Simulating Endosulfan Transport in Runoff from Cotton Fields in Australia with the GLEAMS Model

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ABSTRACT

Endosulfan (6,7,8,9,10,10-hexachloro-1,5,5a,6,9,9a-hexahydro-6,9-methano-2,4,3-benzodioxathiepin 3-oxide), a pesticide that is highly toxic to aquatic organisms, is widely used in the cotton (*Gossypium hirsutum* L.) industry in Australia and is a risk to the downstream riverine environment. We used the GLEAMS model to evaluate the effectiveness of a range of management scenarios aimed at minimizing endosulfan transport in runoff at the field scale. The field management scenarios simulated were (i) *Conventional*, bare soil at the beginning of the cotton season and seven irrigations per season; (ii) *Improved Irrigation*, irrigation amounts reduced and frequency increased to reduce runoff from excess irrigation; (iii) *Dryland*, no irrigation; (iv) *Stubble Retained*, increased soil cover created by retaining residue from the previous crop or a specially planted winter cover crop; and (v) *Reduced Sprays*, a fewer number of sprays. Stubble Retained was the most effective scenario for minimizing endosulfan transport because infiltration was increased and erosion reduced, and the stubble intercepted and neutralized a proportion of the applied endosulfan. Reducing excess irrigation reduced annual export rates by 80 to 90%, but transport in larger storm events was still high. Reducing the number of pesticide applications only reduced transport when three or fewer sprays were applied. We conclude that endosulfan transport from cotton farms can be minimized with a combination of field management practices that reduce excess irrigation and concentration of pesticide on the soil at any point in time; however, discharges, probably with endosulfan concentrations exceeding guideline values, will still occur in storm events.

Endosulfan is widely used in Australia for control of caterpillar (*Helicoverpa* spp.) in cotton, but is readily transported in runoff and is highly toxic to fish and other aquatic organisms. The major pathways for endosulfan movement from the farm to the river are via runoff or drift, and to a lesser extent by volatilization (Raupach and Briggs, 1996). The surface runoff pathway is particularly important during periods of intense rainfall. Endosulfan has been found in river systems downstream of cotton-growing areas in central and northwestern New South Wales (Cooper, 1996). A large number of fish were killed during the 1995–1996 cotton season in New South Wales when pesticide-contaminated water was released from nearby cotton farms (Cooper, 1996).

The potential exists for reducing the amount of endosulfan movement in runoff from cotton fields with better management of soil surface conditions and soil water status. In current management systems, fields are often left bare of surface cover in the early stages of a cotton crop, and endosulfan is sprayed directly onto bare soil between plants. Cotton crops are irrigated frequently, so the soil is often wet and infiltration capacity low. Irrigations commonly occur soon after spraying and excess irrigation water can carry relatively high endosulfan concentrations from the field. Currently, much of this excess irrigation water is captured and recycled, but endosulfan transported off the field may be deposited in drains and storages and could later become a source.

In work associated with this study, the fate and properties of endosulfan have been studied extensively (Kennedy et al., 2001; Silburn, 1997; Simpson, 1997). Experimental studies, however, suffer from climate variability, operate over a relatively short duration, and are limited by resource constraints. Models have been employed as tools for analyzing and extending this type of experimental data (Knisel et al., 1995). Properly parametized and tested, models can simulate long periods of cropping, account for climate variability, and analyze a wider variety of management practices than could not be realistically undertaken with a purely experimental approach.

We used the GLEAMS model (Leonard et al., 1987) to estimate transport of endosulfan in runoff from cotton fields in Queensland and New South Wales. GLEAMS was parametized and tested using measured data, then used to simulate a range of management scenarios that experimental data indicated could reduce the magnitude and incidence of endosulfan movement in runoff from cotton fields.

METHODS

The GLEAMS Model

The GLEAMS model (Groundwater Loading Effects of Agricultural Management Systems; Leonard et al., 1987) was used. GLEAMS is a field-scale model of hydrology, crop growth, erosion, and chemical transport. GLEAMS simulates on a daily time step and long-term simulations (up to 50 yr) are possible. GLEAMS has been successfully used throughout the world, mostly to simulate pesticide and nutrient leaching and for pesticide assessment (Knisel et al., 1995). GLEAMS was designed for relative predictions and comparative analysis, and is most useful when simulating long-term effects of the interrelations between pesticide properties, soil characteristics, management, and climate (Leonard et al., 1995).

Input to the model includes a description of the catchment topography, soil characteristics, and channel system. Daily rainfall, average weekly climate information, agronomic operations, and chemical applications are input. Parameter values describing soil type and topography are important for the prediction of erosion and pesticide transport in runoff. Outputs from the model include daily runoff, sediment and chemical transport, crop growth, and soil water. Runoff and soil and chemical transport predictions can be output for various

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Abbreviations: GLEAMS, Groundwater Loading Effects of Agricultural Management Systems.

segments within the field, including furrow hills, furrows, and drains.

Runoff in GLEAMS is predicted using the modified SCS curve number method (Williams and LaSeur, 1976). Curve number for average soil water conditions is input, and the model varies runoff potential according to soil moisture. Erosion and movement of sediment through the channel network is simulated using methods described in Foster et al. (1981, 1985). Erosion prediction is sensitive to slope, which reduces flow velocity, and surface roughness elements (represented in the model using Manning's *n* and the universal soil loss equation [USLE] cover factor), which reduce sediment detachment and transportability.

The pesticide component of GLEAMS is based on methods given in Leonard and Wauchope (1980) and Leonard et al. (1987). Amount of pesticide applied to the soil and vegetation is input; volatilization, spray drift, or other losses during application are not considered directly in the model, but can be represented via the application amount. Pesticide can be applied to the surface, incorporated to a specified depth, or applied in irrigation water. Time-varying concentrations of up to 10 pesticides in soil and on foliage are represented as a first-order process with input half-lives. Different half-lives can be specified for vegetation and different layers in soil. Transformation into metabolites can be represented. GLEAMS does not represent effects of soil water or temperature on pesticide degradation rate. The fraction of pesticide washed off foliage by rain is input by the user. Partitioning of pesticide between the soil and water fractions in runoff is simulated using a linear, reversible, Freundlich-type adsorption–desorption process. Soil organic matter is assumed to be the primary adsorbent, and the parameter K_{oc}, a pesticide property, in conjunction with soil organic carbon and an empirical parameter, B, determine partitioning between soil and water. B is defined as the soil mass per unit volume and is set internally within the model depending on the value of K_{oc} for each pesticide.

Idealized leaf area data are used to simulate crop water extraction and growth. Root water extraction, transpiration, and leaf area index are simulated, though yield is not.

The Modeling Strategy

The simulation strategy was to first "tie" the model in with existing experimental studies and to then use the model to test the effectiveness of a range of field management strategies aimed at reducing endosulfan transport off-field. This study did not intend to be a comprehensive test of GLEAMS for Australian conditions, rather an application of the model to a comparative analysis in close conjunction with site-specific experimental data. We chose GLEAMS because it contains the necessary detail to represent runoff, erosion, and pesticide transport, operates at a field scale, has been used extensively to simulate pesticide transport, and was available as shareware.

We "tied" GLEAMS in with the experimental study by simulating the various components of the experimental study, varying selected parameters to ensure runoff and pesticide transport was accurately predicted, and evaluating the robustness of model predictions across various surface management treatments, catchment management scales, and weather inputs. The experimental data available contained runoff measured from rainfall simulator plots (12 m^2) and irrigation bays (30–60 ha) at two sites with different topography, soil, and weather.

