of more limited use at larger scales of analysis.

5. Specific models

Many different erosion and sediment/nutrient transport models are currently available, ranging across the broad model categories described in Section 3. These models differ in complexity, the processes modelled, the scale to which they are applied, and assumptions on which they are based. This section provides an outline of a number of currently available models. Not all models are considered, the intention being to illustrate the range of models available. Models are reviewed in terms of their model structure (and the implications of this structure on model outputs), input data requirements, and their spatial and temporal resolution. Table 1 summarises these models in terms of their classification, scales of application and input data requirements.

The review of models is limited to those models with explicit considerations of either the sediment generation or transport process. Thus widely used water quality models such as QUAL-2E, CMSS and AQUALM are not discussed.

The models discussed vary considerably in their treatment of the sediment generation, transport and deposition processes, the scale of application for which they were developed, and the time-scales at which they operate. Such an eclectic set of models reflects the nature of catchment scale models, many of which invoke at least some of the concepts of other models that were developed for application at smaller scales or that focus on one component of the erosion process (e.g. in-stream erosion). Regardless of the model type or structure, most erosion models can be applied in a spatially distributed manner (Toy et al., 2002, p. 141) and, although care is required to apply models developed at smaller scales to larger scales, many examples of this application type exist in the literature. Models are reviewed in alphabetical order with the exception of the USLE. This model has been frequently incorporated in other models, including catchment scale models. Given this, it is introduced prior to the other models.

5.1. USLE and modifications

The Universal Soil Loss Equation (USLE) is a soil erosion model used widely within the United States and worldwide. Developed in the 1970s by the USDA, the model has undergone much research and a number of modifications (e.g. MUSLE; USLE-M, Kinnell and Risse, 1998). The model has also been upgraded to take into account additional information that has become available since the development of the USLE (RUSLE, Renard et al., 1994). Although developed for application to small hillslopes, the USLE and its derivatives have been incorporated into many catchment scale erosion and sediment transport modelling applications.

5.1.1. Model outputs

The typical output from the USLE is an annual estimate of soil erosion from hillslopes.

5.1.2. Input data

Input data requirements are low compared with most other models. Annual rainfall, an estimate of soil erodibility, land cover information and topographic information is required.

5.1.3. Model structure

The basic USLE is an empirical overland flow or sheet-rill erosion regression equation based primarily on observations. Model outputs are both spatially and temporally lumped. As with most empirical models, the USLE is not event responsive, providing only an annual estimate of soil loss. It ignores the processes of rainfall-runoff, and how these processes affect erosion, as well as the heterogeneities in inputs such as vegetation cover and soil types.

5.1.4. Erosion/transport modelling

The USLE estimates the average annual soil loss from:

$$A = RKLCSP$$

where A is the estimated soil loss per unit area, R is the rainfall erosivity factor, K is the soil erodibility factor, L is the slope-length factor, S is the slope-steepness factor, C is the cover and management factor, and P is the support practices factor (Wischmeier and Smith, 1978).

5.1.5. Predictive accuracy/limitations

The simplicity of this equation and the availability of parameter values, at least in the United States, has made this model relatively easy to use (Loch and Rosewell, 1992).

There are a number of limitations to the USLE. The model is not event-based and as such cannot identify those events most likely to result in large-scale erosion. Gully erosion and mass movement are ignored and the deposition of sediment is not considered to occur in the modelled area (Zhang et al., 1995). Runoff leaving a field generally concentrates in a few major channels, the profiles of which are often concave, such that ephemeral gully erosion can occur along the upper reach of a channel and deposition occurs in the lower reaches of the channel. This gully erosion can be as extensive as sheet and rill erosion (Lane et al., 1992). Additionally, unlike in the United States, the use of USLE outside the US has been limited by the perceived lack of data for the parameters required to run the model under new conditions (e.g. Loch and Rosewell, 1992). Nearing et al. (1994) noted that the adaptation of USLE to a new environment requires a large investment of time and resources to develop the database required to run the model. With regards to applications to mine spoils, Evans et al. (1992) identified that due to rainfall variability, data must be collected for at least 10 years and this, combined with the lack of data for overburden spoil and replaced spoils, was a disadvantage for the use of this model in spoil pile erosion prediction.

Due to the identified limitations of USLE, a number of modifications and revisions to the basic format for have been proposed in the literature. These include the modified USLE, the revised USLE (Renard and Ferreira, 1993; Renard et al., 1994), and the USLE-M (Kinnell and Risse, 1998). These continue to improve components of the model making it more process-based. RUSLE maintains the basic form of the USLE, although all equations used to arrive at the factor values have been modified (Lane et al., 1992). Changes to the form of the length of slope (L) factor in RUSLE enables the prediction of soil loss due to Hortonian overland flow in three-dimensional terrains with convergent and divergent slopes (Ryan and McKenzie, 1997). The main advantage of RUSLE over the USLE is that it has the capacity to estimate the C factor from information on vegetation form, decay and tillage practices rather than from experimental plot data as used in the USLE. USLE-M, for example, provides a more complex representation of processes than the USLE as it more directly considers the effect of runoff on erosion with changes to the R factor (Kinnell and Risse, 1998).

5.2. AGNPS

The Agricultural Non-Point Source model (AGNPS) is a non-point source pollution model developed by the US Department of Agriculture, Agricultural Research Service (USDA-ARS) in cooperation with the Minnesota Pollution Control Agency and the Soil Conservation Service (SCS) in the USA (Young et al., 1989). The model was developed to predict and analyse the water quality of runoff from rural catchments ranging from a few to over 20 000 hectares.

The calculations in AGNPS occur in three stages. Initial calculations, including estimates of upland erosion, overland runoff volume, pollutants from point source inputs, time until overland flow becomes concentrated and the level of soluble pollutants leaving the catchment via overland runoff, are made for each grid cell in a catchment. In the second stage, the runoff volume leaving the cells containing impoundments and the sediment yields for primary cells are calculated. The calculated sediments and nutrients are then routed through the rest of the cells.

AGNPS is now used by the United States Department of Agriculture to refer to a system of modelling components that includes the RUSLE, a stream network channel evolution model (CCHE1D, Wu and Vieira, 2002), CONCEPTS (Langendoen, 2000) and an annualised pollutant loading model (AnnAGNPS). CONCEPTS was developed for analysis of stream network reaches in watersheds where the channel network is complex due to channel evolution or erosion and is not sufficiently represented by the simplified channel system representation in the AnnAGNPS.

5.2.1. Model outputs

AGNPS uses a grid cell representation of the catchment, with cell resolution ranging from 0.4 to 16 hectares. Runoff and sediment, nutrient and chemical oxygen demand transport are simulated for each grid cell, with potential pollutants being routed through cells to the catchment outlet.

Output values for the whole watershed include characteristic storm precipitation and the storm energy-intensity value.

Hydrological outputs include runoff volume, peak runoff rate, and the fraction of runoff generated in the cell. Sediment outputs are sediment yield, sediment concentration, sediment particle size and distribution, upland erosion, amount of deposition (%), sediment generated in the cell, enrichment ratios by particle size, and delivery ratios by particle size. The pollutant loading module computes sediment bound nitrogen (N), soluble N in runoff, sediment-bound phosphorus (P), soluble P in runoff, and sediment bound organic carbon.

5.2.2. Input data

Input data for the AGNPS model include parameters describing catchment morphology, and land use variables and precipitation data. For each grid cell, the input parameters for AGNPS include, cell number (from), receiving cell number, SCS curve number, a channel indicator that indicates the existence of a defined channel in a cell, land slope, land slope shape factor, field slope length, channel slope, channel sideslope, Manning's roughness coefficient, soil erodibility factor cover and management factor, support practices factor, surface condition constant, aspect, soil texture, fertilisation level, fertilisation availability factor, point source indicator, gully source level, COD factor, impoundment factor, and channel indicator.

5.2.3. Model structure

AGNPS contains a mix of empirical and physics-based components. The model utilises components of existing models in its structure including the RUSLE (see Section 5.1) for predicting soil loss in grid cells. The inclusion of these model components results in a model that contains both empirical and quasi-physically based algorithms.

The model is fully distributed with land surface runoff and sediment processes modelled for the individual grid cell, and the outputs routed through to the catchment outlet.

5.2.4. Runoff modelling

Runoff in a catchment is simulated using the SCS curve number method, an empirical rainfall-runoff modelling technique developed in the United States by the Soil Conservation Service (SCS, 1972). This method deals with baseflow separately and combines channel runoff, surface runoff and subsurface flow into 'direct' runoff.

5.2.5. Erosion/transport modelling

Erosion and sediment transport are modelled using forms of the Universal Soil Loss Equation (USLE, Section 5.1). Two different versions of the AGNPS model have been developed by the USDA-ARS. The original model implemented the USLE, while more recent versions now implement the RUSLE. A modification of the model, AGNPSm, replaces the SCS curve number and USLE topographic (LS) factor with alternative algorithms and links channel erosion by individual categories of particle size to runoff velocity and replacement of the uniform rainfall input by grid based precipitation input (Grunwald and Norton, 2000). Soil loss is calculated in AGNPS for each cell in the catchment.

The AGNPS suite of models includes gully erosion components and sediment reach routing models. Sediment reach routing is based on a modified Einstein deposition equation and the Bagnold suspended sediment formula is used to describe sediment transport in the reach.

5.2.6. Nutrient modelling

The original versions of AGNPS used relationships from the CREAMS model (see Section 5.4) and a feedlot evaluation model to simulate the transport of nitrogen, phosphorus and chemical oxygen through a catchment. The current chemical component of AGNPS computes a daily mass balance of nitrogen, phosphorus and organic carbon for each model grid cell (http://www.sedlab.olemiss.edu/agnps.html). In the channel reach, instant partitioning between the adsorbed and solute states, after mixing at the upstream end of the reach and again at the downstream end, is assumed so as to reflect the loss of adsorbed chemicals due to deposition of the fine sediment.

5.2.7. Predictive accuracy/limitations

The greater data requirements and computational complexity of AGNPS compared with empirical models must be weighed against the added modelling capabilities of the model. Panuska et al. (1991) identified that the grid size selected by the model user was a major factor influencing sediment yield calculations. Consequently, care needs to be taken when applying such a model to ensure that the resolution chosen for modelling is adequate for the task. This statement applies equally to all distributed models that apply algorithms on a grid basis.

5.3. ANSWERS

From the mid-1980s, advances in sediment and nutrient transport modelling included the development of a grid or cellular approach, dividing the landscape into cells which were modelled individually and summed for the catchment. This approach subsequently provided a common basis for the structure of process-based hydrologic and water quality models (Moore and Gallant, 1991). One pioneering model was the Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS) program (Beasley et al., 1980). ANSWERS differs from AGNPS in its representation of the erosion process with a more physically based approach to erosion and transport modelling being implemented. Initial development of ANSWERS focused on the sediment and erosion components, whereas development of AGNPS placed more emphasis on nutrient components and utilised existing models and relationships in the model structure to model runoff and sediment generation.

