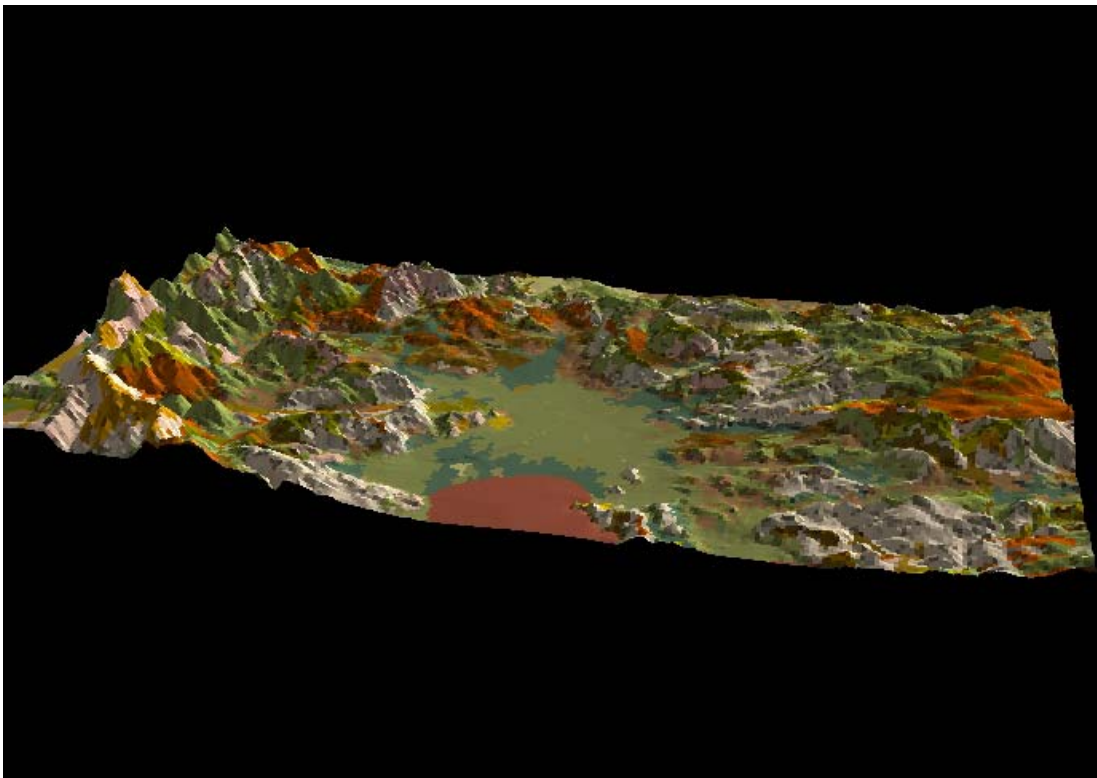


On Modelling and Integration of Models II : Adaptation of Existing Models

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First Interim Report



The CORINE Land Cover data for the ARGOLID Site

MODULUS

DGXII of the Commission of the European Union EU FPIV
Climatology and Natural Hazards (Contract ENV4-CT97-0685)

SCIENTIFIC REPORT

The involvement of the King's College London group in MODULUS stems from a background of research in monitoring and modelling environmental processes in the Mediterranean within the context of two major research projects funded by the EU : EFEDA and MEDALUS. To provide an introduction to the research outlined in this report a brief introduction to these research projects is given below. The reader is referred to the following key publications for further detail in this respect.

Bolle, H.-J., J.C. Andre, J.L.Arrue, H.K.Barth, P.Bessemoulin, A.Brasa, H.A.R. deBruin, J.Cruces, G.Dugdale, E.T.Engman, D.L.Evans, R.Fantechi, F.Fiedler, A. van de Griend, A.C. Imeson, A. Jochum, P.Kabat, T.Hratsch, J.-P.Lagouarde, I.Langer, R.Llamas, E.Lopez-Baeza, J.Melia Miralles, L.S.Muniosguren, F.Nerry, J.Noilhan, H.R.Oliver, R.Roth, S.S.Saatchi, J.Sanchez Diaz, M.de Santa Olalla, W.J.Shuttleworth, H.Sogaard, H.Stricker, J.Thornes, M.Vauclin, D.Wickland (1993) European Field Experiment in Desertification Threatened Areas. Annales Geophysicae.11: pp.173-189.
Thornes, J.B. and Brandt, C.J. (1996) Mediterranean Desertification and Land Use. Wiley.

MEDALUS

The MEDALUS project (Mediterranean Desertification and Land Use) has seen three phases of funding from 1991-present and currently involves 44 groups of researchers from throughout the EU. The objectives of the project are broad and can be summarised as the investigation, modelling and mitigation of the processes of desertification in the Mediterranean. The key emphasis of the project in its current phase is an extensive field monitoring network throughout the Mediterranean but especially in target (threatened) areas. The field data is supported by remote sensing and GIS studies and together these activities support a significant research modelling effort at the catchment scale. The outputs from MEDALUS I, II and III have included various databases, the MEDALUS hillslope model, the ME-DRU-SH catchment model, and more recently an integration of the complex ME-DRU-SH model with a GUI for decision support. King's College London were involved mainly in co-ordination, model testing and development of surface hydrological models.

EFEDA

The EFEDA project (ECHIVAL Field Experiment in a Desertification Threatened Environment) was funded for two phases from 1991-1995. In its final phase the project involved 28 groups of researchers. The objectives of EFEDA were much more biased towards understanding the impact of land surface change on the climate (whereas MEDALUS research is directed at the opposite). The research was concentrated at three sites and throughout the region of Castilla La Mancha, central Spain. The objectives of EFEDA included Soil-vegetation-atmosphere-transfer scheme (SVAT) modelling, understanding Planetary Boundary Layer (PBL) dynamics, developing techniques for the remote sensing of surface fluxes, as well as mesoscale climatic modelling, and the modelling regional water resources. King's College London were involved mainly in the modelling of regional hydrological dynamics and soil-vegetation-atmosphere-transfer. The key outputs of EFEDA were a data bank, and SVATs including the PATTERN model which is now being used for MODULUS.

A Brief overview of The PATTERN MODEL

King's College London comes to MODULUS without experience of working in the target areas (the Argolid, Greece and Marina Baixa, SE Spain). Rather than discuss the characteristics of the target areas, the introductory section of this report will concentrate on a description of the PATTERN model and its role in the MODULUS DSS.

PATTERN can be used as a 1-Dimensional or 2-Dimensional (that is, at-a-point or cellular at the hillslope scale) model. It is an integrated hydrology and plant growth model which was developed between 1991 and 1995 as part of the EFEDA project with further funding from UK NERC. A full description and sensitivity analysis of the model is available (Mulligan, 1996b). All of the model results have been verified and the key state variables (moisture/biomass) have been validated through field experimentation between 1994 and 1996.

The model processes simulated include: rainfall, surface detention storage of water, overland flow, groundwater recharge, soil evaporation, plant transpiration, leaf water relations, plant germination, plant phenology, plant growth, allocation of assimilate, leaf litter production and grazing. All plants are represented as one of three pre-defined functional types : grasses, dwarf shrubs and trees which are parameterised by the user. The model is implemented in the Windows environment, and is coded in Borland Turbo Pascal for Windows. The components of PATTERN are summarised in Table 1.

COMPONENTS OF PATTERN

Inputs :

daily rainfall, temperature and humidity
soil and plant parameters

Models :

Storm generator (produces storms of instantaneous rainfall intensities)
weather generator (produces day/night integrated solar radiation, net radiation, cloud cover, temperature, humidity and wind speed.)
PATTERN hydrology/growth model

Outputs : (written as twice daily, daily, weekly or monthly integrals for whole run period (1 year to n hundred years)

Hydrology - soil moisture, evapo-transpiration, groundwater recharge, soil infiltration, overland flow, soil and leaf water potential...