The simulation study complements the experimental studies by sampling a greater range of weather variability and management options, while retaining the characteristics of the catchments on which the experimental studies were undertaken. The experimental studies only operated for 1 to 2 yr, so the range of environmental conditions sampled was limited. A 30-yr period was simulated with GLEAMS, increasing the range of weather sampled and allowing a probabilistic analysis of management effects on runoff. The experimental studies only characterized a limited range of management options (conventional management with some additions of cover), so we used the simulation analysis to evaluate various stubble, pesticide, and irrigation management options. The two sites simulated, Emerald in Queensland and Warren in New South Wales, cover the geographical extent of the cotton-growing area in eastern Australia, and so give an indication of the relative effectiveness of the management strategies simulated for a range of conditions likely to be encountered in much of Australia's cotton-growing area. In addition, close links between the experimental and simulation studies allow some judgment to be made on the absolute accuracy of the model's predictions. Such a close link between experimental and simulation studies is not common, but is useful because it encourages a more detailed evaluation of processes involved in pesticide transport and increases confidence in model predictions.

The Experimental Studies

Data from two experimental sites were used to parameterize and test GLEAMS. One site was near Emerald (Hopsons, Fields 2 and 5), in Queensland, Australia (23°31.6′S, 148°9.3′E) and is called the *Queensland* site. The other, termed the *New South Wales* site, is located near Warren (Auscott, Fields 4 and 23) in New South Wales (31°48.8′S, 147°42.5′E). Both sites have a subtropical climate. Average annual rainfall is 604 and 625 mm for the Queensland and New South Wales sites, respectively. Rain falls throughout the year, but the Queensland site has more rainfall in the summer months (December to February). There is a greater incidence of large rainfall events at the Queensland site (1:10 year daily rainfall is 114 mm at the Queensland site and 70 mm at the New South Wales Site). Average annual pan evaporation is 2440 mm at the Queensland site and 1997 mm at the New South Wales site. Average annual temperature is 22.4°C at the Queensland site and 17.2°C at the New South Wales site. Soil at the Queensland site is a Black Vertosol (Isbell, 1996) or a Typic Haplustert (Soil Survey Staff, 1975) with 62% clay and pH 8.5 in the surface. Soil at the New South Wales site is a Grey Vertosol or an Entic Chromustert with surface clay content of about 47% and pH 8.1. Cotton is planted from September to November and picked in February to April. In the past, endosulfan has typically been applied aerially 6 to 12 times throughout the cotton season at the Queensland site, and two to three times at the New South Wales site.

Data for parameterizing and testing GLEAMS was available from rainfall simulator plots and field studies at both sites, described in Kennedy et al. (2001), Silburn (1997), and Simpson (1997). Rainfall simulator data consisted of measured runoff, sediment, and endosulfan movement from 12-m-long by 1-m-wide (one furrow) plots with 30 to 60 min of high-energy rainfall. Data were available for surface cover levels varying between bare and 60% cover, with between two and eight duplicate measurements made for each cover level. The amount of endosulfan transported in the runoff and sediment phases and the undispersed size distribution of transported sediment was measured at the plot outlets.

The field studies were carried out in commercial cotton crops managed with conventional practices. Soil endosulfan concentration, projected vegetative cover, and soil water were measured regularly throughout the cotton-growing season. Runoff, sediment, and endosulfan movement from irrigations and storms were measured at the outlet of a tail drain bordering the downslope edge of each field. Discharge was measured

Table 1. Summary of sources of data and methods for parameterizing GLEAMS.

GLEAMS component	Data source	Method of parameterization
Catchment description	measured topography and soil type information	measured data
Weather	measured at nearby locations	measured data
Runoff curve number	field study (for bare conditions and field scale), rainfall simulator for change in curve number with cover	optimization against measured runoff
Soil erosion parameters	sediment transport from rainfall simulator plots for a range of surface covers, and from the field outlet for bare conditions	tabulated values; optimization of soil erodibility and Manning's *n* against measured sediment transport
Pesticide application, degradation, and transport parameters	field decay studies associated with field and rainfall simulator studies; endosulfan transport in runoff from the simulator and field studies	measured application amounts, tabulated and measured chemical properties; optimization of decay rates and application efficiencies against measured soil and vegetation concentrations; optimization of *B* against measured runoff data
Crop growth	field studies	measured planting and harvest dates and plant available soil water contents, tabulated crop parameter values

at a rated weir structure using electronic depth sensors. Runoff samples were taken manually and using automated pumping samplers from the mixed flow immediately downstream of the weir. Details of irrigation amounts, pesticide applications, and agronomic operations were recorded. Measured data were available for two cotton seasons (1993–1994 and 1994–1995) at the Queensland site and one season (1994–1995) at the New South Wales site. A total of 15 runoff events at the Queensland site and 9 events at the New South Wales site were observed.

Parameterizing and Testing GLEAMS

GLEAMS was parameterized for testing using data and methods summarized in Table 1. Time variation and transport of the principal isomers of endosulfan (α and β) and their toxic degradation product (sulfate) were represented separately. To simplify output, soil concentration and transport are presented as total endosulfan ($\alpha + \beta +$ sulfate). Runoff, sediment, and endosulfan transport are presented for the field outlet, though individual furrows were represented in the model.

Tabulated (Knisel et al., 1992) or measured values were used for most parameters, but some parameter values were derived by optimization from the dataset used for testing. Runoff curve number, soil erodibility, surface roughness, and pesticide application, degradation, and partitioning parameters were varied until runoff, erosion, sediment and endosulfan transport, and partitioning of endosulfan between the soil and water phases was accurately predicted. Curve number varied with scale and location because of differing catchment and rainfall characteristics. Soil erodibility and Manning's *n* (hill slope and furrow) were varied until erosion and sediment transport measured on the rainfall simulator plots were accurately predicted, then used unchanged at the field scale. GLEAMS does not allow input of the size distribution of eroded soil, so primary particle sizes of surface soil (0–20 cm deep) were varied until the size distribution of eroded sediment matched the available measured data, as described by Connolly et al. (1999). Parameters describing pesticide application amounts, wash-off fraction, and degradation rates on soil and vegetation were varied until concentrations of endosulfan measured on the soil and vegetation in the field and rainfall simulator studies was adequately represented. The parameter *B* was varied (by changing GLEAMS's source code) until measured transport and partitioning between soil and water was adequately represented. K_{oc} was calculated from concentrations of endosulfan in the soil and water phases in runoff from rainfall simulator plots. K_{oc} did not vary across treatments and was averaged. The values of K_{oc} used were not substantially different from published values measured using a batch adsorption method (Peterson and Batley, 1993; Hugo, personal communication, 1999) and had the benefit of being determined after desorption, rather than adsorption, and in a rainfall environment in the field.

Weather information was measured at the experimental sites or nearby. Irrigations were simulated by entering the observed daily irrigation amounts into the rainfall file.

Model accuracy was tested by comparing measured observations with predictions. Goodness of fit was indicated using the coefficient of determination calculated about the line of best fit (R) and the line $y = x$ (EF) [where EF is the efficiency factor of Mayer and Butler (1993)] and root mean square error expressed as a percentage of the measured mean (RMSE). Hedden (1986) described criteria for deciding goodness of fit for models such as GLEAMS: As site specific information was available for parameterization, the model should be able to match the measured data within a factor of two. As such, a RMSE less than 100% was considered a good fit.