5.3.1. Model outputs

The primary outputs of model simulation are runoff and erosion (Fisher et al., 1997), although the model has been extended to include nutrients (Moore and Gallant, 1991).

5.3.2. Input data

The model uses four main categories of landform parameters: soil, land uses, elevation based slope and aspect, and channel descriptions (Fisher et al., 1997). Within these broad categories many parameters are required. For example, for each soil type the following eight variables are required: total porosity, field capacity, steady state infiltration, the difference between steady state and maximum infiltration, the rate of decrease in infiltration with an increase in soil moisture, infiltration control zone depth, antecedent soil moisture, and erodibility.

5.3.3. Model structure

As with AGNPS, ANSWERS has varying degrees of empiricism in the algorithms describing model processes. AGNPS has been undergoing continuous development since its inception (Dillaha et al., 1998). This work has largely involved replacement of the more empirical components with conceptual or physics-based alternatives. The description of the runoff processes is empirical, while the erosion and sediment transport processes are based on physics-based continuity equations.

The model is both temporally and spatially distributed, providing an advantage over less complex models like USLE. The effects of rainfall intensity and spatial variation in soil infiltration capacity, surface conditions and topography are explicitly represented by ANSWERS (Connolly et al., 1997). The original model version concentrated on the simulation of events, however updates to the model have moved towards a continuous simulation model (e.g. ANSWERS 2000, Dillaha et al., 1998, 2001).

5.3.4. Runoff modelling

Runoff modelling in the original ANSWERS model considered runoff as occurring only where rainfall intensity exceeds the infiltration capacity and used the method of Holtan (1961). Modifications of ANSWERS have seen the replacement of the original runoff component with the Green and Ampt infiltration model for the inclusion of surface sealing (e.g. Connolly and Silburn, 1995; Connolly et al., 1997; Dillaha et al., 2001).

5.3.5. Erosion/transport modelling

Detachment of soil particles is calculated using an empirical relationship, although Dillaha et al. (1998) noted that plans exist to replace the existing empirical sediment detachment component with a reliable and robust physics-based sediment detachment sub-model.

ANSWERS uses a form of the Yalins' (1963) bed-load transport equation to predict the transport of cohesionless grains over a movable bed for steady uniform flow of a viscous fluid (Loch et al., 1989). An extended version of ANSWERS is capable of simulating the transport of individual particle size classes (Rose and Ghadiri, 1991).

Plans exist to add a channel erosion and scour sub-model (Dillaha et al., 1998).

5.3.6. Predictive accuracy/limitations

The applicability of ANSWERS is limited in many catchments by the large spatial and temporal input data requirements of the model. Given the lack of such data in most catchments, parameters may need to be calibrated, raising problems with model identifiability and the physical interpretability of model parameters. There are also other potential problems with the model. Fisher et al. (1997) concluded from a spatial sensitivity analysis on the model that many outputs were insensitive to changes in the spatial distribution of input variables to the model. The authors proposed three possible explanations: lack of variability of important parameters in the study catchment; key model components were unaccounted for; or variables not subjected to spatial mixing in any run may swamp the effect of mixing. These findings indicate the possible shortcomings of the model in effectively modelling the processes addressed by the model (Fisher et al., 1997).

Additionally, ANSWERS considers erodibility to be a relatively time constant parameter, contrary to the large variations in this parameter that have been recorded (Govers and Loch, 1993). This assumption is likely to limit the effectiveness of the model in predicting runoff and soil erosion. Many models make similar assumptions.

5.4. CREAMS

The Chemical Runoff and Erosion from Agricultural Management Systems model (CREAMS, Knisel, 1980) was developed as a tool to evaluate the relative effects of agricultural practices on pollutants in surface runoff and in soil water below the root zone (Knisel, 1980; Lane et al., 1992; Lane et al., 1995). CREAMS has been extended and modified in GLEAMS, the Groundwater Loading Effects of Agricultural Management Systems (Ball and Trudgill, 1995; Connolly et al., 1999). Both models consist of three components: hydrology, erosion/sedimentation, and chemistry and target non-point source pollutants. Algorithms in CREAMS have been used in numerous other models of erosion and water quality (e.g. PERFECT, see Section 5.13; WEPP, see Section 5.17).

5.4.1. Model outputs

The model predicts erosion, deposition and transport of sediment on a slope profile and into first and second order channels (Silburn and Loch, 1991). Flow volume, peak flow, soil infiltration, evapotranspiration, soil water content, percolation to groundwater and sediment yield can be calculated temporally on a daily or event basis. Outputs are provided for a field sized catchment assumed uniform in soil topography and land use.

5.4.2. Input data

Input data to CREAMS requires precipitation series, monthly air temperature and solar radiation values, and soil and crop type data.

5.4.3. Model structure

An initial objective prior to the development of CREAMS was that the model be physically based and not require calibration for each specific application. Despite this, CREAMS retains some empiricism in the model algorithms, particularly the runoff component, and aspects of the erosion module. The processes of sediment transport and deposition are described using physics-based sediment transport capacity relationships. CREAMS can operate either on a continuous or event basis, and is designed for application to field sized areas assumed uniform in soil, topography and land use.

5.4.4. Runoff modelling

Rainfall-runoff processes in the CREAMS model are simulated using the SCS curve number approach (SCS, 1972). Alternatively, a Green-Ampt approach for infiltration excess can be used.

5.4.5. Erosion/transport modelling

The CREAMS model uses a physics-based approach to erosion and sediment transport, although significant simplifications are made as a consequence of limitations imposed on model size and computational speed, and limited hydrologic data. The erosion component maintains elements of the USLE, but includes sediment transport capacity for overland flow. The erosion model is run for individual storms and assumes a quasi-steady state through the use of a characteristic runoff rate for each storm (Silburn and Loch, 1989). Additionally, slope is assumed to be uniform and is computed on a per unit width basis. Sediment transport is calculated according to the steady-state continuity equation while sediment yield, as with the ANSWERS model, is calculated using Yalins' equation. CREAMS also can be used to predict gully erosion which can produce as much or more sediment as that produced by sheet and rill erosion (Lane et al., 1992).

5.4.6. Predictive accuracy/limitations

The model applies to field-sized catchments, of approximately 40 ha, although it can be used on scales up to 400 ha (Lane et al., 1992). The field-sized catchments are assumed to be uniform in soil topography and land use.

An advantage of CREAMS is that it accounts for gully erosion and deposition, in addition to overland erosion sources. Additionally, the model allows for the erodibility factor to be updated from one runoff event to the next (Govers and Loch, 1993). As soil erodibility factors have been shown to be quite variable in time, this could be an important aspect of the model. However, Govers and Loch (1993) noted that the 'dynamic nature of runoff erosion may limit any increase in prediction accuracy that can be obtained using physics-based models rather than statistical models, as the performance of a model such as CREAMS will become highly dependent on the accuracy of the input data'. Another potential disadvantage of the CREAMS model is that the plot or catchment being modelled is assumed to be uniform in soil topography and land use, a highly unrealistic assumption. In other words, the benefits associated with the consideration of gully erosion and deposition processes may be nullified by the dependency of the model on data accuracy and on assumptions of homogeneity.

5.5. EMSS

The Environmental Management Support System (EMSS) is a software tool (as opposed to a model) developed to aid water quality management in catchments and waterways in the South-east Queensland region of Australia. The system is being developed in the Cooperative Research Centre for Catchment Hydrology (CRCCH) and is implemented in the Tarsier modelling framework (Watson et al., 2001). At present, the EMSS is composed of three models: a lumped conceptual rainfall-runoff and pollutant export model ('Colobus'), a flow and pollutant routing model ('Marmoset') and a storage model referred to as 'Mandrill' (Vertessey et al., 2001). The EMSS platform is undergoing further development.

5.5.1. Model outputs

EMSS predicts daily runoff and daily loads of total suspended sediment, total nitrogen and total phosphorus for individual subcatchments and routes these through the river network and reservoir storages (Vertessey et al., 2001).

5.5.2. Input data

Spatial data required by EMSS are GIS layers of subcatchment boundaries, and grids of land use, daily rainfall and daily potential evapotranspiration.

5.5.3. Model structure

The models currently included in the EMSS platform are relatively simple conceptual and physics-based models that operate on a daily time-step. The rainfall-runoff module is conceptual in its structure. Sediment and pollutant loads are estimated based on prescribed concentrations for a given land use for both baseflow and runoff, although the sediment and nutrient transport modules use the physics-based concepts of transport capacity and the preservation of continuity of mass.

5.5.4. Runoff modelling

The rainfall-runoff model 'Colobus' is based on the SIMHYD model (Chiew et al., 2002) a nine parameter model that partitions estimated daily runoff into four components: impervious area runoff, infiltration excess runoff, interflow runoff, and baseflow runoff.

The Muskingum-Cunge routing method (Ponce and Yevjevich, 1978) is used to route water between nodes.

5.5.5. Erosion/transport modelling

The pollutant export model estimates daily loads of total suspended sediment, total phosphorus, and total nitrogen. Loads for each constituent are computed by multiplying the event runoff volume by the event mean concentration (EMC) and the baseflow runoff volume by dry weather pollutant concentration (DWC). Values of EMC and DWC are ascribed for various land uses.

The amount of sediment transported at each time step is the minimum of the transport capacity and the volume of sediment input from the stream bed and upstream sources. Transport of nutrients is estimated by accounting for nutrient concentrations in the flowing water, and preserving continuity of mass.

5.5.6. Predictive accuracy/limitations

The EMSS is still under development and consequently the software tool still requires further application and testing. The models in the EMSS have been kept to a relatively low complexity, while retaining the ability to model runoff and pollutant generation and transport dynamically. Despite the simplicity of the pollutant export module, Chiew et al. (2002) noted that the variability of EMC and DWC is extreme, necessitating further monitoring data with which to drive the model. This is particularly so for EMC where pollutant loads and runoff are greater.

The structure of the EMSS is such that modules can be added relatively easily (or removed) depending on the requirements of a model user. Despite being developed for the South-east Queensland region, the EMSS appears to be relatively simple to adapt to other regions.

5.6. GUEST

The Griffith University Erosion System Template (GUEST) is a steady-state, process-based model developed to interpret temporal fluctuations in sediment concentration from bare soil in single erosion events (Misra and Rose, 1996). The model relates measured runoff and rainfall rates, soil characteristics and plot geometry of uniform slope to the concentration of eroded sediment. The model is based on the work of Hairsine and Rose (Hairsine and Rose, 1991, 1992a,b; Rose, 1993).