Ecology - hillslope cover, leaf, stem, root, and reproductive biomass, growth, death, leaf area index, and litter production..

Table 1 An overview of the components of the PATTERN model.

A thorough sensitivity analysis of the PATTERN model has revealed that hydrology and plant growth as simulated by the model are highly sensitive to :

- (a) rainfall, solar and net radiation (which are the main controls on the input and output of water),
- (b) soil texture, soil thickness, soil stoniness (which control the manner in which water is stored in the soil profile) and
- (c) slope and aspect which control both evapo-transpiration and growth.

These sensitivities hold strategic information for the application of such as model within the context of a DSS such as GRIDSS. Importantly, the sensitivity analysis of the PATTERN model also indicates that a strong coupling between hydrology and vegetation processes is critical since the presence of dynamic vegetation sensitizes some parameters and desensitizes others.

Applications of PATTERN

The PATTERN model has been applied to a number of research problems in the recent past. It was developed within the context of a research project called *Modelling hydrology and vegetation change in a degrading semi-arid environment*. The model was applied as a 1 dimensional SVAT for matorral areas in central Spain in order to understand the impact of climatic variability and climatic change on hydrology and vegetation competition in matorral communities. This research is published in Mulligan (1996a,1996b, 1998a,1998b,1998c)

The model has been applied since to a project called *Modelling recharge response to land use and climate change in the Upper Guadiana*. In this project the PATTERN was integrated (offline) with a Geographical Information System (GIS) and applied across the whole Upper Guadiana catchment in order to understand the relative impact of climate and land use change on recent changes in the contribution of recharge to groundwater levels in this area. This application is published in Burke, Mulligan and Thornes (1996); Mulligan and Burke (1998), Burke Mulligan and Thornes (1998a) and Burke, Mulligan and Thornes (1998b)

The role of PATTERN within MODULUS

Water is a key issue in the management of all semi arid environments. A marginal climatic environments, combined with high demands for water (from agriculture and tourism) make it an important element in the environmental, social, economic and political future of all Mediterranean regions. The role of PATTERN in MODULUS is to provide :

- (a) the computational engine for understanding and modelling the spatial and temporal characteristics of the climate for MB and AR for the past and the future,
- (b) the computational engine for all surface and shallow subsurface hydrological processes outside the Riparian zone (i.e. for all of the hillslopes) including erosion.
- (c) The computational engine for the modelling of plant growth and yield in a spatially distributed manner for the various crops grown in the target areas

In addition King's College London will assimilate and homogenize temporal datasets for climatic parameters and spatial GIS based datasets. PATTERN was developed as a research model under EU FP III and IV. A review of available models in the field of desertification (Mulligan, 1998) carried out for the EU concerted action on Mediterranean Desertification highlights the models available for the kind of DSS proposed for MODULUS and the limitations of these models for application in a policy relevant context.

GROWTH	HYDROLOGY
1. Initialise variables	1. Initialise variables
2. Open files	2. Open files
3. Generate or read slope characteristics	3. Generate or read slope characteristics
4. Set initial conditions	4. Set initial conditions
5. Open met data file	5. Open met data file
6. Loop to 30 for years	6. Loop to 30 for years
7. Loop to 29 for met data timesteps	7. Loop to 29 for met data timesteps
8. Read met data for timestep and calculate any transient change to be included	8. Read met data for timestep and calculate any transient change to be included
9. Calculate Potential evapotranspiration	9. Calculate Potential evapo-transpiration
10. Loop to 24 for Y spatial direction	10. Loop to 24 for Y spatial direction
11. Loop to 23 for X spatial direction	11. Loop to 23 for X spatial direction
12. HYDROLOGY MODEL	12. Calculate actual evaporation for bare, rock or vegetated surface
13. Calculate stress function and growth	13. Calculate depth of dry layer
14. Calculate grazing loss	14. Calculate Infiltration
15. Calculate growth allocation	15. Integrate fluxes if too large
16. Sum fluxes over range of writestep (twicedaily,daily,weekly,monthly)	16. Calculate detention storage
17. End X loop	17. Update soil water budget

18. End Y loop	18. Calculate leaf water potential if cell is vegetated
19. Calculate new germination	19. Set water budget if cell is a rock outcrop
20. Calculate change in cover	20. Calculate potential for overland flow occurrence
	21. GROWTH MODEL
	22. Sum fluxes over range of write step (twicedaily,daily,weekly,monthly etc.)
	23. End X loop
	24. End Y loop
	25. Germination, change in cover
	26. Overland flow model
21. Output to files	27. Output to files
22. Output to screen	28. Output to screen
23. End met data loop	29. End met data loop
24. End years loop	30. End years loop
25. Close files	31. Close files

Table 2 Basic processes in the PATTERN model.

The complexity of the PATTERN model is indicated in the outline of processes summarised in Table 2.

EU FP III and IV : The Lessons

A review of all of the EU funded projects in the field of desertification (which includes all of the projects incorporated in MODULUS) reveals a number of key obstacles to the policy-relevant application of these models. These can be summarised as :

- (a) *Model complexity*. Many of the research models developed under FP III and IV are complex physically based models. Besides the large scale and specialist data requirements of such models, these models are often designed for scales of application outside of the main policy-relevant scales *i.e.* the models are applied at the hillslope scale or for small catchments rather than for regions or for socio-economic/political units. In addition, the complexity of the model equation render these models computationally very demanding and thus time-consuming for simulation of periods longer than a year. In this way, the models are not suited to understanding change at policy relevant timescales - of the order of 4-30 years.
- (b) *Availability, variability and uncertainty of field data for models*. The data demands of research models are extremely high. Such models are often applied at the small (hillslope, village) scale or, where they are applied at larger scales are applied within the context of extensive data collection programmes in the target areas. Such models cannot be applied outside of the catchment of their development without extensive scientific investigations to provide the model parameters required. They are thus unsuitable for application by non-experts in a policy relevant context outside of the area for which they were developed. A policy model must be built to run, as much as possible, from routinely collected data.
- (c) *Validation of models*. Lack of available data has meant that most of the models developed under FP III and IV remain unvalidated for Mediterranean regions. Model validation is critical for the confidence application of environmental models to policy-relevant problems. The lack of validation, to some extent, also reflects the difficulty of validating complex models : even where the validation of gross (aggregated) state variables is achieved this does not validate the internal workings of the model. In other words a model is perfectly capable of producing correct results for the wrong physical reasons. Validation for policy application must mean the validation of individual simulated processes in addition to aggregate model results.
- (d) *The model-policy maker hiatus*. There is a clear gap between the output of research level models (and some policy models) and the tangible measures of change that are of use within a policy context. Whereas models will output variables such as overland flow, erosion, crop productivity, water resources, these are not the kind of variables of immediate relevance within the policy context. Health, wealth, growth, education, environmental sustainability and other such variables are much more likely to be required as outputs from a modelling exercise by the policy maker. Many of the models produced deal with the hard science only with little modelling effort put into bridging this gap. This leaves the policy maker with the unenviable task of deciding what the implications of reduced quality or quantity of water resources may be on human health. It is important that such complicated tasks as this be incorporated within the decision tool.

These obstacles reflect the nature of the model building commissioned under FP III and IV - modelling to develop and push forward the science of desertification, not necessarily for policy relevant application. Now that this scientific basis is well developed, there is the opportunity for the policy - relevant application of these models. Indeed policy-relevant application of models is now a much more important issue. In my view, however, the models cannot be applied in their current forms. They are designed fundamentally as research models and, as we shall see later, research models and policy models have fundamentally different requirements. As such, for efficient and appropriate policy-relevant application the models will have to undergo a number of important *adaptations*. It is the purpose of this chapter to examine the types of modifications required for the application of research models in a policy context and to examine how this can be achieved. This will be supported by reference to the adaptations developed for the integration of the PATTERN model with the MODULUS DSS.