Management Scenarios Simulated

The scenarios simulated involved varying tillage, crop residue, irrigation, and spray application management to reduce the chance of endosulfan transport in runoff. The field management scenarios simulated were:

(i) *Conventional*: Cotton stubble was raked and burned after picking, and tillage used to control weeds and prepare hills for planting. One irrigation before planting (140 mm) and six irrigations (100 mm each) during the cotton season applied 740 mm of water at the Queensland site. At the New South Wales site, 700 mm was applied in the same number of irrigations (70 mm before planting and 105 mm at each in-crop irrigation). Preplanting irrigation at the New South Wales site was applied over 2 d, the other irrigations at both sites were applied over 3 d. This level of irrigation was maintained in all years unless there were insufficient rain-free days available during the desired irrigation period, in which case irrigation was applied on any available days. Endosulfan was applied on fixed dates 10 times per season (730 g ha^{-1} per spray) at the Queensland site and three times per season at the New South Wales site. Cotton was planted on fixed dates in October–November.

(ii) *Improved Irrigation*: GLEAMS autoirrigation was used (irrigation was automatically applied by the model when soil water content was between 5 and 25% of plant-available water, applying sufficient water to increase soil water to between 35 and 80% of plant-available water content). This scenario resulted in more frequent but smaller irrigation events with reduced excess runoff of irrigation water compared with the Conventional scenario. The same agronomic and spray operations as the Conventional scenario were used.

Table 2. Summary of parameter values used for the test simulations of the rainfall simulator and field studies.

GLEAMS parameter	QLD	NSW
Runoff curve number	78–85	65–90
Average furrow (land) slope (%)	0.8–1.3	1.0–0.1
Average tail drain slope (%)	0.02	0.1
Catchment area (ha)	0.0012, 28.7	0.0012, 59.4
Soil (0–10 cm) clay content (%)	5	20
Soil (0–10 cm) silt content (%)	20	75
Organic matter (0–10 cm) (%)	2.2	1.7
Cotton rooting depth (cm)	70	60
Endosulfan water solubility (mg L^{-1})	0.32	0.32
Partitioning coefficient, K_{oc}, (mL g^{-1})	9 800–17 800	9 800–17 800
Pesticide availability, *B*, rainfall simulator plots	0.01	0.1
Pesticide availability, *B*, field scale	0.0001–0.0008	0.005
Endosulfan alpha half life on soil (days)	5	5
Endosulfan beta half life on soil (days)	17	25
Endosulfan sulfate on soil half life (days)	60	60
Endosulfan alpha half life on plants (days)	0.5	0.5
Endosulfan beta half life on plants (days)	4	4
Endosulfan sulfate half life on plants (days)	10	10
Wash-off fraction from foliage	0.05	0.05
Coefficient of transformation to metabolite	0.15	0.15
Pesticide application efficiency (%)	70	60
USLE soil erodibility†	0.04	0.04
USLE cover factor	0.5–1.0	0.1–1.0
USLE contouring factor	1.0	1.0
n overland flow	0.01–0.075	0.05–0.085
n furrow	0.03–0.075	0.03–0.06
n field drain	0.03	0.03

† USLE, universal soil loss equation.

(iii) *Dryland*: No irrigation was used, but the same agronomic and spray operations as the Conventional scenario were followed.

(iv) *Stubble Retained*: About 40% stubble cover throughout the cotton-growing season was maintained, either by retaining cotton stubble from the previous season or from a winter cover crop. The same irrigation, agronomic and spray operations as the Conventional scenario were used.

(v) *Reduced Sprays*: The number of endosulfan sprays was reduced from 10 to 5 to 2 for the Queensland Site, and 3 to 1 for the New South Wales site. All other operations were the same as the Conventional scenario.

Parameter values derived for the test simulations were used as far as possible, but parameters representing crop residue, irrigation, and pesticide application were varied to simulate the management scenarios. The effect of residue cover on parameter values was estimated from the rainfall simulator experiments, where runoff was measured from plots with different levels of cover. Curve number for the Stubble retention scenario was derived by reducing curve number from that used for the Conventional scenario by about 15%, based on the reduction in runoff observed in the rainfall simulation experiments. Pesticide wash-off fraction and half-lives on vegetation were based on concentrations on vegetation measured

Table 3. Summary of goodness of fit of simulations with measured daily or event data. Results are presented for total endosulfan, though the principal components ($\alpha + \beta +$ sulfate) were simulated individually.

	m†	*B*‡	R^2	EF	RMSE (% of measured mean)
Simulator studies, Queensland and New South Wales (number of events = 10)					
Runoff (mm)	1.02 ± 0.03	−0.1 ± 0.6	0.99	0.98	4
Sediment transport (Mg ha^{-1})	1.02 ± 0.07	0.14 ± 0.22	0.96	0.81	22
Endosulfan transport (g ha^{-1})	0.87 ± 0.12	−0.40 ± 2.06	0.88	0.76	31
Fraction of endosulfan in the water phase (%)	0.98 ± 0.14	0.25 ± 6.04	0.87	0.59	12
Field study, Queensland (number of events = 15)					
Runoff (mm)	0.94 ± 0.05	1.2 ± 1.9	0.96	0.96	21
Sediment transport (Mg ha^{-1})	1.03 ± 0.05	0.04 ± 0.14	0.96	0.96	33
Endosulfan transport (g ha^{-1})	1.34 ± 0.16	−0.07 ± 0.36	0.82	0.72	72
Soil endosulfan concentrations (g ha^{-1})	0.84 ± 0.09	48 ± 38	0.80	0.75	25
Soil water (mm over 1 m soil depth)	0.54 ± 0.21	188 ± 92	0.29	−0.09	5
Crop growth (measured cover, %, predicted leaf area index, m^2 m^{-2})	0.14 ± 0.22	0.03 ± 0.003	0.95	nc§	nc
Field study, New South Wales (number of events = 9)					
Runoff (mm)	0.91 ± 0.14	5.0 ± 10.0	0.88	0.87	20
Sediment transport (Mg ha^{-1})	1.61 ± 0.60	−0.24 ± 0.58	0.47	0.41	102
Endosulfan transport (g ha^{-1})	1.08 ± 0.19	1.08 ± 0.90	0.84	0.73	68
Soil endosulfan concentrations (g ha^{-1})	0.65 ± 0.15	105 ± 40	0.53	0.57	34
Soil water (mm over 0.6 m soil depth)	0.36 ± 0.31	132 ± 62	0.08	−0.19	11
Crop growth (measured cover, %, predicted leaf area index, m^2 m^{-2})	0.56 ± 0.34	0.03 ± 0.006	0.95	nc	nc

† *m*, slope parameter in linear regression.
‡ *B*, intercept parameter in linear regression. Numbers after regression parameter values are standard error.
§ nc, not calculated, as measured and predicted values have different magnitudes.