5.6.1. Model outputs

The GUEST model calculates the sediment concentration at the transport limit. If event-based average sediment concentration is measured then an erodibility parameter can be determined.

5.6.2. Input data

The minimum data requirements for soil erodibility calculations and soil loss predictions are

- Hydrological—runoff rate or rainfall rate in addition to runoff amount or peak rainfall rate in addition to runoff amount;
- Soil loss—mean sediment concentration for each runoff amount;
- Plot characteristics—length, width and slope, and
- Characteristics of the soil layer from which erosion is likely to occur—either wet density or percent of sand grains of primary particles, and either soil particle/water-stable aggregate size distribution obtained from wet sieving or settling velocity distribution.

If additional data are available on surface contact cover and rills exits then descriptors of the rills could be included. For use as a predictive model, GUEST requires information on plot geometry, sediment properties, roughness characteristics, erodibility and hydrologic variables.

5.6.3. Model structure

The model algorithms describing the erosion, sediment transport and deposition processes in the GUEST model are physics-based equations describing steady state sediment flux. These algorithms deal specifically with land surface sediment dynamics. The model is developed for application to single rainfall events at the plot scale.

5.6.4. Runoff modelling

The hydrology component of the GUEST model requires measured rainfall rates and the runoff rate per unit area for a bare plot of known area and downslope length. These inputs are used to obtain the volumetric flux of water per unit width of plot and from this discharge–depth relationships to obtain an estimate of the depth of the water produced.

5.6.5. Erosion/transport modelling

Two types of erosion processes are considered in GUEST, those due to rainfall impact and those due to the shear stress exerted on soil by overland flow (Ciesiolka et al., 1995; Rose et al., 1997).

GUEST allows for the consideration of sheet erosion and rill erosion (where rill shape is either trapezoidal or rectangular). Discharge–depth relationships are used to calculate shear stress on the soil or sediment surface associated with runoff water. Shear stress and the velocity of flow are then used to estimate stream power. Whether or not an erosion event leads to differences in sediment concentration from the equilibrium conditions is assumed to be controlled by the stream power and the threshold stream power (Misra and Rose, 1996). Entrainment and re-entrainment are considered to occur only when the stream power exceeds the threshold stream power. Table 2 shows the steady state sediment flux equations in GUEST in the presence and absence of rills.

5.6.6. Predictive accuracy/limitations

GUEST is a complex process-based model and consequently has a reasonably large data requirement. Runoff measurements in particular are often unavailable. Likewise, the need for detailed information regarding the frequency and geometry of rills requires detailed survey of the plot site prior to modelling. Despite the work of Huang et al. (1999) which demonstrated that the representation of land surface erosion in GUEST described their experimental findings well, the incorporation of such concepts into the land surface component of a catchment scale model is, to date, prohibited by the amount of required plot scale information.

5.7. HSPF

The Hydrologic Simulation Program, Fortran (HSPF) was developed based on the 1960s Stanford Watershed Model, for the simulation of watershed hydrology and water quality (nitrogen, phosphorus, suspended sediment and other toxic organic or inorganic pollutants) (Walton and Hunter, 1996). The model is a catchment scale, conceptual model whereby catchments are divided the into hydrologically homogeneous land segments. Water quantity and quality is calculated for each land use in a land segment. Water, sediment and chemical fluxes are then added to the stream, and these fluxes are routed to the catchment outlet. The model consists of three main modules: the pervious land module, the impervious land module, and the river/mixed reservoir module.

5.7.1. Model outputs

The model is able to simulate a wide range of water quality components. The outputs from the simulation are a temporal history of runoff, flow rate, sediment load and nutrient concentrations along with a time series of water quantity and quality at any subcatchment outlet in the catchment.

5.7.2. Input data

The inputs to the model include rainfall, evaporation, air and water temperature, solar radiation, sediment grain size distribution, point source discharge volume, and water quality data (Cheung and Fisher, 1995). The inputs are required for all subcatchments. Streamflow and in-stream water quality data are used for comparison with the model results.

5.7.3. Model structure

HSPF considers in detail most of the processes involved in moving sediment and nutrients through a catchment. The model conceptualises these processes and requires calibration against measured water quantity and water quality constituents, thus distinguishing it (in theory) from physics-based models. The model is semi-distributed in that the modeled area can be disaggregated in to hydrological homogenous zones. Any incidence of a zone is assumed to behave in a hydrologically similar manner, and homogeneity is assumed in each zone. Model algorithms are applied to each zone type. Any time step from 1 min to 1 day can be used as long as the time-step divides equally into 1 day.

5.7.4. Runoff modelling

5.7.4.1. Pervious land module In the pervious land module, hydrologic processes are driven by rainfall and include interception of rainfall, evaporation, overland flow, infiltration, interflow, soil moisture storage and groundwater (Cheung and Fisher, 1995).

5.7.5. Erosion/transport modelling

5.7.5.1. Pervious land module Surface erosion is accounted for by the processes of detachment and transport, although dust deposition and wind blown removal can also be simulated. Sediment adsorbed water quality components are treated as washed off with sediments and entering the receiving stream (Cheung and Fisher, 1995).

5.7.5.2. Impervious land module The impervious land module is simpler than the pervious module with dissolved solutes and accumulated sediments being transported off the land surface with overland flow. Sediment adsorbed water quality components are treated as with the pervious land module. Urban areas that consist of pervious and impervious surfaces are modelled by assigning a portion of the land as impervious and the remaining land according to the make-up of the land (Cheung and Fisher, 1995).

5.7.5.3. River/mixed reservoir module HSPF considers only one-dimensional flow and is suitable for non-tidal reaches of rivers. The river and mixed reservoir module includes physical processes, such as transport advection, diffusion, sediment deposition and scouring. The model also considers the following chemical processes: aeration, nitrification, denitrification, biochemical oxidation, adsorption and desorption of solute from suspended sediment and settlement (Cheung and Fisher, 1995). Chapman (1991) tables the specific transport and reaction, as well as general, characteristics of HSPF and other toxicant models.

5.7.6. Predictive accuracy/limitations

HSPF is one of the few conceptual models of watershed hydrology and water quality that explicitly integrates the simulation of land and soil contaminant runoff processes with in-stream hydraulic and sediment–chemical interactions. The model was developed as a generic model designed to apply to most catchments using existing meteorological and hydrological data, soils and topographic information, and information on drainage and other characteristics (Rahman and Salbe, 1993). A limitation to this model is that it relies heavily on calibration against field data for parameterisation (Walton and Hunter, 1996). With the relatively large number of parameters required to be calibrated this raises problems associated with parameter identifiability, and the physical meaningfulness of model parameters. Although HSPF has the potential to be a useful tool for catchment management, Cheung and Fisher (1995) note that the calibre of models developed is related to the availability and accuracy of input data and the skills of the modeller. In recognition of this, the United States Geologic Service (USGS) have developed an expert system designed to assist in the calibration of the model (Lumb et al., 1994).

5.8. IHACRES-WQ

The IHACRES-WQ model consists the IHACRES rainfall runoff model (Jakeman et al., 1990, 1994a, 1994b; Evans and Jakeman, 1998) and the STARS model (Green et al., 1999; Dietrich et al., 1999) for instream transport of suspended sediment and runoff-suspended sediment and sediment-nutrient components.

5.8.1. Model outputs

IHACRES predicts daily streamflow while the STARS model can be used to predict downstream suspended sediment concentration.

5.8.2. Input data

The IHACRES rainfall-runoff model requires time series data for streamflow, precipitation and, depending on the version of IHACRES, temperature or evapotranspiration. The STARS model requires upstream and downstream concentration for calibration purposes.

5.8.3. Model structure

The IHACRES model is a hybrid metric-conceptual model that simulates streamflow on a continuous basis.

The model is conceptualised as a set of storages (either in series or parallel) through which effective rainfall is modelled to produce runoff. The metric component of the model comes from the number and configuration of storages used for each catchment being determined using a statistical identification procedure. The model is a lumped model providing outputs at the catchment outlet. However, when linked with a model such as STARS, it can be applied in a distributed manner with IHACRES applied to individual subcatchments and the runoff generated from each subcatchment routed through to the catchment outlet by STARS.

The STARS model, while it is distinguished from empirical models by explicitly considering the processes of particle settling, deposition and re-suspension of sediments, describes these processes with conceptual algorithms.

5.8.4. *Runoff modelling*

The IHACRES rainfall runoff model is used for predicting discharge at catchment outlets and a simple discharge routing model (STARS) is used for instream sections. IHACRES is based on the instantaneous unit hydrograph. This model accounts for the effects of evapotranspiration, drainage and precipitation on rainfall-runoff. Rainfall is modified using temperature data to reflect the effects of drainage, evapotranspiration and antecedent weather conditions to become effective rainfall, the water that contributes to runoff. IHACRES has been widely applied over a range of hydroclimatologies. It has been shown to predict runoff as effectively as other models, but has the advantage of containing only five to seven parameters. It has been augmented with power law relations between sediment concentrations and discharge (and between phosphorus and sediment concentrations) to predict water quality concentrations. This has been successfully prototyped in several catchments of the Namoi Basin (Jakeman et al., 1999).

5.8.5. *Erosion/transport modelling*

The Solute Transport with Advection, Resuspension and Settling (STARS) model was developed at the Australian National University. It is a one-dimensional model of advective transport between two gauging stations or nodes, given flow at both nodes. The model simulates processes such as particle settling, deposition and resuspension of sediment, as well as lateral sources of sediment from bank erosion and sediment inputs associated with local rainfall.

The STARS model is conceptually based, and requires upstream and downstream concentration time series over some period (including a few events) for calibration of the model parameters. The model has only five parameters and is thus less likely to experience problems with model identifiability than more complex models.

5.8.6. *Predictive accuracy/limitations*

IHACRES-WQ has the advantage of requiring relatively little input data, as its conceptual nature means that spatially distributed input data on catchment characteristics is not required for model calibration. The small number of model parameters in both IHACRES and STARS suggests that the models are less likely to suffer from problems of identifiability than more complex models. However, parameters values must be calibrated against observed data, or inferred from regionalisation of similar catchments. Regionalisation of IHACRES parameters have been undertaken by Post and Jakeman (1999) and Gilmour and Croke (2001). By linking the IHACRES and STARS models, the runoff and in-stream components of catchment scale sediment transport and deposition are accounted for. However, there is no land surface erosion component to the model that predicts the sediment generation due to overland erosion and the contribution of this sediment into the stream network. Likewise, contribution from gully erosion is not considered.

Questions as to the applicability of using a one-dimensional model like STARS to simulate three-dimensional processes can be raised. However, this is a common attribute of in-stream water quality models and is justified in modelling at the catchment scale in terms of minimising computational requirements and the amount of data required to drive the model.