The requirements of research and policy models

Before a strategy for model adaptation can be developed it is important to understand the requirements of research and policy models and identify their key differences. These are summarised in Table 3. The requirements of the two types of model are driven by fundamental differences in the objectives of modelling. Research models are built to develop, test or extend hypotheses concerning how a particular process or system works whereas policy models aim to simplify complex systems in order to understand the outcomes of particular actions. In this way research models are model centred and policy models are output centred.

Research models	Policy models
accurate representation of processes	adequate representation of processes
complexity and resolution reflect processes	complexity and resolution reflect data
accurate representation of spatial variability	adequate representation (reflects existing data)
scientifically innovative	scientifically proven
raises more questions than answers	provides simple(?), definitive(?) answers
interesting and worthwhile in its own right	interesting and worthwhile only through its output
process centred	input/output centred
numbers validatable	outcomes validatable
as complex as necessary	as simple as possible
INTERFACING ISSUES	
model centred	Interface centred

Table 3 The requirements of research and policy models (Mulligan, 1999)

The end-user requirements of the MODULUS DSS

Within the context of MODULUS we can be much more specific concerning the end-user requirements of the DSS. The key end-user requirements of the model can be summarised:

- (a) *Interactive*. The model must be fast, responsive and interactive and should cater for a very short attention span. Simple models and efficient code will be required to achieve this.
- (b) *Scale*. The model must operate at a scale which is of relevant in the policy process - for example the region and must provide information at a sufficient level of spatial detail (resolution) to reflect the scale of variation in the most important environmental and human variables.
- (c) *Scenario based*. The model should provide easy to understand scenarios which the user can be taken through. These may be for environmental changes (e.g. climate variability, climate change, anthropic impacts (e.g. land use change) and management options (e.g. conservation, water recycling).
- (d) *Processes*. The DSS must adequately represent **all** of the important processes necessary to provide the required output.
- (e) *Based of routine data*. The complexity of the DSS must reflect the availability of data, in other words, the DSS must be sufficiently simple to run from routinely measured data without the need

for scientific field programmes for model application. At the same time the DSS should be sufficiently complex to include all of the relevant processes. Routinely available data may include data collected by government or intergovernmental agencies such as the EU.

- (f) *Scientifically proven.* The process descriptions within the MODULUS DSS should be well known and scientifically proven. It is better to have a well understood, proven but crude process description than an innovative but poorly documented and less proven description. The model results, after all, have to be robust, reliable and accurate.
- (g) *Output centred.* The model must be output centred. It will be judged only upon the quality of its output and not upon the scientific or technical innovation in the model code. It should provide simple, appropriate results using indicators or variables that directly interface with the policy implementation process rather than more abstract scientific or technical variables.

The key trade-offs here are between accuracy (of the data and of the model process representation) and simplicity (of models and of data). The model must have sufficient spatial and temporal detail and sufficient model complexity to accurately represent the processes but must achieve this over large areas in a fast and responsive manner with the minimum of data.

The very important differences between model requirements for policy and model requirements for scientific indicate highlight the difficulties in adapting existing models for incorporation into the MODULUS DSS, especially where these models are fundamentally research models and need to be applied within a policy context.

Adaptation of the models : integrate, adapt or rebuild?

There are three levels at which existing models can be integrated within a DSS for policy application. First, the models can simply be *integrated* as code or executables in close to their original form, providing that the interactions with other models are clearly specified. In this case, unless the models were specifically built for policy application or cover only small parts of the modelled system, it is likely that many of the end-user requirements on speed and responsiveness will not be fully met. Secondly, models can be kept in their original form but the code *adapted* in minor ways to meet the end-user requirements more successfully. The kinds of adaptations carried out may include changes to the spatial resolution, scale or timesteps of the model or simplification of key process equations.

The third level at which models can be integrated with a DSS is through a complete *rebuild* of the model for incorporation into the DSS. This has a number of significant advantages over the other methods. In particular it allows the model to be specifically designed to meet the user requirements. Realistically, for many research models, rebuild is the only way in which the very extensive end-user requirements outlined here can be fully met. At the same time, the key innovations and most significant processes and lessons from the original model can be transferred to the rebuild. In this way the research model is rationalised, simplified, modified to the correct scale and rebuilt to the new objective.

The PATTERN model is a very complex model, which describes hydrology and plant growth in great detail. Whilst this detail is important to answer the kind of questions for which the model was designed the requirements of the MODULUS DSS are much more general and the level of complexity in PATTERN is not required. Similarly the level of detail required to understand hydrological and ecological processes at the hillslope scale is no longer relevant as one scales up from the hillslope to the region. As scale increases fewer parameters and simpler equations can be used to represent the same processes accurately (Ehleringer and Field, 1993; Wood, 1994; Braun et al., 1997; Dooge and Bruen, 1997; Kabat et al., 1997). For these reasons and because of the need to develop new functionality for the model the rebuild approach was implemented for PATTERN.

Strategy for PATTERN in MODULUS

The decision on rebuild offers a number of opportunities for improvement of the model to fit with the objectives required for MODULUS and for DSS in general. The rebuild strategy for PATTERN can be summarised as:

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- (a) Take the key innovations of PATTERN and rationalize the model, cutting it down to the most significant processes.
- (b) Replace equations that require specialised data with simpler equations which use data that is routinely measured such as topography (DEM), soil type, standard government meteorological records. As much as possible create the more complex model parameters from simpler, routinely measured surrogates or proxies.
- (c) Validate the key relationships in the rationalized model.
- (d) Re-code the model and spatialise within the context of the GridDSS.
- (e) Regionalise the model parameters required for the model.

PATTERN^{LITE} : THE NEW PATTERN MODEL

This strategy has been adopted and carried out over the last year, to produce a re-write of the PATTERN model, PATTERN^{LITE}. PATTERN^{LITE} has been developed from the lessons learned through the application of PATTERN to a number of projects and through the knowledge of significant processes obtained from a thorough sensitivity analysis of the PATTERN model (see Mulligan, 1996b; Burke, Mulligan and Thornes, 1996). The level of complexity of the new model is limited by :

- (a) the emerging fact that complex process models are not necessarily better than simple process models.
- (b) the logic that it is better to have a parameterisable, validatable simple model than an unparameterisable non-validatable complex one.
- (c) the reality that data for parameterisation, calibration and validation is time consuming and expensive to obtain and is lacking throughout much of the Mediterranean.

Some of the key lessons derived from the PATTERN model were that:

- a) extreme events do most of the hydrological work in the Mediterranean landscape,
- b) partitioning of rainfall between infiltration and overland flow at the land surface is critical for understanding the impact of rainfall events,
- c) the status of the vegetation cover throughout the year but particularly at the end of the dry season is critical
- d) the feedback loops between vegetation, hydrology and erosion are critical so that a good hydrology model must be tightly and interactively coupled with the erosion and plant growth models
- e) surface processes are controlled, to a large extent, by subsurface properties.

PATTERN^{LITE} has been developed to ensure that these factors, and others, are adequately represented within the context of a more interactive and responsive model requiring as little data as is possible.

Simplification of existing processes

This section describes the ways in which PATTERN has been rationalised to form PATTERN^{LITE}. It outlines the logic upon which certain of the processes were rationalised and incorporated into PATTERN^{LITE} and upon which others were removed. The process of simplification will be discussed process by process.

Meteorological Processes

Rainfall

Routinely available data is only available as monthly total or daily total rainfall, however one of the key lessons from PATTERN was that the interaction of infiltration and overland flow really depends on the sum of instantaneous differences between the intensity of rainfall and infiltration. Both of these factors change dramatically through the course of a storm. Daily total rainfall gives no indication of the intensities at which rainfall hit the land surface. Since the hydrological pathway for water depends on the difference between rainfall intensity and the intensity of the various hydrological pathways at a point in time, it is essential that hydrology is modelled at a temporal resolution of less than one month

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and less than one day if possible. In the PATTERN model this is achieved by using a Monte Carlo based rainfall generator which generates storms from daily rainfall totals. This model is described in Mulligan (1996).