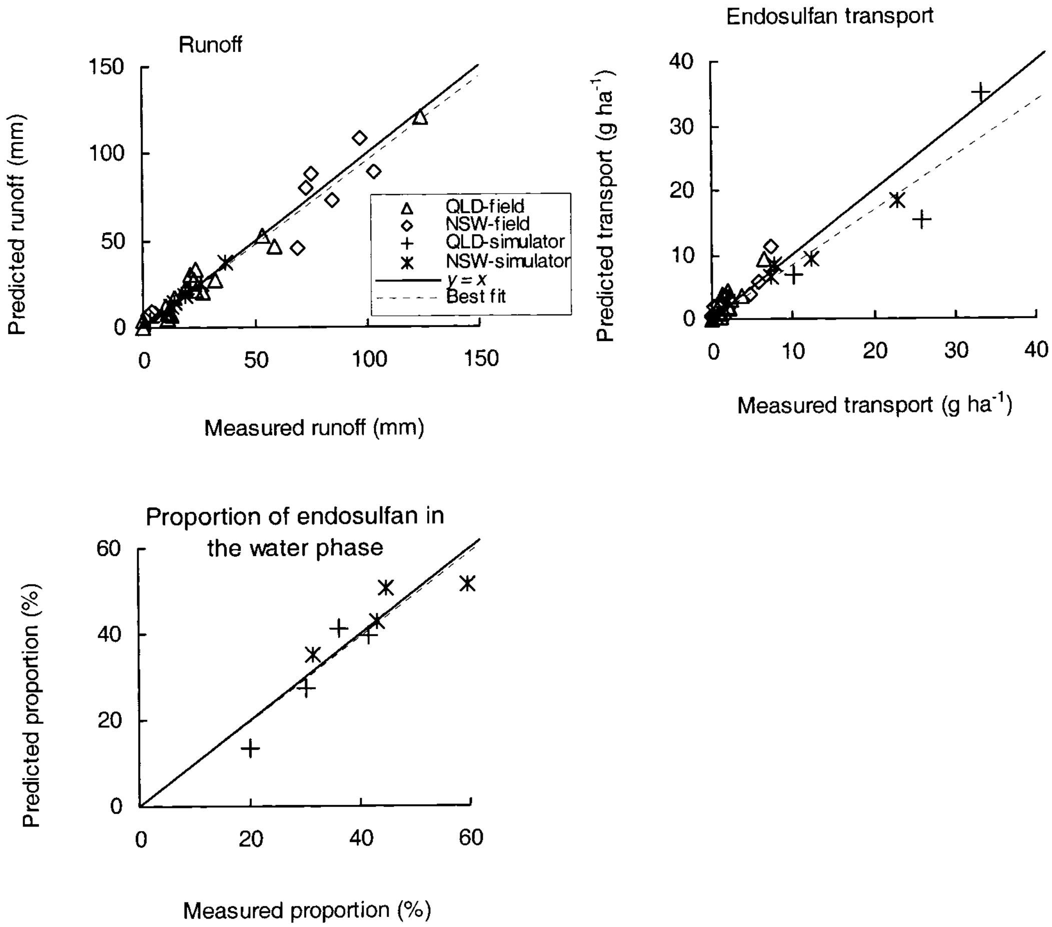

Fig. 1. Measured and predicted runoff, endosulfan transport, and proportion of endosulfan transported in the water phase for all the experimental studies.

in the experimental studies. Values of Manning's *n* used to simulate 40% cover in the rainfall simulator study were used with the Stubble retention scenario. Weather data from a nearby location and typical spray, irrigation, and crop operations were input to the model. Simulations of a 30-yr climate record were made.

Annual Series Analysis

The annual series method (Pilgrim, 1987) was used to evaluate effectiveness of the management scenarios in large events. An annual series analysis involves sorting the largest event in each year and assigning a probability based on rank. Daily runoff amount, endosulfan mass, and runoff concentration likely to be exceeded once every 30 years, 10 years, 4 in every 5 years, and about every year are presented. The analysis only considered daily runoff; average endosulfan concentrations in a runoff event that spans several days could be lower. Runoff amount, endosulfan mass, and concentration were analyzed separately and the value for a given probability may occur in different events.

RESULTS AND DISCUSSION

Model Accuracy and Reliability

Overall, the model accurately and reliably reproduced important characteristics of the physical system, but some parameters required optimization against the experimental data and were site and scale specific (Table 2). Runoff, sediment, and endosulfan transport in runoff, partitioning between the soil and water phase, and soil concentrations were all simulated accurately, with RMSE generally <100 and EF > 0.7 (Table 3, Fig. 1). Slope of the best fit regression between the measured and simulated outputs generally did not vary significantly from 1, nor the intercept from 0, indicating that there was no distortion in model predictions over the range of observed experimental conditions. Seasonal variation in soil water was reasonably well tracked by the model, as indicated by RMSE, but the R^2 and EF measures of goodness of fit were poor because variation in the data was small compared with the mean. However, errors in soil water predictions did not adversely affect predictions of runoff. Sediment transport was fairly poorly predicted for the field study at the New South Wales site. This was probably a function of a short record and variable experimental data, because sediment transport in the other experimental studies, including rainfall simulator studies at the New South Wales site, was accurately predicted. Crop growth was closely tracked by the model, but apart from influencing soil water, was not overly important for simulating pesticide transport.

Of the parameters optimized against the measured data, the most important was the parameter describing pesticide availability, *B*. *B* varied with scale and site,

Table 4. Summary of parameter values varied to simulate management scenarios for the Queensland and New South Wales sites.

GLEAMS parameter	Conventional	Improved irrigation	Dryland	Stubble retained	Reduced sprays (5 and 2 sprays)
Queensland					
Runoff curve number	78	78	74	70	78
Cotton rooting depth (cm)	70	70	100	70	70
USLE cover factor†	1.0	1.0	1.0	0.30	1.0
n overland flow	0.01	0.01	0.01	0.075	0.01
n furrow	0.03	0.03	0.03	0.075	0.03
Preplant irrigation (mm)	nu‡	30	nu	nu	nu
Fraction of plant available water to start irrigation	nu	0.05	nu	nu	nu
Fraction of plant available water to stop irrigation	nu	0.80	nu	nu	nu
Average irrigation applied (mm per cotton season)	730	345	0	734	734
Number of endosulfan applications (each 730 g ha^{-1} of active ingredient)	10	10	10	10	5, 2
New South Wales					
Runoff curve number	80	80	78	72	80
Cotton rooting depth (cm)	60	60	130	60	60
USLE cover factor	1.0	1.0	1.0	0.30	1.0
n overland flow	0.05	0.05	0.05	0.075	0.05
n furrow	0.03	0.03	0.03	0.075	0.03
Preplant irrigation (mm)	nu	30	nu	nu	nu
Fraction of plant available water to start irrigation	nu	0.25	nu	nu	nu
Fraction of plant available water to stop irrigation	nu	0.35	nu	nu	nu
Average irrigation applied (mm per cotton season)	700	470	0	700	700
Number of endosulfan applications (each 730 g ha^{-1} of active ingredient)	3	3	3	3	1

† USLE, universal soil loss equation.
‡ nu, not used.

and optimized values were considerably lower than evident in the literature (as low as 0.0001, Table 2). Endosulfan availability, as indicated by the model's representation of the experimental data, was much lower at the field scale (30–60 ha) than at the rainfall simulator scale (12 m^2). Predictions of endosulfan transport were highly sensitive to the value of *B* used. Using values of *B* hard-coded into GLEAMS (0.1 for endosulfan) caused endosulfan transport at the field scale to be overpredicted by an order of magnitude. There was no experimental evidence to explain why pesticide availability varied to such an extent.