With respect to predicting water quality loads in Australian catchments, Letcher et al. (2002) compared the performance of the IHACRES-WQ model with three other empirical or simple conceptual water quality models and a number of direct estimation techniques. Large differences were observed in terms of the loads predicted by the different methods, however, the authors concluded that due to a lack of observed water quality data it was impossible to say which of these methods provided the most accurate prediction of sediment and nutrient loads in the catchments studied.

5.9. *IQQM*

The Integrated Water Quantity and Quality Model (IQQM) is a largely conceptual model being developed by the NSW Department of Land and Water Conservation in Australia. The model is designed for use as a tool for planning and evaluating water resource management policies at the river basin scale (DLWC, 1999). IQQM has modules for instream water quality and quantity as well as for rainfall-runoff and groundwater quantity (DLWC, 1995; Simons et al., 1996).

5.9.1. *Outputs*

The rainfall-runoff model is used to predict daily streamflow while the in-stream water quality model is used to model the movement of conservative and non-conservative constituents, dissolved oxygen, biological oxygen demand, coliforms, and algae.

5.9.2. Input data

The minimum data requirements for running IQQM are catchment areas and slopes, river system configuration, daily rainfall, daily evaporation, daily streamflow, characteristics of storages, diversion points and design water use. Additional information that can be used if available include actual water use, licensing, crop types and areas, actual pump capacities, water user decisions and existing or proposed operating rules and management policies (DLWC, 1999).

5.9.3. Model structure

IQQM has a conceptual framework containing a mix of empirical, conceptual and physics-based components. Runoff is modelled using the conceptual Sacramento model, while the in-stream water quality module is based on the QUAL2E model (Brown and Brownwell, 1987). IQQM operates on a continuous basis, using time steps of 1 day, down to 1 h for some processes. The lumped rainfall-runoff model is applied to subcatchments and the outlet flows routed through the in-stream model.

5.9.4. Runoff modelling

The main processes that are simulated in the instream water quantity module include flow routing, effluent systems and irrigation channels, reservoir operation, irrigation, urban water supply and other consumptive uses and wetland and environmental flow requirements.

The rainfall-runoff module used in IQQM is the Sacramento model, developed by the US National Weather Service and the Californian Department of Water Resources. This module simulates flow using calibrated model parameters and long-term daily runoff and evaporation. This module has 18 major parameters, including the proportional increase in percolation from saturated to dry conditions, channel or transmission losses per unit area, and the fraction of baseflow that does not appear in stream. These parameters are determined by calibration against observed flow data.

Two forms of flow routing are available in IQQM: Muskingum routing and non-linear routing with lag. Both methods include the ability to vary routing characteristics with flow depth for simulating bank overflows.

5.9.5. Erosion/transport modelling

There is currently no erosion or sediment generation modelling in IQQM. Modules for this are under development.

5.9.6. Water quality modelling

The in-stream water quality module is based on the program QUAL2E, developed by the United States Environmental Protection Agency (USEPA), and accounts for factors such as nitrogen, phosphorus, dissolved oxygen and sediment, as well as coliforms and algae. QUAL2E uses a finite difference solution to the one-dimensional advective-dispersive mass transport and reaction, and conceptualises a stream as a number of sub-reaches over which a hydrologic balance, a heat balance, and a materials balance (in terms of concentration of a water quality constituent) are computed (Brown and Brownwell, 1987). IQQM also has a module designed to simulate salt mobilisation in catchments, where the major source of salt is rock weathering.

5.9.7. Predictive accuracy/limitations

A risk associated with the use of IQQM is over-parameterisation of the model. Each of the modules in IQQM has a large number of parameters which must be calibrated or estimated in other ways. For example, QUAL2E requires more than 100 individual inputs, some of which require considerable judgment to estimate. Much of the literature concerning IQQM has dealt with water quantity issues, particularly for water management and allocation purposes (e.g. Podger and Hameed, 2000; Porter and Delforce, 2000). There are currently few examples in the literature of the water quantity module being used with the water quality module, and sediment models are still being developed. Although the QUAL2E model has been tested considerably by the USEPA, further work is required to illustrate the performance of the IQQM water quality module as a whole.

5.10. LASCAM

LASCAM, a salt and water balance model, has been adapted to include a sediment generation and transport algorithm for modelling hydrological processes at a catchment scale (Viney and Sivapalan, 1999) and, more recently, a model of nutrient mobilisation and transport (Viney et al., 2000). The model is capable of predicting long-term estimates of daily stream loads of water, salt, sediment and nutrients.

5.10.1. Model outputs

The outputs for the hydrological model are surface and subsurface runoff, actual evaporation, recharge to the permanent groundwater table, baseflow, and measures of soil moisture and salt outflows. These outputs are provided for each subcatchment and the entire catchment of interest. The outputs for the sediment and nutrient components and sediment are constituent loads.

5.10.2. Input data

The inputs to the hydrological model are distributed daily rainfall, pan evaporation and land use information. Topographic data is required to define sub-catchments and the stream network (Viney and Sivapalan, 1999). Calibration of the model requires streamflow records at one or more locations in the catchment.

The sediment model requires daily streamflow from the hydrological model, land use information and catchment areas. Calibration of the sediment component requires sediment load records in the catchment.

The nutrient component contains 29 model parameters, 11 for phosphorus and 18 from nitrogen, many of which are prescribable using observed values. The authors considered that as the model can be calibrated against as many as five observational records per gauged subcatchment: soluble P, particulate P, particulate N, NO_3^{2-}, NH_4^+, the number of parameters per response series is not excessive (Viney et al., 2000).

5.10.3. Model structure

The runoff, sediment and nutrient components are conceptual models that operate on a continuous basis. The model is distributed in the sense that a catchment is divided into a series of subcatchments to which the model algorithms are applied.

5.10.4. Runoff modelling

The LASCAM hydrological model considers water quantity and salt mobilisation and transport. The model uses topographic information to define a stream network and break up the catchment into a series of sub-catchments (Viney and Sivapalan, 1999). The hydrological processes are then modelled at the sub-catchment scale before being summed up to represent the total catchment.

The model considers three interconnected conceptual stores of soil water and salt, representing the perched near-stream aquifer, the permanent groundwater and an intermediate unsaturated store. For each subcatchment a set of global constitutive relationships is used to direct water and salt between the three stores and distribute rainfall into the stores or into streamflow (Viney and Sivapalan, 1999, Viney et al., 2000). Generated runoff, and the salt it contains, is routed along the stream network towards the catchment outflow.

5.10.5. Erosion/transport modelling

Viney and Sivapalan (1999) incorporated a conceptualisation of the USLE (see Section 5.1) to predict sediment generation. The sediment generated from hillslopes is related to the predicted daily surface runoff and the USLE crop factor (C), the latter of which is assumed related to the leaf area index (LAI) of the vegetation cover. The remaining USLE parameters are subsumed in an optimisable parameter that is considered uniform across a catchment (Viney and Sivapalan, 1999).

Sediment transport involves the processes of channel deposition, re-entrainment and bed degradation which are all assumed to be governed by a stream sediment capacity. Stream sediment capacity is a function of stream capacity (Viney and Sivapalan, 1999). The sediment transport model conceptualises processes in existing physically based sediment models, making process descriptions as simple as possible, while retaining the capacity to model the effects of landscape and climate change. The authors recognised that the understanding of sediment processes at the catchment scale is far from complete. In the absence of complete knowledge, Viney and Sivapalan contend that a sediment model should remain conceptually simple, while retaining the capacity to model the effect of land use change.

The sediment model includes six global parameters that require calibration against observed sediment load records at one or more locations in the catchment. As with the hydrological model, the sediment model parameters are intended to apply globally.

5.10.6. Nutrient modelling

The nutrient model considers phosphorus and nitrogen in both dissolved and suspended forms. Soluble nutrients are considered to leach into surface and subsurface water fluxes and once in stream are routed conservatively. Suspended nutrients are assumed to be attached to eroded sediment material and transported non-conservatively, although transport is conservative in the sense that it is assumed there is no cycling or uptake of nutrients once they enter the stream network.

Unlike more complicated representations of phosphorus cycles, in the LASCAM organic and inorganic stores are combined into a single store since they contribute in the same way to erosion of particulate phosphorus. Viney et al. (2000) noted that, given the large-scale, lumped nature of their application, the complexity of the process representation in other models was not warranted for LASCAM.

5.10.7. Predictive accuracy/limitations

The model has shown considerable potential as a sediment yield model (Viney and Sivapalan, 1999) and has been used to predict water yield, salinity, sediments, nitrogen and phosphorus for the entire Swan-Avon River Basin in Western Australia. Despite the need for calibration, LASCAM can potentially provide an advantage over the use of physics-based erosion and sediment models (Viney and Sivapalan, 1999). The smaller number of parameters needed in the water quality component that need to be calibrated means that this part of the model is less likely to suffer from problems associated with identifiability than other more complex models.

Modelling results described in Viney et al. (2000) demonstrate the sensitivity of the nutrient model to water and sediment balances. The authors suggested modelling strategy involves calibrating the water balance model, using the optimised model to calibrate a sediment balance model and using both optimised models to calibrate the nutrient model. Any weakness in this chain of calibrations compromises the quality of the nutrient predictions (Viney et al., 2000). This is generally true of all water quality models.

5.11. LISEM

The Limburg Soil Erosion Model (LISEM, De Roo and Jetten, 1999) is a spatially distributed, physics-based hydrological and soil erosion model, developed by the Department of Physical Geography at Utrecht University and the Soil Physics Division at the Winard Staring Centre in Waneningen, the Netherlands, for planning and conservation purposes. The LISEM model is based on EUROSEM (Morgan et al., 1998).

LISEM incorporates a number of different processes including rainfall interception, surface storage in micro-depressions, infiltration, vertical water movement through the soil, overland flow, channel flow, detachment by rainfall and throughfall, detachment by overland flow and transport capacity of flow.

5.11.1. Model outputs

Outputs of the LISEM model include totals for such variables as runoff, sediment, infiltration and storage depression. Maps showing the spatial distribution of such factors as soil erosion and deposition, and maps of overland flow at desired time intervals during the simulation are also produced by LISEM. The model is also capable of producing hydrographs and sediment graphs for a rainfall event simulation.

5.11.2. Input data

The GIS nature of LISEM means that inputs to the model simulation are in the form of GIS maps. Approximately 25 maps are required for simulation, including maps describing catchment morphology, leaf area index, random roughness of the soil and the fraction of the soil with crop cover. Rainfall data from multiple rainfall gauges must also be input. LISEM generates from this a map showing the spatial distribution of rainfall intensity. Thus LISEM incorporates both the spatial and temporal variability of rainfall.