The importance of the partitioning between infiltration and overland flow for water resources, soil erosion and crop growth means that the Monte-Carlo based storm generator of the PATTERN model must be retained. This gives two advantages :

- (a) it allows more accurate representation of overland flow events by modelling the pattern of storm characteristics from rainfall intensity through to storm duration and storm length and,
- (b) it avoids having to integrate the model on a fixed timestep (hourly) - the model is integrated only when rainfall occurs. Since rainfall occurs infrequently in Mediterranean environments this provides a significant runtime economy and also allows intensive integration during those periods when rainfall is occurring and the hydrological landscape is therefore undergoing rapid change. The variable timestep of PATTERN and PATTERN^{LITE} is discussed in more detail later.

However, the PATTERN storm generators require an input of daily rainfall. Since this is not available in some regions and is certainly not available for the output of general circulation models of the atmosphere (GCMs), a new generator had to be designed for MODULUS. This Markov chain based generator, described in detail later, is used to produce daily rainfall from monthly data for the two regions.

Meteorological Generators

In addition to rainfall, hydrological models also require other meteorological data including air temperature, solar and net radiation. Since these are likely also to be unavailable in routinely measured datasets, and because their variability is high, they must also be simulated.

PATTERN includes a solar radiation simulator applied to a single hillslope on the basis of its latitude, longitude, slope and aspect (Mulligan, 1996). Some modifications of this model were required to allow its application within the MODULUS DSS. The model calculates solar radiation receipt for the top of the atmosphere for grid cells with various slopes and aspects. Since the model equations are complex and cannot readily be simplified it was decided that, as solar radiation receipt at the top of the atmosphere does not change from year to year, the model would be pre-run for a particular region. The results are then stored as daytime and nighttime averages for each cell in the grid and subsequently read from the CDROM at runtime. At runtime the solar radiation receipt has to be corrected for the current cloud cover. This avoids having to repeat the calculations every year and thus has advantages for the speed of the model. Figure 1 shows example output from the solar radiation module for the Marina Baja site.

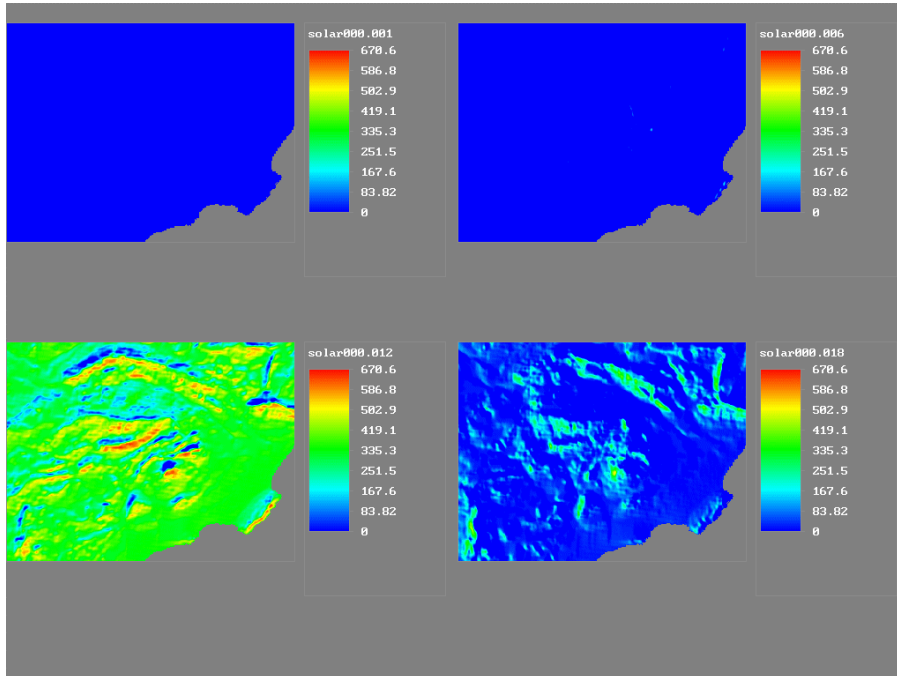


Figure 1 Output from the regionalised solar radiation model for 1st January (a) 1 AM, 6 AM, 12 NOON and 6 PM. Solar radiation (W/m^2)

Because of the computational overheads associated with running the hydrology model on an hourly basis, the solar radiation values are integrated offline into daytime and night-time integrals. This (a) captures the essential variability of the data, (b) reduces the number of timesteps by 22 per day (8030 per year) and reduces the storage space required for the output files. Because of non-linearities and different process domains across the day-night interface, the day-night timestep provides significantly more accurate results for many processes than integration at a daily timestep. Table 4 shows the differences in simulated evpo-transpiration for the same dataset when integrated at the hourly, daily and day-night timesteps. Clearly hourly integration is most accurate. In balancing the computational demands of hourly integration with the needs for adequate accuracy, daily integration provides considerably greater error than day-night integration. Day-night integration is used in PATTERN and carried forward to PATTERN^{LITE}.

Transpiration (mm/30 days)		
	January	June
Hourly	9.6	35.0
Daily	20.9	54.9
Day/night	9.7	40.7

Table 4 The effect of data resolution on transpiration estimates.

Cloud cover

Although solar radiation at the top of the atmosphere remains constant for a particular time and day, solar radiation at the land surface is subject to diurnal fluctuation in atmospheric transmissivity, which is controlled mainly by changing cloud cover. This fluctuation can amount to many $Watts/m^2$ of energy and can significantly affect evapo-transpiration and plant growth. PATTERN models cloud cover from a single probability distribution function (PDF) of atmospheric transmissivity calculated from the difference between modelled top-of-the-atmosphere and measured land surface solar radiation for a year of AWS data (Figure 2). The distribution is bimodal, with raindays producing higher cloud covers than dry days, as indicated in Figure 3. Different peaks are sampled for raindays and dry days.

The main adaptation for PATTERN^{LITE} is that separate PDFs for raindays and dry days are now calculated from the meteorological data. This is in recognition of the fact that not all raindays produce high cloud cover and not all dry days low cloud cover. The PDF for a rainday is sampled during a rainday whilst the PDF for a dry day is calculated for dry days. In this way cloud cover tracks rainfall in a physically realistic way.

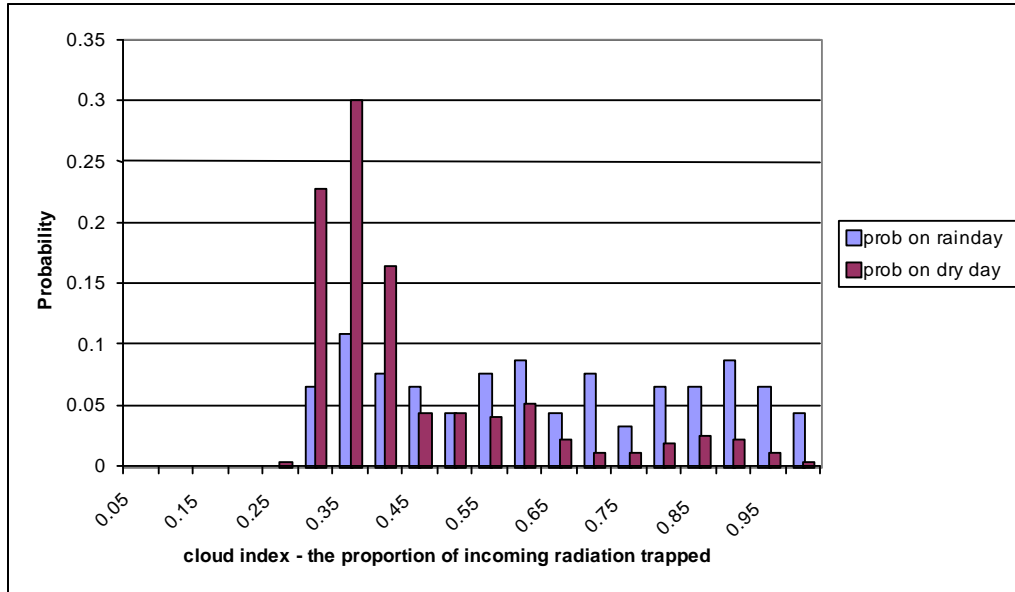


Figure 2 Cloud index PDFs for raindays and dry days.