That *B* varied to this extent is surprising, as this parameter typically varies from 0.05 to 0.5, with 0.1 giving an adequate fit in many circumstances (Knisel, 1980; Leonard et al., 1987). Knisel (1980) says that *B* is dependent on runoff conditions. The sensitivity of this parameter to catchment scale and soil type has important implications for model applications to catchments where measured pesticide transport data are not available. Uncertainty in model output will be increased if values of *B* used are uncertain. More research is needed to characterize the processes that influence *B* and determine how best to derive this parameter.

Other important parameters were the fraction of endosulfan washed off vegetation with rainfall, soil erodibility and Manning's *n*, and curve number. From the rainfall simulator studies, we found the wash-off fraction from foliage was stable at 0.05 one day or more after application. This value for wash-off fraction appeared suitable even though irrigation was applied as "rainfall" in the model (measured irrigations could only be entered in the rainfall file), probably because the amount of wash-off with endosulfan was small in any case. Values for soil erodibility and Manning's *n* derived from the rainfall simulator studies could be applied unchanged at the catchment scale as the model represented the hydraulics of water flow from the cotton furrows in a similar level of detail at both scales. Curve number varied with catchment scale and rainfall intensity, but was readily optimized to reproduce measured runoff.

Overall, confidence in the ability of GLEAMS to realistically represent the management scenarios was high because of accurate simulation of the physical system and close links between the simulation and experimental studies. Close links with the experimental studies were particularly important in order to maintain confidence that parameters that required optimization against observations of field behavior, particularly pesticide availability, were adequately specified. Accordingly, the management scenarios were based on the same field catchments as the experimental studies, and only parameters related to the effect of the management strategies on irrigation, crop residue, and rates of pesticide application were varied (Table 4). Accuracy of predictions of endosulfan transport and related outputs was at least as good as other evaluations of GLEAMS in the literature (Leonard et al., 1987; Sichani et al., 1991; Smith et al., 1991; Truman et al., 1998), no doubt because the physical system was well characterized with the experimental studies.

General Characteristics of the Two Sites

The Queensland site received more intense rainfall than the New South Wales site, had steeper land slopes, the cotton season was earlier, and spray application

Table 5. Predicted proportion of total runoff, sediment, and endosulfan transported in runoff water from irrigation (Conventional scenario). The remainder was transported in storm runoff.

Site	Average annual runoff	Proportion attributable to irrigation		
		Runoff	Sediment transport	Endosulfan transport
	mm	%		
Queensland	213	61	50	62
New South Wales	184	71	65	66

rates were much higher. Figure 2 shows the typical variation in concentration of endosulfan on the soil for the management scenarios. The greatest risk of endosulfan transport occurred during the tail of the endosulfan application period (Fig. 2), but when runoff risk was highest (Fig. 3). At the Queensland site this was in December; at the New South Wales site, it was from December to March. These periods corresponded to the peak irrigation period and the months when most storm runoff occurred. The runoff peak in September–October was caused by preplant irrigation, prior to the endosulfan application period.

An important characteristic of the Stubble Retained scenario at both sites was that crop residue intercepted and effectively neutralized a substantial portion of endosulfan that would have otherwise contacted the soil. Wash-off from vegetation was observed in the simulator studies to be low (about 5%) and endosulfan was assumed to degrade much more quickly than on soil. As a result, stubble reduced the concentration of endosulfan on the soil (Fig. 2) and potential for entrainment in runoff. Reducing the number of sprays also reduced soil concentrations.

Simulated Effect of Management in Reducing Endosulfan Export

Of the management strategies simulated, reducing excess irrigation was the most successful in reducing average annual transport of endosulfan off the field (Fig. 4 and 5). Reducing the amount of irrigation by between a third and a half (the Improved Irrigation scenario) reduced average annual endosulfan transport by 80 to 90%. Eliminating irrigation (Dryland scenario) had only a marginal extra benefit, indicating excess irri-

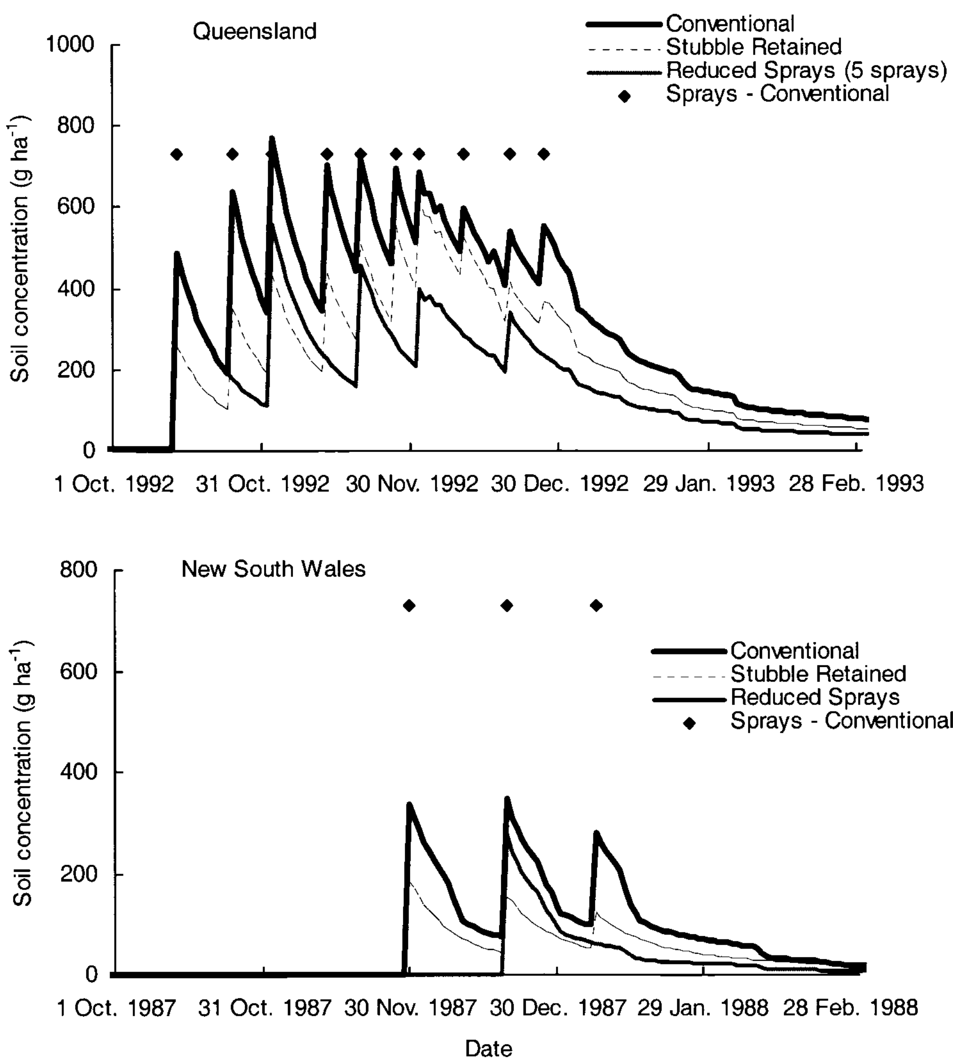

Fig. 2. Typical endosulfan concentrations on soil at the Queensland and New South Wales sites predicted for the Conventional, Stubble Retained, and Reduced Sprays scenarios.