5.11.3. Model structure

The development and structure of LISEM is based on the experiences with the ANSWERS (see Section 5.3) and SWATRE (Belmans et al., 1983) models, although process descriptions have been highly modified. Model simulation is based on the solution of a number of physics-based equations describing water and sediment yield processes. The model is designed to simulate runoff and erosion from individual rainfall events in agricultural catchments ranging in scale from 0.01 km^2 to approximately 100 km^2. The model is fully distributed, being completely incorporated in a GIS, with model algorithms applied to each grid cell in a study region.

5.11.4. Runoff modelling

A modified version of the SWATRE soil water model is used to simulate the vertical movement of water in the soil. In addition to descriptions of the vertical movement of water in the soil, processes describing overland flow, channel flow, rainfall, interception, surface storage in micro-depressions and infiltration are included.

5.11.5. Erosion/transport modelling

LISEM does not simulate concentrated erosion in rills and gullies; rather it simulates flow detachment in the ponded area only. This can be seen as an intermediate between sheet and rill erosion. Processes describing sediment detachment by rainfall, throughfall and overland flow are included in addition to the transport capacity of the flow.

5.11.6. Predictive accuracy/limitations

The detailed spatial representation required for LISEM, even though it is linked to a GIS, is likely to limit the application of LISEM, or similar models, except for large detailed research projects on fairly small catchments. The LISEM model requires detailed spatially and temporally variable data inputs. While there is an increasing trend to develop spatial databases, such as the United States Department of Agriculture (USDA) STATSGO soil database, there is often limited data sets for variables other than topography. Additionally, regardless of how well constructed or sophisticated a model is, the performance of a model such as LISEM ultimately is constrained by the resolution and quality of these GIS inputs. As the extent and quality of GIS databases improves, the value of fully distributed models will increase. However, as most other physics-based models, LISEM can be expected to suffer from difficulties associated with identifiability and data availability.

5.12. MIKE-11

MIKE-11 is a software system used for water quality modelling, developed by the Danish Hydrologic Institute (DHI). The model is a one-dimensional (cross-sectionally averaged) dynamic model consisting of a number of modules (Hanley et al., 1998). The basic modules are a rainfall-runoff component, a hydrodynamic module, a water quality module, and a sediment transport module.

5.12.1. Model structure

MIKE-11 contains a mix of conceptual and physics-based modules. The runoff components are relatively simple conceptual models although flow routing is described using physics-based St Venant's equations. MIKE-11 operates on a number of timescales from single storm events to monthly water balance.

5.12.2. Runoff modelling

The rainfall-runoff component contains three models that may be used to estimate catchment runoff:

- NAM: A lumped, conceptual rainfall-runoff model simulating overland flow, interflow and baseflow as a function of the moisture content in each of four storages: the snow, surface, root zone and groundwater storages;
- UHM: Uses the unit hydrograph technique module to simulate the runoff from single storm events;
- SMAP: A monthly soil moisture accounting model.

The rainfall-runoff model has up to 17 model parameters, although often only nine are used (e.g. Madsen, 2000).

The St Venant's complete non-linear equations of open channel flow are solved numerically between all points at specified time intervals for given boundary conditions.

5.12.3. Erosion/transport modelling

The model simulates unsteady one-dimensional flows and accounts for the interdependence of sediment transport, alluvial roughness and hydrodynamics in the simulation of equilibrium conditions of the river; a capacity essential in determining morphological changes and erosion patterns associated with mining operations (Kwan and Abbey, 1993).

The erosion and transport module includes a description of the erosion and deposition of both cohesive and non-cohesive sediments (http://www.dhisoftware.com/mike11). Erosion and deposition are modeled as source or sink terms in an advection–dispersion equation. The advection–dispersion module is based on the one-dimensional equation of conservation of mass of dissolved or suspended materials. It is also possible to simulate non-cohesive sediments with the AD module. For non-cohesive sediments, the erosion and deposition terms are described by conventional sediment transport formulations.

The water quality module simulates the reaction processes including the degradation of organic matter, photosynthesis and respiration of plants, nitrification and the exchange of oxygen with the atmosphere.

5.12.4. Predictive accuracy/limitations

The accuracy of the MIKE-11 model is undermined by a number of factors. The first of these is the use of one-dimensional equations to represent three-dimensional processes. Many of the important interactions in the system are ignored or simplified in this process. It neglects secondary currents and, like most models, ignores bank erosion processes. This raises questions about the physical interpretability of the model. The justifiability of using measured physical parameters in the model given the oversimplification of physical processes inherent in a one-dimensional representation of the physics of the catchment system is also questionable. In practice, a more complicated representation of these processes is difficult, given the detailed description of channel characteristics that would be required.

The large data requirements of the model mean that the model is likely to suffer from problems caused by error accumulation and from a lack of identifiability of model parameters in situations where model parameters must be calibrated. For example, Madsen (2000) developed an automatic calibration scheme for the MIKE-11/NAM model to optimise numerical performance of four calibration objectives: overall water balance, overall shape of the hydrograph, peak flows, and low flows. Application of the procedure, considering only the nine most important parameters, by the author demonstrated that significant tradeoffs between the objectives existed, thus implying that no unique single solution was able to optimise all four objectives simultaneously. Madsen (2000) also showed that a large range of parameter values may produce equally good solutions according to a specified objective function.

5.13. PERFECT

The Productivity, Erosion and Runoff, Functions to Evaluate Conservation Techniques (PERFECT) model was developed by the Queensland Department of Primary Industries (Land Management Branch, Queensland Wheat Research Institute) and the QDPI/CSIRO Agricultural Production System Research Unit (Littleboy et al., 1992b). The model was developed in response to the limited applicability of models, such as CREAMS, for analysing the effects of soil management practices, such as tillage or fallow management strategies (Littleboy et al., 1996). Models such as CREAMS calculate runoff as a function of rainfall and soil water content, excluding surface and crop cover changes resulting from tillage practices. PERFECT was designed to predict runoff, erosion and crop yield for some management options in dryland cropping areas of Australia, including sequences of plantings, harvests and stubble management during fallow (Littleboy et al., 1996). The model is comprised of six modules: data input, water balance, crop growth, crop residue, erosion and model output. These modules are arranged in a framework that allows alternative modules to be used as required for the potential range of applications. The modules draw on other models such as MUSLE (see Section 5.1) and CREAMS (see Section 5.4).

5.13.1. Model outputs

PERFECT predicts water balance, erosion and crop growth on a daily time-step.

5.13.2. Input data

The inputs to the models are daily climate data, soil parameters, cropping sequence criteria (i.e. crop type and length of fallow), crop growth parameters and fallow management (tillage) options. The climate data requirements include daily rainfall, pan evaporation, temperature and evaporation.

5.13.3. Model structure

Reflecting the models incorporated into PERFECT, the model has a mix of empirical, conceptual and physics-based components. The model operates on a daily time step and is applied at the field scale.

5.13.4. Runoff modelling

Runoff is calculated as a function of rainfall, soil water deficit, surface roughness, surface residue and crop cover. Partial area runoff processes and subsurface flow are not considered (Hook, 1997).

5.13.5. Erosion/transport modelling

Erosion is simulated in the model using MUSLE, while the mineral nitrogen removed from the topsoil by erosion is simulated using a relationship taken from CREAMS.

5.13.6. Predictive accuracy/limitations

Littleboy et al. (1992b) found that PERFECT was more reliable than CREAMS in predicting runoff, accounting for 77–89% of the variation in daily runoff volume. The authors argued that this, in addition to the consideration of the effect of crop cover and surface runoff on infiltration and soil evaporation, indicated that PERFECT is a more appropriate model to analyse runoff from cropping systems with complex crop/fallow rotations than the CREAMS model.

The erosion component of the model does not account for rainfall intensity thus raising the possibility for overestimation, or underestimation, of erosion depending on the rainfall event. Although the model structure is generally robust, Littleboy et al. (1992a) noted that the model was not designed for application beyond those environments typical of north-east Australia and recommended that the model be calibrated against suitable field data before use in any other environment. PERFECT also requires very detailed information on crop management and tillage practices: information that is not always available for large areas.

In summary, PERFECT provides a potentially valuable tool for assessing conservation cropping options by simulating the water balance, crop yield and erosion for combinations of soil type, climate, fallow management strategy and cropping sequence. The incorporation of a sediment transport and nutrient component would be required for the model to be useful in water quality modelling. If this were to occur, the detail of the crop cover and management components may provide an advantage over other models, in situations where these processes are considered important.

5.14. SedNet

The Sediment River Network model is a steady-state model that was developed for estimating sediment generation and deposition from hillslopes, gullies and riverbanks in a river network (Prosser et al., 2001b). SedNet was developed as a tool for addressing land and water management issues at the catchment or larger scale. For example, the model can be used to identify the subcatchments that supply much of the sediment to a stream network, where deposition is occurring and the dominant erosion process contributing sediment to the network (Prosser et al., 2001c).

5.14.1. Model outputs

SedNet is linked with a GIS and provides outputs of the spatial patterns of sediment entrainment, in-stream sediment loads and deposition.

5.14.2. Input data

A Digital Elevation Model (DEM) is required to define the network of river links to which the model is applied and to calculate topographic attributes for the catchment and each river link. The hillslope model requires a grid of mean annual rainfall, soil erodibility, crop management factors, slope length and slope, and management practices. The gully erosion model requires a grid of gully density and a description of the mean characteristics for each link. SedNet requires descriptions of the in situ sediment, bank vegetation and bank dimensions for modelling in-stream sediment generation and sediment transport.

5.14.3. Model structure

The model was specifically developed for application at continental scale for the Australian National Land and Water Resources Audit (NLWRA). First-order streams typically have contributing areas of 25–50 km^2 and stream reach lengths of approximately 10 km. The river network is split into river links that represent a river reach between two stream junctions (or nodes). Reservoirs are represented as links in the river network.

SedNet uses simple conceptual and empirical models of sediment detachment, transport and deposition to describe long-term sediment loads in individual river reaches.

5.14.4. Runoff modelling

For each river link, SedNet requires a number of hydrologic variables. Mean annual flow is required to model reservoir deposition, the sediment transport capacity discharge is required to estimate the transport capacity of the bed-load sediment fraction, bankfull discharge is use as a predictor of bank erosion and floodplain deposition and the median overbank streamflow is used to model floodplain deposition. These four variables are related to the upstream area and the spatially averaged mean annual rainfall of the upstream. Full details of the hydrologic module are provided by Prosser et al. (2001b) and Prosser et al. (2001c).

The hydrologic model in SedNet uses very simple algorithms to describe the key hydrologic variables. However, Newham et al. (2001) noted that these variables represent the influences of river hydrology on sediment transport and are thus critical in the overall model performance.

5.14.5. Erosion/transport modelling

Each river link is connected to an internal catchment that contributes sediment generated from hillslopes or gullies to the link. Models of streambank erosion, floodplain deposition and sediment transport capacity are used to simulate sediment transport through the river network. Unlike bed-load sediment, suspended sediment is sourced from all three erosion models. It is assumed that hillslope erosion does not contribute to the bedl-oad.