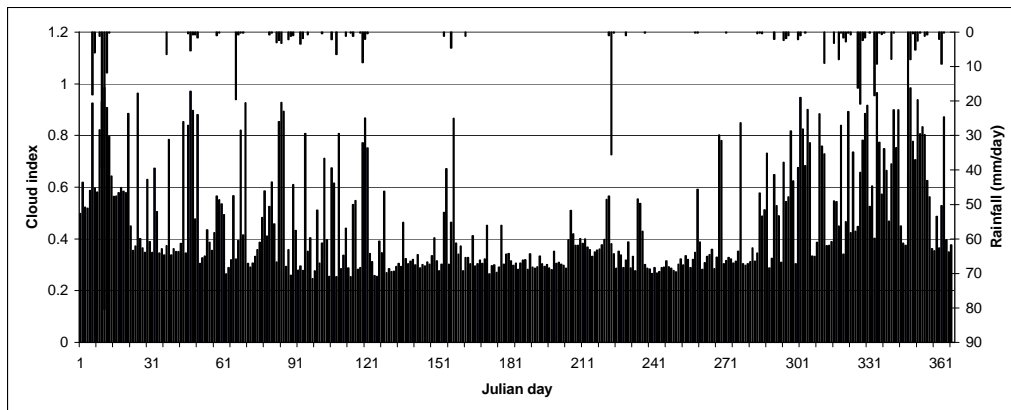


Figure 3 The association between cloud cover and rainfall on a daily basis for the Argolid, data courtesy of P. Giannouloupoulos, Agricultural University of Athens, Department of Natural Res. and Agr. Engineering.

Though there is a relationship between cloud cover and the actual amount of rainfall falling at both of the target areas, the relationship is too weak to model the amount of cloud cover empirically from this hence the use of the Monte Carlo approach. Similarly this weak relationship means that there is no evidence for the spatial modelling of cloud based on altitudinal or zonal rainfall differences. In other words cloud cover is modelled stochastically for a particular day and is assumed uniform over the region for that day, irrespective of spatial differences in rainfall receipt. This is an appropriate simplification for this kind of model.

Net radiation

Evapotranspiration is controlled by net radiation. Net radiation is the energy remaining at the land surface after all electromagnetic fluxes are taken into account. In other words the net radiation is the sum of the incoming short wave and long wave radiation minus the sum of the outgoing (reflected) short wave radiation and (emitted) long wave radiation. The absolute value for net radiation is determined by the absolute value of solar radiation input and is a constant proportion of the incoming solar for particular surface conditions. The proportion of solar radiation that becomes net is determined by the characteristics of the land surface, in particular the reflectivity and emissivity of the surface. These properties are a function of the vegetation cover and the soil conditions. In the PATTERN model (applied to matorral communities) net radiation is calculated as a linear function of solar radiation. This provides good accuracy for a matorral surface. Where this equation has to be applied across a much larger number and diversity of cover types, the effect of different surfaces must be taken into account. This can only be achieved with a better understanding of the physical basis of reflection and emission from common surfaces than is currently available and requires satellite characterization of reflectivity and emissivity of each grid cell in the MODULUS DSS, expertise which is not currently available under MODULUS. Nevertheless one of the main controls on reflectivity and emissivity has been characterized and can be taken into account, this is the impact of surface wetness on energy partitioning. The relationship between solar and net radiation is significantly different for wetted soils (Figure 4) and wetted soils (Figure 5). The relationship between solar and net radiation may also be expected to differ between soil types but this is outside of the scope for work in MODULUS.

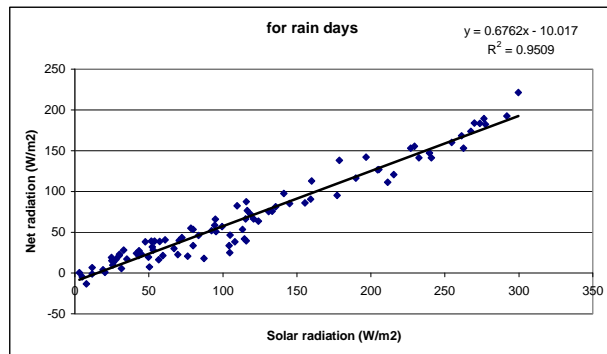


Figure 4 Relationship between solar and net radiation for the Argolid site, rain days.

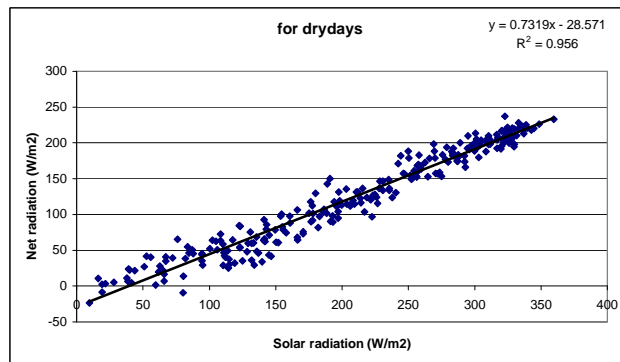


Figure 5 Relationship between solar and net radiation for the Argolid site, dry days.

Surface and soil hydrological processes

A number of adaptations were required to the PATTERN hydrological equations for simplification and regionalisation.

Infiltration

The infiltration model adopted for PATTERN^{LITE} differs somewhat from the model implemented in PATTERN because of the need for a model capable of operating at much larger scale. The model's basic requirements are an understanding of the propagation of the wetting front through a soil profile, since this is what controls the ingress of water through the soil surface (Mulligan and Thornes, 1998*). The rate of propagation of the wetting front is determined by the saturated hydraulic conductivity at the wetting front, itself calculated from the pedo-transfer function of Campbell (1985, see page 29). The PTF is applied to calculate the rate of propagation of a wetting front from the soil surface in accordance with the overall soil texture and a hypothesised increase in soil bulk density with depth in the soil profile (

Figure 6). This increase is a generic property of porous, loose-grain based materials such as soils. As a generic property this assumption is suitable for application at the regional scale and has been measured in a number of non-skeletal soils within and outside of the Mediterranean (Mulligan and Thornes, 1998). Because soil bulk density affects porosity it also affects soil hydraulic conductivity and thus controls the rate of propagation of the wetting front (Figure 7).

Skeletal soils (i.e. those supported by stone clasts) do not share this generic property since they are matrix is supported. They have a more uniform distribution of soil bulk density density with depth, in these soils, fine earth bulk density can be calculated using the relationships between stone fragment content and fine earth bulk density proposed by Childs and Flint (1990) and Torri *et al.* (1994). The Torri *et al* model proposes the following relationship between fine earth bulk density and soil rock fragmentation content and is used here to correct for stone fragment content effects on bulk density and thus infiltration:

$$BD_{fe} = BD_{fe}^0 \left(1 - 1.67 Rm^{3.39}\right)$$

Equation 1

where

Bd_{fe} = bulk density of the fine earth (g/cm³)

Bd_{fe}⁰ = bulk density with no rock fragments present (g/cm³)

Rm = rock fragment content by volume.