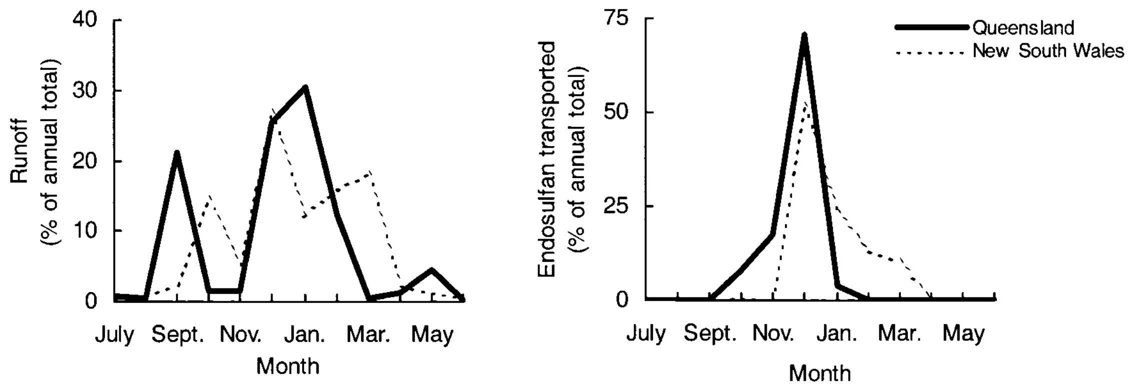

Fig. 3. Predicted variation in runoff and endosulfan transport during the year (Conventional scenario).

gation was an important export mechanism. Irrigation management in the Conventional scenario, which was based on observations of current farmer practices, caused 17% of irrigation water to run off and this made up 60 to 70% of average annual runoff (Table 5). While this is a function of the irrigation strategy used (i.e., applying as much of the target irrigation each year as possible), it does flag the important contribution excess irrigation can make to annual endosulfan export.

In general, endosulfan transport was not as sensitive to reducing the amount of endosulfan applied as reducing runoff (Fig. 5). The proportion of applied endosulfan exported off the field did not appear to change substantially until the application amount dropped below about 2000 g ha^{-1} season^{-1} (three sprays). This is a function of the relative timing of runoff events (either irrigations or storms) and the timing and number of spray applications.

The simulated proportion of endosulfan transported in the water phase was highly influenced by site, but the Stubble Retained scenario was the only treatment to have a marked effect on partitioning between the soil and water phases (Table 6). Proportion in the water phase was highest at the New South Wales site, presumably a function of lower slopes and rates of erosion. The Stubble Retained scenario substantially reduced sediment transport by increasing flow hydraulic roughness. Because runoff was not decreased by as much as the

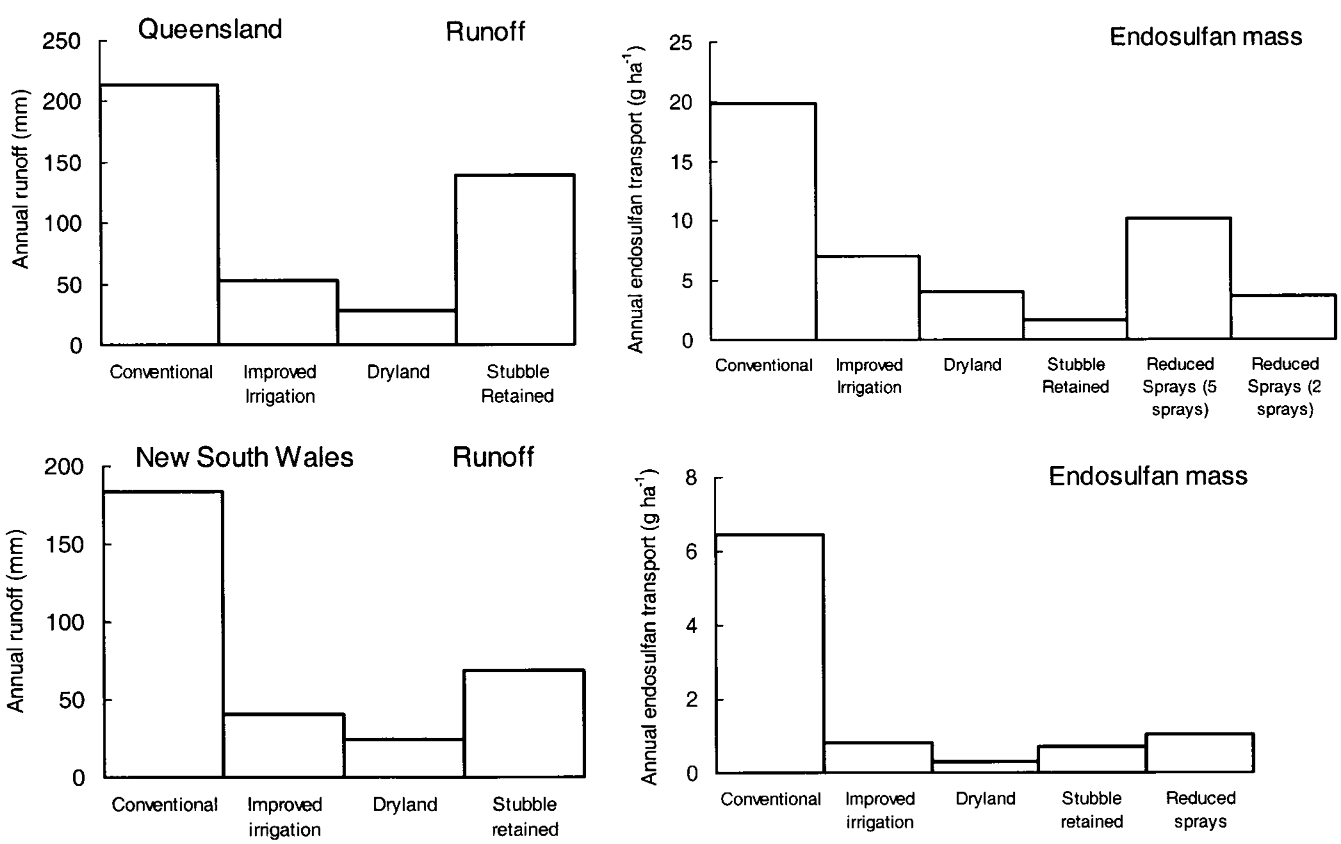

Fig. 4. Predicted average annual runoff and endosulfan transport from the two sites. Runoff from the Reduced Sprays scenario is the same as Conventional.