The mean annual gully derived sediment that is delivered to a river link from a linked internal catchment is related to the area, the mean cross-sectional area of gullies, the density of gullies, the bulk density of the eroded sediment, and the age of the gullies.

Hillslope erosion is estimated using the USLE (see Section 5.1). A hillslope sediment delivery ratio is applied to obtain the contribution of suspended sediment from the internal catchment of a river link from hillslope sources.

For each link, the rate of lateral erosion from the stream bank and the characteristics of the river link are used to estimate streambank erosion. Each river link is described by the bank height, lateral migration constants, the in situ sediment bulk density, the estimated 1.58-year recurrence interval flow and the proportion of intact riparian vegetation bordering the link.

The transport and deposition of the suspended and bed-load sediment fractions are modelled separately in the river network. Bedload is routed by a sediment transport capacity sub-model. The capacity of the channel to transport bed-load sediment is related to the energy gradient, the sediment transport capacity discharge, the mean channel width and settling velocity of bed-load particles. Deposition of suspended sediment in the river network is modelled using floodplain and reservoir deposition sub-models. The sediment remaining in suspension is then routed through to the next river link.

A reservoir/lake trap-efficiency sub-model, based on the work of Brune (1953), is used to estimate sediment deposition in reservoirs. All of the transported bedload is deposited in a reservoir, although a proportion of the suspended loads can pass through the reservoir outlet. The percentage of suspended load trapped by the reservoir depends on the volume of the reservoir and the mean annual input to the reservoir.

5.14.6. Predictive accuracy/limitations

Whilst the models in SedNet comprise relatively simple relationships, the model as a whole is complex in terms of the large number of river links in the catchment and the cumulative parameter requirements. Much of these data are difficult to obtain for each link in a catchment. Currently parameter values tend to be prescribed from the literature based on empirical or theoretical prior knowledge. This raises considerable uncertainty in the range of parameter values in the catchment, thus limiting the confidence that can be placed in outputs. Relative to other grid-based models, however, such as LISEM (see Section 5.11) or AGNPS (see Section 5.2) the simplified process representation provides a more manageable tool for initial exploration of the amount and patterns of sediment moving through a catchment or basin. Unlike many empirical or simple conceptual models, SedNet incorporates most of the sediment processes occurring at the catchment scale, albeit in a temporally lumped manner. The major advantage of a model such as SedNet is that it attempts to provide a spatial representation of the sources and sinks of sediment in large catchments or basins. The model has the potential for being a highly useful tool in exploring impacts of land management and stream channel management on downstream sediment transport and deposition processes.

Newham et al. (2001) noted that if reliable conclusions are to be made from models like SedNet, the sensitivity of model outputs to uncertainty in inputs, parameters and the model structure needs to be properly addressed.

5.15. SWRRB/SWRRB-WQ

The Simulator for Water Resources in Rural Basins (SWRRB, Arnold et al., 1990) was developed to simulate hydrologic, sedimentation, and nutrient and pesticide transport in large complex rural watersheds. The model incorporates five major components: climate, hydrology, sediment, nutrients and pesticides. The models in these modules borrow to a large extent from existing models.

SWRRB-WQ is an extension of SWRRB that includes water quality components (Arnold et al., 1991).

5.15.1. Model outputs

SWRRB provides estimates of streamflow, sediment, nutrient and pesticide yields. The model provides estimates of predicted rainfall, surface runoff, subsurface flow, water yield, percolation, transmission losses, evapotranspiration, soil water content, reservoir volume, groundwater flow, groundwater height, sediment yield, organic nitrogen, organic phosphorus, nitrate in surface runoff, soluble phosphorus, nitrate in crops, nitrate in percolation, and nitrate in lateral surface runoff.

5.15.2. Model Inputs

Precipitation, air temperature, and solar radiation data are required to drive SWRRB. Data required for the basin include the total drainage area, basin slope, and the fraction of field capacity (USEPA, 1994). The model requires sub-basin data to describe the physical representation of the sub-basin, routing data, pond and reservoir data, pesticide data, soil data, crop inputs, fertiliser and pesticide inputs, and lake water quality data.

The physical representation of the sub-basin is described by fraction of the basin area, channel characteristics (average main channel width, slope, length, and Manning's *n*, the effective hydraulic conductivity), runoff curve number, soil albedo, and the initial water content of snow.

Routing data include average channel depth, width, slope, length, and Manning's *n* from the sub-basin outlet to the basin outlet.

Pond and reservoir data include the fraction of the sub-basin that flows into ponds and reservoirs, the total surface area of all ponds and reservoirs, runoff volume, initial reservoir volume, and initial and normal sediment concentrations.

Pesticide data include the initial concentration on foliage, initial concentration on the ground, and the enrichment ratio. SWRRB-WQ requires data on the number of soil layers, erosion factor, soil depth, soil density, water capacity, conductivity, clay content, initial nitrate concentration, maximum rooting depth and particle size distribution.

Cropping information include vegetation types, tillage operations, biomass conversion factors, water stress yield factors, harvest index, maximum leaf area index, average annual C factor (see the USLE description in Section 5.1) and initial residue cover. The dates and amounts of fertiliser, pesticide applications, and irrigation applications are required.

If predictions of lake water quality are to be made, then initial concentrations of constituents, reaction coefficients, settling velocity, resuspension velocity, lake volume, lake depth and temperature are required. Monthly values of effluent flow, temperatures of effluent and natural flows, and dew point temperature are also required.

5.15.3. Model structure

SWRRB is conceptual in framework although it components utilise both physics-based and empirical algorithms to describe the major processes.

SWRRB operates on a continuous basis and, based on soil, land use, and climatic characteristics, subdivides basins into relatively homogenous regions. Computations are performed simultaneously for each subregion, with the outputs routed from the subregion outlet to the basin outlet.

5.15.4. Runoff modelling

The hydrological component includes methods to predict surface runoff volume using the SCS curve number approach, predict flow through the root zone through the percolation component using a storage routing model linked with a crack-flow model, calculate transmission losses, account for pond storage water balance, compute reservoir water balance, and predict peak runoff rate based on a modification of the rational formula.

5.15.5. Erosion and nutrient modelling

Sediment yields from land surface sources are computed for each subregion using the Modified Universal Soil Loss Equation (MUSLE). These yields are then routed through to the catchment outlet using a floodplain and channel routing model. The channel routing model consists of two components operating simultaneously: deposition based on the fall velocity of the soil particles and degradation based on Bagnold's stream power concept.

The nutrient yield component is adapted from the EPIC model (Williams et al., 1984) and the pesticide component is based on CREAMS (see Section 5.4).

5.15.6. Predictive accuracy/limitations

SWRRB has been shown to predict the effect of management decisions on water sediment and pesticide yield with reasonable accuracy through basins in the United States watersheds. However, with the large number of components in SWRRB, the data requirements are considerable. For applications in the United States, pesticide, soil and rainfall coverages are available. Application elsewhere requires the establishment, or continued development, of such large databases. Without these databases, applications SWRRB are limited to previously well studied and described catchments.

5.16. TOPOG

TOPOG was initially developed as a physics-based, catchment scale hydrological model that linked three-dimensional terrain attributes with a simple description of water movement (O'Loughlin, 1986). The program has received on-going attention and now is a package that can be used to simulate water, carbon, solutes and the sediment balance of catchments. A detailed description of the current modules in the package can be found at http://www.per.clw.csiro.au/topog/.

5.16.1. Model outputs

The model provides as outputs: water fluxes, conservative solutes and sediments.

5.16.2. Input data

The model requires detailed information on topography, soils climate and vegetation in order to run (Grayson et al., 1999).

5.16.3. Model structure

The models included in the TOPOG platform are largely physics based and can operate using daily to sub-daily time steps. The package implements a contour-based DEM, which uses natural flow lines and contours to define the element network in the model (Maunder, 1999). It is intended for application to catchments up to 10 km^2. Channel erosion and sediment transport modules are not currently incorporated into TOPOG.

5.16.4. Runoff modelling

The rainfall-runoff module in TOPOG simulates the hydrologic behaviour of the catchment and the way this is affected by changes in catchment vegetation. Surface runoff will be generated where rain falls on a soil that is saturated to the soil surface. TOPOG contains two rainfall-runoff modules: a steady state water balance model (Topog—Simul) and a dynamic water balance modeling program (Topog—Dynamic) that can be run on either a daily time step or on a sub-daily time step to simulate stormflow (http://www.per.clw.csiro.au/topog/user/contents/frame6.0.html).

5.16.5. Erosion/transport modelling

For each catchment element, the sediment transport module computes soil detachment by rainfall splash and by overland flow, the sediment transport capacity of overland flow and the net flux of sediment. The sediment transport capacity is calculated using the Engelhund and Hansen (1968) energy transport equation for transport and deposition of sediments along a movable bed (Table 2). Alternatively, total sediment load can be calculated using Yang's unit stream power theory.

5.16.6. Predictive accuracy/limitations

TOPOG was initially developed for specifying hillslope zones that become saturated (O'Loughlin, 1986). It has since been used to predict the spatial distribution of erosion hazard, landslide risk indices and the dynamic interactions between soil-vegetation-atmosphere systems over a catchment (GHD-EPA, 1991; http://www.per.clw.csiro.au/topog/). The TOPOG package is intended as a research tool and is reasonably complex in its overall structure. The requirement for detailed topographic, soils, climate and vegetation data potentially limits the widespread application of TOPOG for water quality studies. Whilst detailed topographic information is becoming increasingly available through digital elevation models, this is not being matched by increased availability of other data, in particular detailed soil data.

5.17. WEPP

The Watershed Erosion Prediction Project (WEPP) is a physics-based model developed in the United States in an initiative between the Agricultural Research Service, the Soil Conservation Service, the Forest Service in the Department of Agriculture and the Bureau of Land Management in the US Department of the Interior (Laflen et al., 1991; NSERL, 1995). The model has been applied to hillslopes widely in the US (e.g. Laflen et al., 1991) and worldwide. The model was intended to determine and/or assess the essential mechanisms controlling erosion by water, including anthropogenic impacts. The model does not consider erosion, transport and deposition processes in permanent channels, such as classical gullies and perennial streams. A watershed version of the model has been developed and applies to field areas that include ephemeral gullies which can be farmed over and links these surface erosion processes to the channel network.

The processes represented by WEPP can be broadly characterised as erosional processes, hydrological processes, plant growth and residue processes, water use processes, hydraulic processes and soil processes (Laflen et al., 1991).

5.17.1. Model outputs

The hillslope version of WEPP outputs estimates of the spatial and temporal distributions of soil loss, sediment yield, sediment size characteristics, runoff volumes and the soil water balance. The WEPP profile also considers sediment deposition and is applicable from the top of a hillslope to a channel. The basic output contains the runoff and erosion summary on a storm-by-storm, monthly, annual and average annual basis.