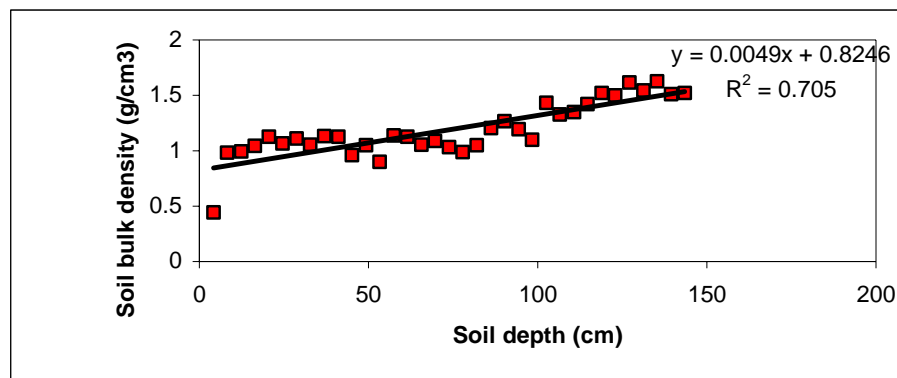


Figure 6 Increasing soil bulk density with depth : a generic property for regional modelling.

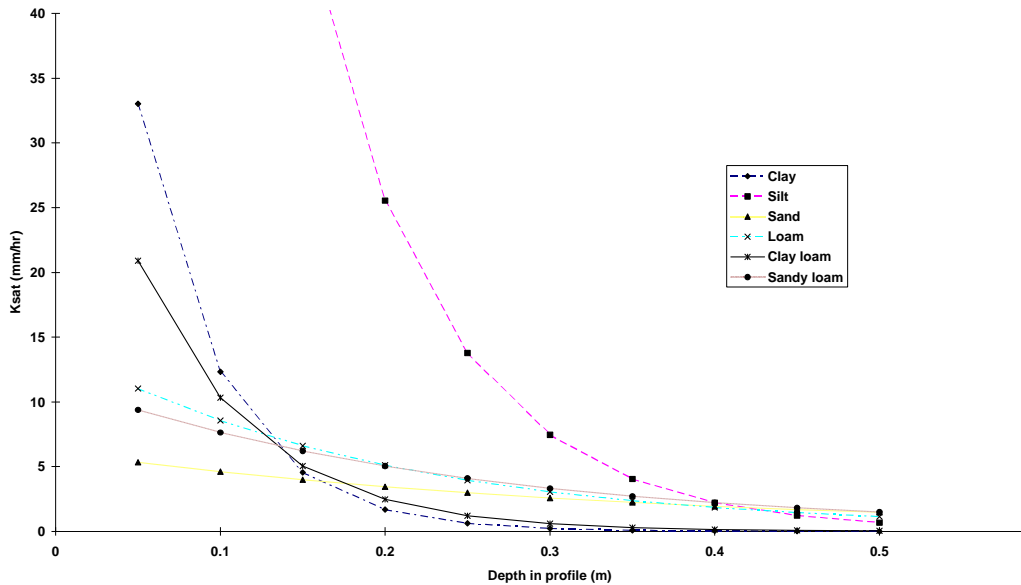


Figure 7 The profile distribution of hydraulic conductivity for different soil types as a function of increasing bulk density with depth.

The new infiltration model applied for PATTERN^{LITE} is based on this data alone and is thus applicable over regional areas with a simple understanding of the variability in texture, soil depth and stone content, all of which are modelled from basic data (see page 29). The instantaneous rate of infiltration at a given time is calculated as the saturated hydraulic conductivity at the wetting front.

Soil bulk density at the wetting front is calculated from the generic relationship:

$$BD_{wf} = (b \cdot dep_{wf}) + a$$

Equation 2

Where:

BD_{wf} = bulk density at the wetting front (g/cm³)

Dep_{wf} = depth of the wetting front (metres)

a, b = regression parameters

where soil rock fragment contents are low. Where the soil is clast supported ($R_m > 0.5$) the bulk density at the wetting front is calculated from Equation 1 and macropore infiltration will be included.

Saturated hydraulic conductivity at the wetting front is calculated from the PTF of Campbell (1985):

$$K_{swf} = 4^{-3} \times 1.3 / BD_{wf}^{1.3b} \times e^{-6.9 \times Clay - 3.7 \times Sand} \times 35280$$

Equation 3

where

K_{swf} = saturated hydraulic conductivity at the wetting front (mm/hr),

b = soils bvalue (calculated as a function of texture),

Clay = fractional content of clay sized particles,

Sand = fractional content of sand sized particles.

As the wetting front travels through the soil profile it slows because of increasing bulk density or reduced porosity (because of higher stone contents) to produce the characteristic ponded infiltration curve observed in the literature (Horton, 1933; Philip, 1957; Scoging and Thornes, 1979).

Overland flow

Overland flow in PATTERN^{LITE} is simplified since it does not incorporate a detention storage component. Overland flow is calculated essentially as the difference between the instantaneous rate of infiltration plus runoff from upslope cells and the instantaneous rate of infiltration at the surface as dictated by the rate of advance of the wetting front. Runoff occurs when rainfall or runoff intensity exceeds the rate of infiltration (Hortonian overland flow) or when the rate of infiltration approaches an asymptote at high soil moisture levels when the rate of infiltration is limited by the rate of recharge (saturated overland flow). The mechanics of routing overland flow across the landscape had also to be included and are discussed on page 34.

Evapotranspiration

Evapotranspiration in the PATTERN model is a complex set of equations which requires data on plant physiological and canopy characteristics, wind speed and atmospheric humidity. Such requirements are not feasible within the context of the MODULUS DSS. Evapotranspiration can be simplified as depending on three factors (a) the supply of energy to drive the process, (b) the supply of water for evaporation and (c) the atmospheric demand for water. With these major controls in mind a new evapotranspiration scheme has been developed for PATTERN^{LITE}. PATTERN^{LITE} first calculates the energy limited evapotranspiration :

$$E_{pot} = R_n / \lambda$$

Equation 4

Where

E_{pot} = potential evaporation (mm)

R_n = net radiation (MJ)

λ = latent heat of vaporisation of water (MJ/Kg)

This is then corrected for water availability on the surface of the vegetation (intercepted water), from the stomata (transpired water) and directly from the soil subsurface (soil evaporation) on the basis of their relative surface areas. The transpiration fraction is calculated as:

$$E_t = \theta \times (1 - C_s / C_c)$$

Equation 5

Where

E_t = transpiration fraction,

θ = soil moisture (m³ water/m³ soil),

C_s = canopy storage of intercepted water (mm),

C_c = canopy storage capacity for intercepted water (mm).

In this equation, the resistance to transpiration is simplified from the SVAT equations of PATTERN to a simple multiplier so that actual transpiration is linearly proportional to soil moisture. The canopy interception loss fraction is calculated as:

$$E_i = C_s / C_c$$

Equation 6

The soil evaporation fraction, E_s is given by :

$$E_s = \theta$$

Equation 7

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Total evapotranspiration is the sum of E_t , E_i and E_s weighted by the surface area available for evaporation from each source :

$$ET = E_{pot} \times [(1 - V_c) \times \theta] + [V_c \times LAI \times E_t] + [V_c \times LAI \times E_i]$$

Equation 8

Where

V_c = plant cover (fractional)

LAI = leaf area index (m^2 leaf/ m^2 ground)

This produces a dynamic allocation of evapotranspiration to the different sources of water depending upon the energy available, the surface area for evaporation of the different sources and a resistance term for the non-free water sources. In the next phase of work the model will be adapted to cope with a temperature dependent atmospheric demand for water.