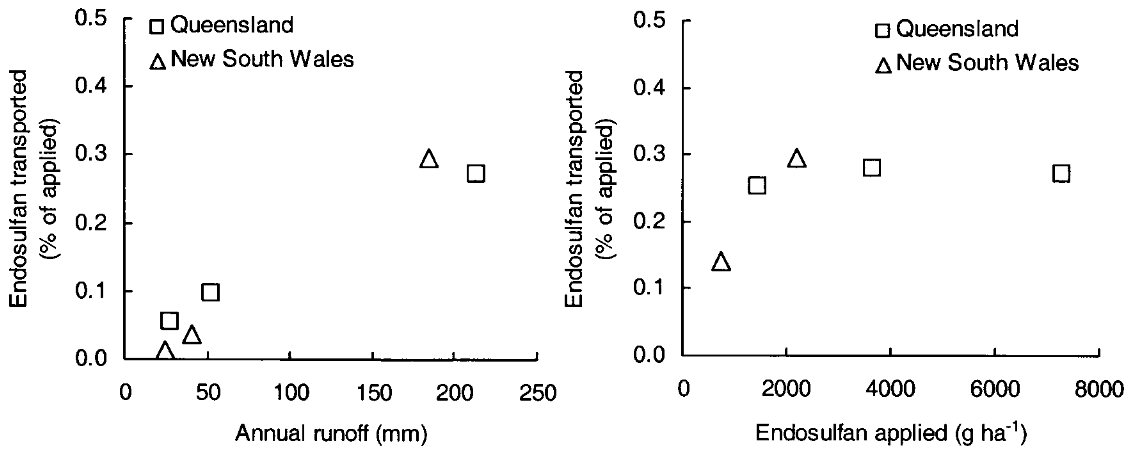

Fig. 5. Change in predicted average annual endosulfan transport when runoff and the amount of endosulfan applied is reduced. Scenarios plotted are Conventional, Reduced Irrigation, and Dryland.

irrigation management scenarios, the proportion of endosulfan transported in the soil phase decreased sharply. In the irrigation management scenarios, erosion was reduced because runoff was reduced, so partitioning between the soil and water phase stayed largely constant.

The Stubble Retained scenario had the benefit of increasing infiltration and flow tortuosity and reducing soil concentration, providing more benefit than the scenarios that targeted either runoff or application amount (Fig. 4). Increasing infiltration may reduce transport by changing the time of runoff initiation, thus allowing more time for pesticide to leach deeper in the soil profile and become unavailable for runoff extraction. We did not have sufficiently detailed experimental data to test whether this process in GLEAMS was accurately simulated nor determine its importance. Most benefit of the Stubble Retained scenario probably lay with increasing flow tortuosity and reducing concentration of endosulfan on the soil. Increased flow tortuosity reduces detachment and transport of sediment. This was particularly important at the Queensland site where, for the Conventional scenario, most endosulfan was transported in the sediment phase (Table 6). Soil concentration was reduced because endosulfan was assumed to contact the soil and vegetative matter in proportion to the vegetative cover. Endosulfan on vegetative matter degrades more quickly than on soil and is less likely to be washed off and enter runoff water (Silburn, 1997).

Table 6. Predicted partitioning of endosulfan between the water and sediment phase in runoff.

Site and scenario	Endosulfan applied	Average annual runoff	Endosulfan transport off-field	Proportion in the water phase
	$g\ ha^{-1}\ yr$	mm	% of applied per year	%
Queensland				
Conventional	7300	213	0.27	17
Improved irrigation	7300	53	0.10	10
Dryland	7300	28	0.06	9
Stubble retained	7300	139	0.02	86
Reduced sprays (5 sprays)	3650	213	0.28	17
Reduced sprays (2 sprays)	1460	213	0.25	16
New South Wales				
Conventional	2190	184	0.30	78
Improved irrigation	2190	40	0.04	78
Dryland	2190	24	0.01	76
Stubble retained	2190	69	0.03	99
Reduced sprays (1 spray)	730	184	0.14	80

Effectiveness of Management in Large Daily Events

Reducing the concentration of endosulfan on the soil surface (Reduced Spray, Stubble Retained) was the most effective strategy for reducing transport in runoff from larger events (Fig. 6 and 7). The management scenarios aimed at reducing runoff (Improved Irrigation and Dryland), while reducing annual runoff and endosulfan transport, were less effective in larger events. Larger events (>1:10) were predominantly caused by intense rainfall in storms, and irrigation strategy did not greatly influence the amount of runoff. Even the Stubble Retained scenario did not reduce runoff in larger events, despite having a higher infiltration capacity. Stubble was, however, very effective in reducing sediment, hence endosulfan load in the runoff. In practice, performance of the stubble retention treatment could probably be improved further by reducing irrigation amounts in response to the increased infiltration.

Simulated concentrations in runoff from the Dryland scenario were quite high, probably because there was less water available to leach endosulfan below the interface between the soil and runoff water (a 1-cm-deep soil layer in the model), so effective concentrations available for transport were higher than in the irrigated scenarios. Whether this is realistic is questionable because in the field, erosion, deposition, and small rills are highly likely to either provide concentrated sources of endosulfan, or erode and expose soil deeper than 1 cm.

In general, simulated endosulfan concentrations in large runoff events were high (Fig. 6 and 7), with potentially negative consequences for downstream water quality. A 1 in 30 year event with conventional management transported about 13 g ha^{-1} off field in a single day at the Queensland site and 3 g ha^{-1} at the New South