5.17.2. Input data

Knowledge of plant growth and residue components is required to make an accurate assessment of the plant and residue characteristics above and below the soil. These include canopy cover and height, above and below ground biomass of living and dead plant material, leaf area index (LAI) and basal area, and are estimated on a daily basis (Laflen et al., 1991). As such, information regarding dates and management practices are essential inputs to the model. The plant characteristics are of utmost importance to describe adequately as they will have a large impact on the soil erosion and hydrological processes in the site.

The hydraulic processes component computes the hydraulic shearing forces exerted on the soil surface by the surface runoff. This requires information regarding surface runoff volumes, hydraulic roughness, and approximations of runoff duration and peak rate.

The final component of the model, the soil processes module, deals with the temporal changes in soil properties important in soil erosion—considering the effect of management practices, weathering, consolidation, and rainfall on soil and surface variables—including random roughness, bulk density, saturated hydraulic conductivity, and the erodibility factors of the rill and interill (Laflen et al., 1991).

The watershed simulation version of WEPP requires additional files to describe the watershed configuration, the channel topography, the channel soils, channel management, and the channel hydraulic characteristics.

5.17.3. Model structure

WEPP uses mainly physics-based equations to describe hydrologic and sediment generation and transport processes at the hillslope and in-stream scales. The model operates on a continuous daily time-step. The watershed model links the hillslope models to the channel network.

5.17.4. Runoff modelling

The erosional processes result from the forces and energies developed in hydrologic processes (Laflen et al., 1991). The components of the hydrological processes are climate, infiltration and a winter component that accounts for snow accumulation and melt.

On hillslopes, the soil water status is updated on a daily basis and is required to obtain infiltration and surface runoff volumes—the driving force in the detachment by flowing water in rills and channels (Laflen et al., 1991). The water balance component uses information about climate, plant growth and infiltration to estimate daily potential evapotranspiration and soil and plant evaporation. Rainfall excess is predicted using the Green-Ampt Mein-Larson (GAML) infiltration equation. The peak runoff rate can be simulated using either kinematic wave overland flow routing or simplified regression equations.

Most hydrological processes are modelled in the same manner for permanent channels or ephemeral gullies as for overland flow on hillslopes (e.g. infiltration, evapotranspiration and soil water percolation). However, two options exist for calculating the peak runoff rate at the channel or watershed outlet; a modified version of the rational equation or the method utilised in CREAMS (USDA, 1995).

5.17.5. Erosion/transport modelling

The erosion processes represented in WEPP are limited to sheet and rill erosion and erosion occurring in channels where detachment is due to hydraulic shear. Through the erosional components of the model, the three stages of erosion (detachment, transport and deposition) are quantified using the rill–interill concept of describing sediment detachment (Laflen et al., 1991; Lane et al., 1995). These equations are the Foster's equation described in Table 2.

Sediment detachment and deposition in ephemeral gullies or permanent channels is simulated using a steady-state solution of the sediment continuity equation.

5.17.6. Predictive accuracy/limitations

The ability of WEPP to accurately predict where detachment and deposition will occur will be useful in establishing appropriate conservation or management practices.

There are a number of possible criticisms of the WEPP model. Firstly, the large computational and data requirements of the model may limit its applicability in catchments where there is often few data or available resources. Many of the model parameters may need to be calibrated against observed data in such studies, creating problems with model identifiability and the physical interpretability of model parameters. Secondly, WEPP does not account for erosion from permanent gullies. In some river catchments, erosion from active gullies that are connected to the stream network can be the largest contributors to sediment load. Finally, the rill–interill concept of erosion used by WEPP may not be applicable in soils that have not been cultivated and do not initially exhibit rill formations.

The watershed version of WEPP may be of limited applicability to large scale catchments, as simulation involves individual hillslope scale models being ‘summed up’ to the catchment scale, greatly increasing overall data requirements, model complexity and raising issues of error accumulation.

Despite the process-based nature of the model, WEPP still contains a degree of empiricism and care should be taken when applying the model to new sites.

5.18. Model summary

A number of erosion and sediment prediction models that have been presented in the literature were summarised in this section. The models reviewed represent many of the approaches that have been used to describe sediment generation and movement through landscapes. The models range significantly in the processes they represent, the manner in which these processes are represented and the temporal and spatial scales of application for which they were developed. However, in one way or another, the concepts behind the reviewed models have been, or have the potential to be, incorporated into catchment scale approaches.

At the catchment scale, to reflect reality as closely as possible, a sediment-associated water quality model requires a number of components: namely a rainfall-runoff module, a land surface erosion module, and an in-stream module. If alternate erosion sources contribute significantly to the generation of sediment (e.g. permanent gullies) then such processes need explicit representation in the selected model. Relatively few of the models reviewed in this section consider all of these components. Table 3 provides a summary of these models and the processes they explicitly represent. Of those models that do consider most of the processes that occur

Table 3
Processes represented in the models reviewed

Model	Rainfall-runoff	Land surface sediment			Gully	In-stream sediment			Sediment associated water quality	
		G	T	D		G	T	D	Land	In-stream
AGNPS	yes	yes	no	no[a]	yes	yes	yes	yes	yes	yes
ANSWERS	yes	yes	yes	yes	no	no	no	no	no	no
CREAMS	yes	yes	yes	yes	yes	no	no	no	yes	no
EMSS	yes	no[b]	no	no	no	yes	yes	yes	no	no
GUEST	yes	yes	yes	yes	no	no	no	no	no	no
HSPF	yes	yes	yes	yes	yes	yes	yes	yes	yes	yes
IHACRES-WQ	yes	no	no	no	no	yes	yes	yes	yes	yes
IQQM	yes	no	no	no	no	no	no	no	no	no
LASCAM	yes	yes	no	no	no	yes	yes	yes	yes	yes
LISEM	yes	yes	no	no	no	yes	yes	yes	no	no
MIKE-11	yes	yes	yes	yes	no	yes	yes	yes	yes	yes
PERFECT	yes	yes	no	no	no	no	no	no	yes	no
SEDNET	yes	yes	no	no[a]	yes	yes	yes	yes	yes	yes
SWRRB	yes	no	no	no	no	yes	yes	yes	yes	yes
TOPOG	yes	yes	yes	yes	no	no	no	no	no	no
USLE	no	yes	no	no	no	no	no	no	no	no
WEPP	yes	yes	yes	yes	no	yes	yes	yes	no	no

G, sediment generation; T, sediment transport; D, deposition.
[a] Requires a sediment delivery ratio (SDR) to compute sediment yield from gross erosion.
[b] Uses prescribed loads for a land use type.

at the catchment scale, the majority of them suffer from problems associated with the high input demands of the model. Such problems include difficulties in the selection of unique parameter sets that best describe the catchment dynamics. This is especially critical if parameters are to be regionalised to ungauged tributaries.

Most of the models reviewed are comprised of a mix of empirical, conceptual and physics-based components. Fully developed catchment scale models are those that explicitly link the major catchment scale processes (rainfall-runoff, land surface sediment processes, and channel network processes). Here, models such as LISEM and WEPP are in the minority. These models, where processes are almost exclusively described using physics-based algorithms, tend to be restricted to study catchments where there has been considerable work undertaken to describe the catchment and develop the necessary model inputs. Should a potential model user intend to apply these types of models to new sites then a lengthy commitment is required before the model can be used. When there is insufficient time or funds to develop such databases, the more conceptual models are more appropriate.

From the models reviewed in this section, it is apparent that selection of an appropriate model for application to a catchment-based study of erosion and sediment movement involves a number of trade-offs. Two extreme model types can be identified: complex conceptual and physics-based models with highly detailed representations of the processes being modelled, and models that considerably simplify process representation. The latter group often exhibit a high degree of empiricism, and tend to operate on a spatially lumped and/or temporally coarse resolution. The complex models are generally capable of operating either on a continuous basis or in an event-based mode. As yet, there are few examples of models that are capable of simulating on an event basis, yet minimise the process representation to only those key processes that control catchment response. Model users then need to decide between the two model extremes. For stakeholders or government agencies who may be responsible for land and water management on a national or regional basis, and therefore may not have the time or interest in focussing on particular catchments, the complex models are prohibitive in terms of the time required to develop and implement them.

An on-going research area needs to be the development of event responsive models that represent, in as parsimonious a manner as possible, only the key processes at work.

6. Discussion and conclusions

Given the large number of models available, the question is then: which model, where and when? The main determinant of an appropriate model for exploring aspects of erosion and sediment movement through catchments is the question(s) that the model user is attempting to address. This will identify those processes that require explicit representation in the model, as well as the spatial and temporal resolution at which a model needs to be applied. From here, determining the appropriate model for an application requires consideration of the suitability of the model to local catchment conditions, data requirements, model complexity, the accuracy and validity of the model, model assumptions, the spatial and temporal variation, components of the model and the objectives of the model user(s).

6.1. Natural complexity

Jakeman et al. (1999) noted that the difficulties in environmental modelling can be characterised as problems of natural complexity, spatial heterogeneity and the lack of available data. The latter point is considered in Section 6.4. The complexity of natural systems is due to differences in transport media, dimensions, temporal and spatial scales, and thresholds of water flow and sediment and nutrient transport through and in the media. Natural systems, from plot to catchment scale, tend to show a great deal of variation. In sediment and water quality models, assumptions of homogeneity in topography and soil characteristics, for example, are employed in many commonly used models. Thus, model predictions are subject to errors as a result of the inconsistency of scale between measured parameters and the way they are used in the model. This problem is particularly evident in data-intensive models.

In catchments, a number of characteristics which may on their own have a predictable effect on catchment response, can lead to a complex pattern of catchment response. Rustomji and Prosser (2001) noted that the effect of topography on sediment delivery patterns is often masked by the correlation of land use with topography. For example, land uses such as broad-acre cropping with high sediment delivery potential are generally restricted to low slopes, while less intensive land uses tend to exist on steeper slopes. Thus, the separate effects of both topography and land use on catchment response become less evident.

6.2. Limitations in the understanding of sediment pathways

A major limitation in modelling the generation and transport of water quality constituents in catchments is our limited understanding of the processes involved, particularly in terms of the spatial distribution of those processes (e.g. Croke and Mockler, 2001). Pickup and Marks (2001) identified that most work on spatially distributed patterns of sediment movement has been undertaken on hillslope or small catchment scales. Scaling up to much larger drainage basins has proved problematic due to the difficulty in obtaining and verifying information on sediment sources, paths, transport rates and delivery. Prosser et al. (2001a) identified this as the dominant reason why most sediment delivery prediction carried out on a large scale is based on empirical relationships. They argued that these relationships need to be replaced with simple physically based predictions of spatial patterns of sediment transport through rivers, although acknowledged that this requires improved understanding of river morphology.