Recharge

Recharge is similar in complexity in PATTERN^{LITE} as in PATTERN. In PATTERN^{LITE} recharge is calculated to occur at the hydraulic conductivity of the soil-rock interface. Geology's are either termed permeable or impermeable. In a permeable geology the rate of recharge is soil limited, in an impermeable geology, the rate of recharge is geology limited (according to the transmissivity value for the geology concerned). Recharge is calculated after Campbell (1985):

$$R = K_{sb} \times \theta^{2b+3}$$

Equation 9

K_{sb} = saturated hydraulic conductivity of the soil at the soil-bedrock boundary (mm/hr),

b = soil b-value.

This is corrected for soil stone content as :

$$R_s = R \times (1 - R_m)$$

Equation 10

where

R_s = Recharge with stone effect (mm/hr).

Plant processes

Biomass production

The most realistic manner in which plant growth can be modelled for a number of different functional types at 100m resolution across a region is through a simplified version of the production efficiency type model used in PATTERN. A production efficiency model simulates growth according to the efficiency of the conversion of energy in the photosynthetically active region to biomass (Monteith, 1977; Prince, 1991; Prince et al., 1994). In order to implement this type of equation one must first simulate the interception of photosynthetically active radiation by a plant canopy according to Beer's Law.

$$I_{par} = 0.95 \times [1 - e^{-0.7 LAI}] \times PAR$$

Equation 11

Where

I_{par} = intercepted photosynthetically active radiation (MJ)

PAR = incident photosynthetically active radiation.

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This is converted to growth through multiplication with the water stress mediated radiation use efficiency for the cover type

$$G = \varepsilon \times \theta \times I_{par} \times 0.8$$

Equation 12

Where

G = growth (g dry weight)

ε = radiation use efficiency (g/MJ)

The impact of growth respiration reduces net growth by around 20% (Penning de Vries and van Laar, 1982) hence the multiplication by 0.8. The standing plant biomass, of which yield is a proportion represents the balance between growth and maintenance respiration. Maintenance respiration is temperature dependent and can be calculated as :

$$M = 0.015 \times [(Ta - 15) / 10]^{1.5}$$

Equation 13

Where

M= maintenance respiration (g/g biomass/day)

Ta = air temperature (C)

Allocation of assimilate

Assimilate is allocated between plant parts according to demand. The PATTERN model has a complex system of allocation equations but in PATTERN^{LITE} only the key control on allocation is considered. Assimilate is *either* allocated to roots or allocated to leaves and fruits. Allocation to roots increases with water stress at the expense of leaves - the represents a water resource conservation strategy which is widely observed in the literature (Gregory et al., 1962; Gardner, 1964; Fawkes and Landsberg, 1981; Kummerow et al., 1977; Karrou and Maranville, 1984; Rambal, 1984; Kummerow, 1986; Caldwell, 1986; Shigenori et al., 1994;). In this way leaf biomass is calculated as the allocation weighted growth minus rge maintenance respiration for roots, shoots and reproductive biomass separately.

$$Bl_t = Bl_{t-1} + [\theta \times G] - [M \times Bl_{t-1}]$$

Equation 14

Where

Bl = leaf biomass (kg dry weight)

$$Br_t = Br_{t-1} + [1 - \theta \times G] - [M \times Br_{t-1}]$$

Equation 15

Where

Br = root biomass (kg dry weight)

Plant structural properties

Plant structural properties are essential for understanding the dynamics of radiation interception but also for understanding the hydrological impact of plants. Whilst PATTERN calculates a number of structural properties, the most significant are leaf area index (LAI) and vegetation cover. These are calculated from leaf biomass according to the following equations:

$$LAI = Bl / lsd$$

Equation 16

Where

Lsd = leaf specific density (g/m²)

Plants are assumed to grow outwards and then upwards (Mulligan, 1996) so that vegetation cover is equal to the LAI when LAI<1 and is equal to 1 when LAI>1.

Yield and plant phenology

Plant yield is an important parameter for understanding the profitability of particular land uses. Yield or reproductive biomass will be calculated as a fraction of leaf biomass depending on plant phenology and resources. This will be implemented in the next months.

Incorporation of new functionality

Various *new* functionality, not present in the PATTERN model is required for the implementation of PATTERN^{LITE} within the MODULUS DSS. These are described briefly below.

GCM Scenarios

One of the key uses of the MODULUS DSS will be as a tool to help understand the implication of future climate change on the hydrology, water resources and crop productivity within a region. In order to achieve this, as well as 30 year series of past temperature and rainfall data, scenarios for future temperature and rainfall must also be generated. Rather than take crude figures for rainfall and temperature deviation from the present at some time in the future, it was decided that the approach most suited to the dynamic nature of the MODULUS DSS would be to obtain and downscale the results of general circulation models of the atmosphere (GCMs). The latest Greenhouse-sulphate transient integrations of three GCMs, HADCM2, GFDL and ECHAM were used.

HADCM2 is the latest release of the UK Hadley Centre coupled ocean atmosphere general circulation model. ECHAM(T42) is a synthesis of the ECMWF atmosphere model and a comprehensive parameterisation package developed at Hamburg. GFDL is the Geophysical Fluid Dynamics Laboratory model. The attributes of the 3 GCMs and the greenhouse sulphate experiments are described in Table 5.

Model	spatial resolution	Output used	Scenario	Reference
HADCM2	2.5 deg. latitude	Monthly average rainfall (mm/day)	Historic CO ₂ 1860-1989, 1 % compound increase 1990-2099 (higher than IS92a), additionally historic SO ₄ 1860-1989, IS92d 1990 - 2099	Cullen (1993)
	by 3.75 deg. longitude	Monthly average temperature (K)		
ECHAM (T42)	2.81 deg. latitude	Monthly average rainfall (mm/day)	Historic CO ₂ 1860 - 1989, IS92a 1990-2049; additionally historic SO ₄ 1860-1989, IS92a 1990 - 2049	DKRZ-Model User Support Group(1992)
	by 2.81 deg. longitude	Monthly average temperature (K)		
GFDL	4.5 deg. latitude	Monthly average rainfall (mm/day)	Historic CO ₂ 1765-1990, 1% compound increase 1990-2065; additionally historic SO ₄ 1766-1990, IS92a 1990-2049	Haywood and Ramaswamy (1998)
	by 7.5 deg. longitude	Monthly average rainfall (mm/day)		
		Monthly average temperature (K)		

Table 5 Attributes of the GCMs and climate forcing scenarios implemented.

Because of the very large grid size of all GCMs, the representation of regional climate is poor. For this reason an involved process of downscaling and calibration of the model results are required in order to produce the scenarios required. The downscaling method used here involved (a) extracting the grid data (b) referencing the grid data from the grid altitude of the GCM to the altitude of the reference ground station (c) the production of a calibration parameter based on comparison of model results for an extended period with data for the same parameter from a ground station, (d) correction of the GCM output using the results of the calibration period.

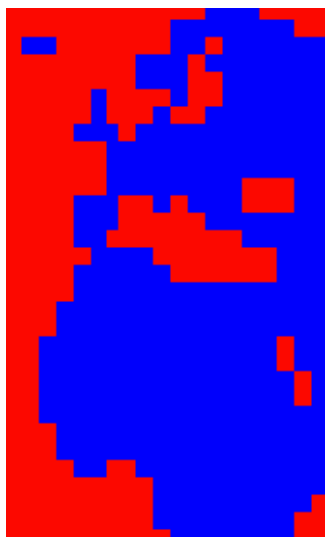


Figure 8 Grid cells of the HADCM2 General Circulation Model. Data courtesy of HADLEY Centre for Climate Prediction, UK Meteorological Office.

Figure 8 shows the grid size of the HADCM2 model, during the downscaling process the data for cells representing Greece and south-east Spain were extracted. The temperature and rainfall data from these cells is reasonable in form and pattern when compared with the ground data even if the actual values produced by the model are somewhat under or overestimated. The fact that all the GCMs reproduced the key features of the Mediterranean climate is encouraging. Since we are only interested in climate change from the present day, it is reasonable to assume that the model results can be calibrated to current or recent climatic norms for the regions. In this way the model results are downscaled from a large area average to a value representative of the climate base station to which all of the climatic regionalisation in the area is referenced (see page 26).