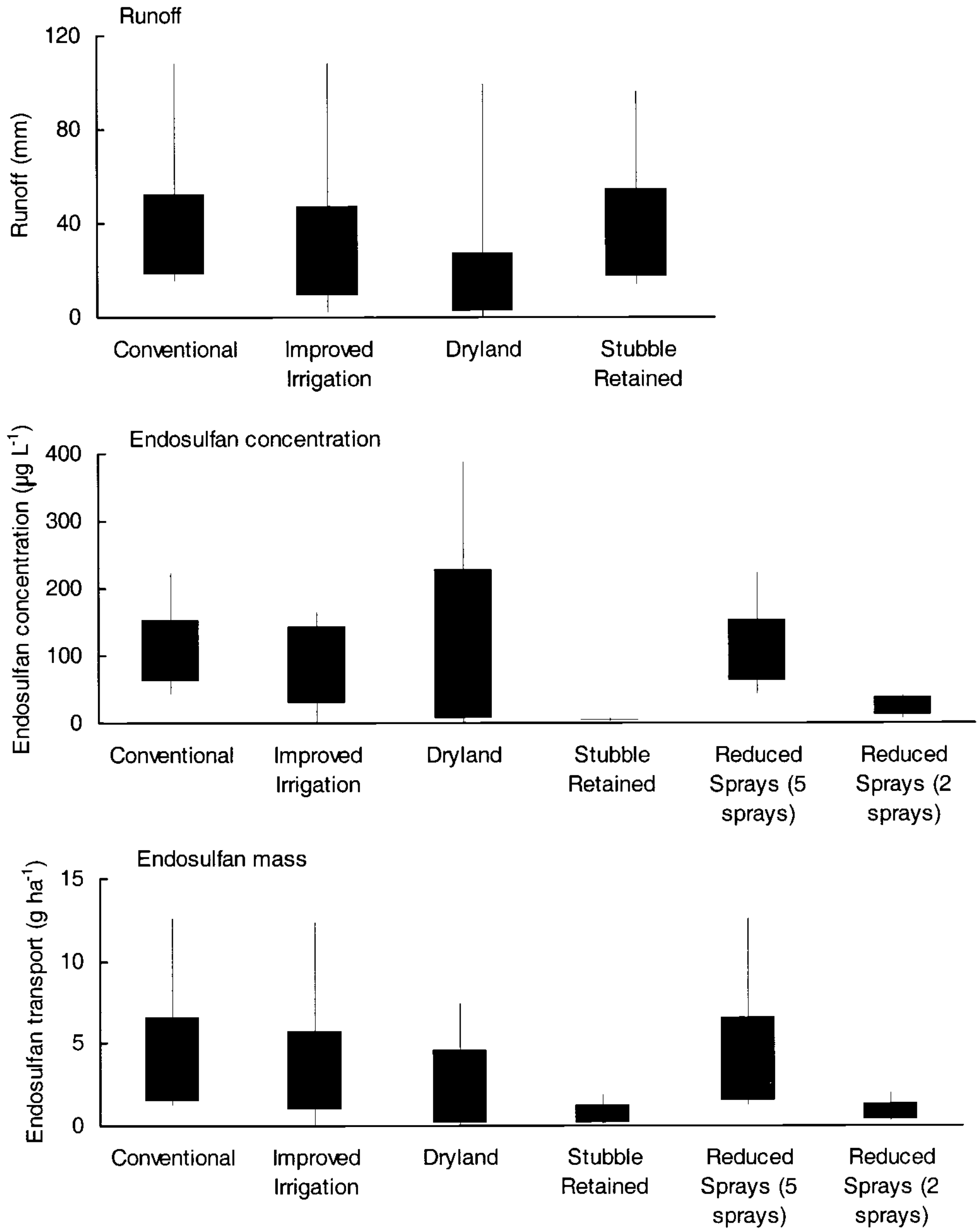

Fig. 6. Daily runoff, endosulfan concentration, and mass predicted in large events at the Queensland site, calculated using an annual series. Top and bottom of the thin bars are the 1:30 and 1:1 year probabilities, top and bottom of the thick bars are the 1:10 and 4:5 year probabilities, respectively. Runoff in the Reduced Sprays scenario is the same as Conventional. Note: Data for runoff, concentration, and mass are calculated independently, and may not be from the same event.

Wales site. Simulated concentration of endosulfan in runoff in these large events was high, exceeding 200 µg L^{-1} at the Queensland site and 12 µg L^{-1} at the New South Wales site. Release of water of this quality into the riverine environment could adversely affect aquatic organisms. Australian guidelines for protection of aquatic ecosystems specify a maximum concentration for endosulfan in water of 0.01 µg L^{-1}. The simulations indicated that this guideline would be exceeded at the field outlet in almost every runoff event, regardless of field management strategy. In practice, though, much of the water leaving the field is either recycled on the farm for irrigation, or filtered through a series of waterways and sediment deposition areas prior to discharge into downstream watercourses, so concentrations entering downstream water bodies are likely to be much lower than those leaving the field outlet.

CONCLUSIONS

GLEAMS accurately reproduced observed runoff and endosulfan transport for sites in Queensland and New South Wales. This strong predictive accuracy relied heavily on optimization of some parameters, particularly pesticide availability (*B*), against measured data and necessitated modification of the program code.

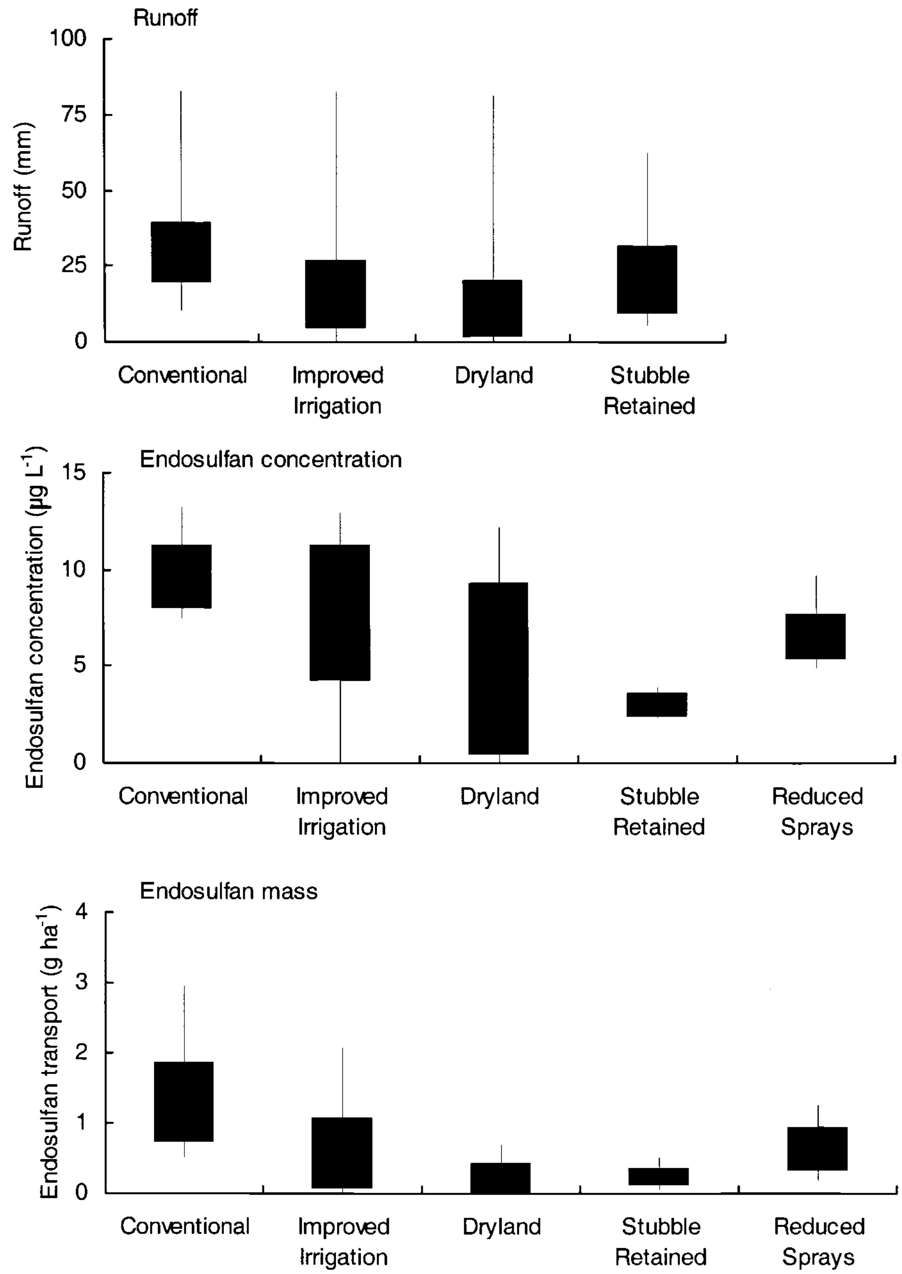

Fig. 7. Daily endosulfan mass and concentration predicted in runoff from large events at the New South Wales site. Top and bottom of the thin bars are the 1:30 and 1:1 year probabilities, top and bottom of the thick bars are the 1:10 and 4:5 year probabilities, respectively. Runoff in the Reduced Sprays scenario is the same as Conventional.

B was variable, and may present problems when applying the model to catchments without the required experimental observations of pesticide availability. This was not a limitation to the analysis of management scenarios in this study because the simulations were linked closely to an experimental program.

To minimize endosulfan export at the field scale, both runoff amount and concentration on the soil need to be minimized. The scenarios aimed at reducing runoff mainly just reduced excess irrigation. Reducing pesticide application amount only reduced transport when three or fewer sprays were applied. Retaining cover on the soil surface was the most effective overall scenario, because infiltration was increased and erosion decreased, while stubble intercepted and effectively neutralized a substantial proportion of endosulfan before it contacted the soil and was available for transport.

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