Deficiencies in our understanding of processes affecting water quality is not limited only to the spatial distribution of processes, but is also with some individual processes. For example, Dollar (2000) noted that a particular deficiency in our knowledge base with regards to river management is with regard to the role of bed material transport in river. This could be partly attributed to the complex nature of the drainage system and limited understanding of the links between runoff and sediment sources within and outside the river channel. However, fundamental problems in measuring bed material transport are also a contributing factor.

Concepts regarding erosion processes have been developed over a considerable length of time. Whilst physical processes of detachment, transport and deposition in overland flow are well recognised and have been widely incorporated within erosion models, the experimental procedures to test conditions when processes are occurring concurrently have only recently been developed (e.g. Huang et al., 1999). The work undertaken by Huang et al. (1999) raised issues relating to the appropriateness of erosion concepts commonly employed in model structures.

As it is difficult to foresee that a complete understanding of the processes, and the interactions between processes, will be achieved in the near future, it is essential that uncertainties associated with model structures and processes are explicitly considered.

6.3. Model complexity and accuracy

The model complexity is determined by the detail of the catchment processes simulated. Not only do the number of equations requiring solution increase in a model representing a large number of detailed processes, but so do the number of input parameters (Bennett, 1974). One common misconception is that model accuracy invariably increases with model complexity. This is not the case. The tradeoff between model complexity and accuracy is not simply that increased model complexity increases model accuracy. Simpler catchment models can perform equally well or at least may not be substantially outperformed by more complex models (e.g. Loague and Freeze, 1985; Perrin et al., 2001). Jakeman and Hornberger (1993) confirmed this result for different levels of complexity in conceptual models. Complex models suffer from problems with error accumulation and model identifiability, due to over-parameterisation

(Beven, 1989, 1991, 1996). Beven (1989) argues that the physical nature of model parameters in physics-based models does not circumvent problems of over-parameterisation unless additional parameter observations are available at an appropriate scale. Beven (1991) states that 'in this sense then, physically based distributed models are no different from any conceptual model'. The lack of available input data for such models means that many of the model parameters must be determined through calibration, often against outlet data. This leads to problems of non-uniqueness and means that the physical interpretability of parameter values is questionable.

6.4. Modelling in data poor environs

Empirical and simple conceptual models tend not to require large quantities of input data and are computationally simple. In contrast, physics-based models tend to require a large amount of input data and consequently can be difficult to use. A large number of parameters in these models will have to be determined through calibration in sparse data situations, raising difficulties with identifiability, model uniqueness and the physical interpretability of calibrated parameters. These problems will also be observed with complex conceptual models.

A common modelling problem is that the data requirements of the models often exceed the data availability in the area being modelled. Water quality prediction is by no means an exception to this. Croke and Jakeman (2001) noted that, despite the influence of storm events in Australia leading to a large variability in concentrations vs. flow, there are relatively few data sets that allow the investigation of the causes of this variability. Such observations can be made elsewhere. Data sets on water quality constituents are generally less extensive than water quantity data. Typically, data sets on sediment and nutrient concentrations are only available for catchments of the order of 100 to 1000 km^2, and often for only a period of up to a few years (Letcher et al., 1999). Data sets therefore limit the model complexity that can be justifiably applied.

Dealing specifically with distributed models, Prosser and Rustomji (2000) noted that with the increasing availability of high resolution topographic data through DEM it is possible to isolate topographic effects on the spatial distribution of sediment transport across the landscape. Currently, such data resolution for topography is not, in most cases, matched by correspondingly high resolution data on soil properties or vegetation cover.

There is a lack of simplified and distributed process-based models that can be applied in data-poor conditions. Applications under such conditions have tended to be of an empirical or conceptual nature. However, often there is a lack of appropriate water quality data for calibration of a model's water quality component even for simpler conceptual streambank erosion models, like STARS. Consequently, many of the water quality predictive tools in data-poor environs have tended to be based on characteristic export rates and data from other areas. More complex models are therefore less likely to be of use. The specific requirements for modelling in data-poor situations are to strip the model down to the basic level, down to just those processes that have been identified as most impacting pollutant generation and export.

Further constraining the use of existing data to support model development and parameterisation is that much of the collected data was not gathered with the end use(s) of the data in mind, thus reducing the value of the monitoring program. Letcher et al. (1999, 2002) noted that data collection is often undertaken in developed areas where access is relatively easy and is limited in more remote areas, often considered only in terms of one constituent (for example, water quality data not being collected at the same location as streamflow data monitoring sites), and routinely undertaken in short monitoring periods that are insufficient for sampling a range of event sizes. This can thus reduce confidence in model predictions.

Letcher et al. (2002) state that the design of major monitoring programs requires coordination between agencies and researchers, and that data must be collected with a clear purpose so as to achieve the most value from the data.

6.5. Uncertainties in sediment generation and transport

Uncertainties in water quality predictions are considerably greater than in water quantity predictions (Croke and Jakeman, 2001). Beck (1987), in a definitive review of uncertainty in water quality modelling, noted that a cause-and-effect is not always self-evident in managing water quality and this has led to increased uncertainty in the field.

Uncertainties in the modelling exercise present themselves in a number of forms. Beck (1987) identified these as errors of aggregation, numerical errors of solution, errors of model structure, uncertainty due to unobserved system input disturbances (natural variability), and measurement errors associated with observed input and output field data. The first three points contribute to uncertainties in the initial state of the system. A major uncertainty associated with model structure arises due to model or parameter identifiability. Parameter identifiability refers to the model containing descriptions of either (a) behaviour not observed in a particular sample of data, or (b) multiple behaviour types of which the individual components cannot be distinguished between by the observed data (Beck, 1987). In other words, it may not be possible to determine 'best' parameter combinations to fit the data. Often a number of 'optimal' parameter groups exist.

Complex models—physics-based and complex conceptual models—are particularly prone to problems of model identifiability. Likewise, they are also prone to problems of error accumulation due to their large parameter requirements. Each parameter has its own inaccuracies, even assuming that the means to measure the parameter exists. These inaccuracies may arise from measurement errors or from spatial and temporal heterogeneity. More complex models demand experimental observations that are technically not feasible particularly with reference to spatial patterns of water circulation (Beck, 1987).

Distributed models pose further problems in assessing their performance. In practice, the 'validation' and calibration of spatially distributed soil erosion and deposition models is most often performed using hydrographs and sedigraphs measured at catchment outlets due to an absence of spatial data (Takken et al., 1999). Takken et al. (1999) collected data for the spatial validation of LISEM where model 'validation' referred to spatial patterns of erosion and deposition only. The authors found considerable disagreement between observed and predicted erosion and concluded that uncertainties and errors were not sufficient to explain the discrepancies between model results and field data. They attributed low model performance to a possible incomplete or incorrect process description in the model. The authors concluded that the behaviour of spatially distributed models can only be understood if they are evaluated using spatially distributed data. Considering the complexity of such models, 'outlet' validations are insufficient and can mask important spatial variation within the catchment (Takken et al., 1999).

Conceptual models, while not as prone to uncertainties associated with parameter identifiability as physics-based models, are prone to errors of aggregation. Most conceptual models lump attributes and consequently can lead to both spatial and temporal aggregation errors.

6.6. Dependence on water quantity predictions

Regardless of the process by which pollutants enter the stream, one major factor drives pollutant transport—the hydrological regime. In many cases, sediment and nutrient loadings are dominated by storm events and this necessitates a good knowledge of flow and load relationships for catchments (Harris, 1995; Croke and Jakeman, 2001).

Erosion, sediment and nutrient transport models generally consist of both hydrological and nutrient/sediment transport components. One major difference between specific models is the complexity of treatment of rainfall-runoff processes in the sediment and nutrient generation process. Models such the basic USLE (Wischmeier and Smith, 1978) do not attempt to model the hydrology of the catchment system, relying on simple non-event based relationships, whereas other models, such as WEPP (Laflen et al., 1991) and AGNPS (Young et al., 1987), include a rainfall-runoff model in their structure.

Water quality models are potentially sensitive to the performance of the water quantity module. Viney et al. (2000) illustrated this in applying a water quality model combined with the LASCAM hydrological model to the Avon river basin in Western Australia. The modelling results demonstrated the sensitivity of the nutrient model to water and sediment balances. The modelling strategy employed by the authors involved calibrating a water balance model, using the optimised model to calibrate a sediment balance model and using both optimised models to calibrate the nutrient model. Any weakness in this chain of calibrations compromised the quality of the nutrient predictions (Viney et al., 2000). In other words, uncertainties in the outputs from hydrological modelling introduce an additional uncertainty into the sediment prediction, and so forth to the nutrient model.

Rustomji and Prosser (2001) examined the effect of hillslope hydrology and sediment transport capacity parameterisations on catchment scale patterns of sediment delivery to valley floors. They concluded that there is relatively little field evidence to assist in the choice of hillslope hydrology models and that this is a greater limitation to predicting spatial patterns of sediment delivery than the current knowledge of spatial patterns of sediment transport capacity.

Consequently, the performance of a water quality model can be no better than the hydrological model on which water quality estimates are based. Within the models described in detail in this review a number of well-known and commonly applied hydrological models have been incorporated, including the SCS curve number (e.g. AGNPS) and the Green-Ampt infiltration equation (ANSWERS, WEPP). Much of the previous discussion relating to the problems and advantages of particular model types applies with hydrological models.

6.7. Synthesis

Overall it may be concluded that physics-based models and the more complex conceptual models are not particularly appropriate for estimating catchment exports for the following reasons:

- Lack of sufficient spatially distributed input data to drive the models;
- Paucity of calibration data in space and time to define an appropriate parameter set for the models and hence reliable output;
- The over-dependency of model results on the experience of the user;
- For physics-based models in particular, demanding computational requirements at large catchment scales.

On the other hand, empirical and conceptual approaches can be combined constructively to provide models without these problems and with the following properties:

- Event responsiveness and sensitivity to climate variability;
- Allow investigation of catchment source strengths;
- General physical interpretability of modelling results.

In order to address the growing requirements of catchment managers for tools that can effectively and efficiently capture spatial aspects of soil erosion and sediment transport, on-going work on such tools is needed. The development of a distributed model of relatively low complexity and plausible physical basis is required.

Whilst considerable work is required to improve erosion and sediment transport models, this needs to be undertaken in conjunction with efforts to improve data quality and monitoring. The quality of model predictions ultimately depends on the data that are used to support the model. Judicious data collection is required in order to achieve the maximum benefit in terms of model utility and performance.

Model performance and accuracy remain a major difficulty in model development particularly with spatially distributed models. Ongoing accuracy and sensitivity assessment of models is needed to prioritise modifications to model structures, identify more efficient parameterisations, and target data acquisition necessary for testing model structure hypotheses and algorithms.

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