Though rainfall and temperature were the only variables used from the GCM output, all other variables, in particular solar radiation were checked for stationarity for the grid cells used. Clearly in our implementation of solar radiation in MODULUS, the background solar radiation cannot change except for through rainfall induced changes in atmospheric transmissivity. The change in solar radiation input simulated by the GCMs ranged from $-0.0012 \text{ W/m}^2/\text{month}$ for HADCM2, SE Spain to $-0.0033 \text{ W/m}^2/\text{month}$. These represent a maximum change of -7.2 W/m^2 from 1860-2049. This is, rather surprisingly a reduction in radiation rather than an increase and may be due to increased cloud cover in the region (which should be reflected in the MODULUS DSS through the rainfall change) or the overriding impacts of atmospheric sulphates compared with greenhouse gases at these latitudes. In either case this amount is not very within the context of MODULUS. Climate scenarios will therefore be based on rainfall and temperature change only.

In general terms rainfall shows little change under the various greenhouse sulphate scenarios whilst temperature shows quite significant changes. The downscaled (*i.e* directly comparable with the base station) results of the various models are summarised in Table 6.

Region	Model and scenario	Rainfall change (mm/month)	Rainfall change (total from 1998, mm)	Temperature change (°C per month)	Temperature change (total, from 1998, °C)
Argolid	HADCM2gs	-0.0084	-10.18 (2099)	+0.0034	+4.12(2099)
Argolid	ECHAMgs	-0.0022	-1.35(2049)	+0.0016	+0.97 (2049)
Argolid	GFDLgs	-0.0029	-2.12 (2059)	+0.0049	+3.58 (2059)
Marina Baixa	HADCM2gs	+0.0003	+0.37 (2099)	**	**
Marina Baixa	ECHAMgs	+0.0006	+0.36 (2049)	**	**
Marina Baixa	GFDLgs	-0.0002	-0.1464 (2059)	**	**

Table 6 Downscaled climate change scenarios for the Argolid and Marina Baixa. The figures in brackets represent the year by which the change is achieved. ** = data not yet available.

For the Argolid temperature is expected to change a minimum of $+0.97^\circ\text{C}$ between 1998 and 2049 and a maximum of $+4.12$ between 1998 and 2099. This represents a very significant change as is clear

from Figure 9. Rainfall in the Argolid also shows a significant change across all of the scenarios with a maximum reduction of rainfall of 10mm/month between 1998 and 2099. The minimum reduction between 1998 and 2049 is around 1.4 mm/month. All of the GCMs show a decrease in rainfall with most of the decline occurring after 2050 (Figure 10). It is also clear from Figure 10 that the very high inter-annual variability of rainfall for the Argolid is underestimated in most of the models with the exception of ECHAM.

Though the downscaling of temperature for Marina Baixa awaits the arrival of historic temperature, the downscaled rainfall scenarios for this area show a much less significant change. In fact, both HADCM2 and ECHAM show a slight increase in rainfall of +0.37 mm/month between 1998 and 2099 for HADCM2 and +0.36 mm/month between 1998 and 2049 for ECHAM. GFDL is the only model which shows a rainfall decline for the region and this is only of the order of 0.14 mm/month between 1998 and 2059. In terms of climate change it appears that the Argolid will see much more serious consequences than Marina Baixa.

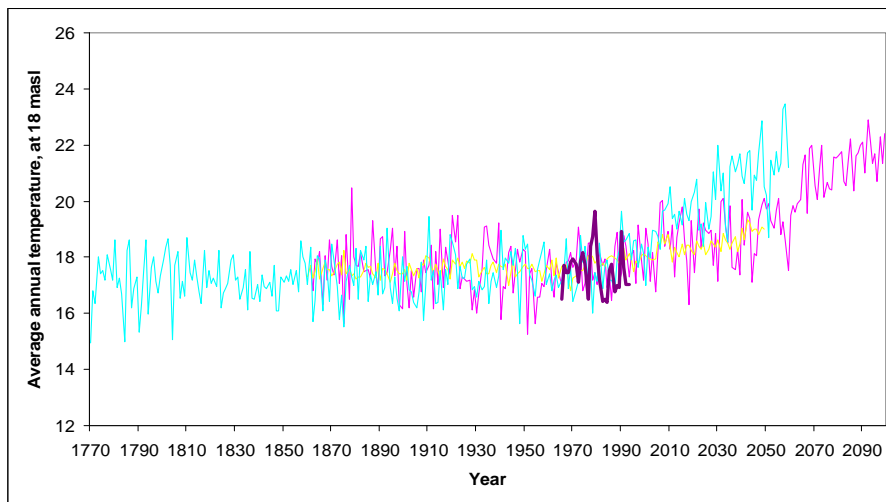


Figure 9 Change in annual average temperature downscaled for the Argolid (sea level). HADCM2gs is represented in pink, GFDLs in blue and ECHAM in yellow. The historic record for Skafidaki is shown in purple.

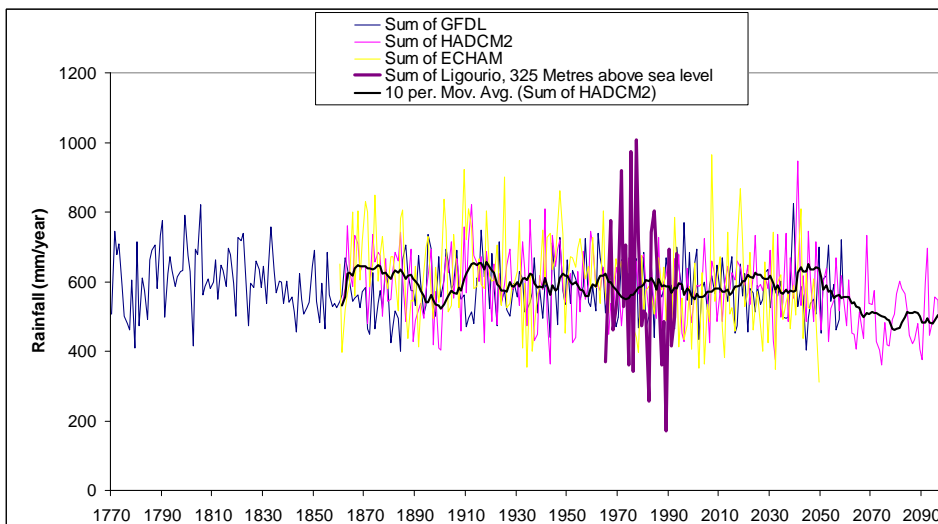


Figure 10 Change in annual total rainfall downscaled for the Argolid (325m above sea level). HADCM2gs is represented in pink, GFDLs in blue and ECHAM in yellow. The historic record for Ligourio is shown in purple.

Generating daily rainfall from monthly totals

In order to make use of these scenarios for change in the MODULUS DSS the monthly output of the GCMs must be converted to daily total rainfall for the storm generator and daily minimum and average, minimum and maximum temperature for the evapotranspiration, frost and plant growth models. This is achieved through the development of further new functionality. To date only the monthly-daily rainfall generator is complete. The temperature generators will be discussed in the final report.

Description of the Rainfall in the Argolid

The characteristics of the rainfall in the Argolid are described in Table 7 and in Figure 11. From the probability distribution, it can be seen that there is an exponential decrease in the probability of occurrence as storm size increases, in other word most days have very low rainfall. The temporal autocorrelation (Figure 12) in the time series is significant over a lag of one day (at the 95% confidence limit), in other words rainfall is highly associated in time.

Property	Measured
Percentage of Raindays	17.1%
Average Daily Rainfall (mm)	1.29
Skew	7.462
Variance	25.362

Table 7 Characteristics of rainfall in the Argolid.

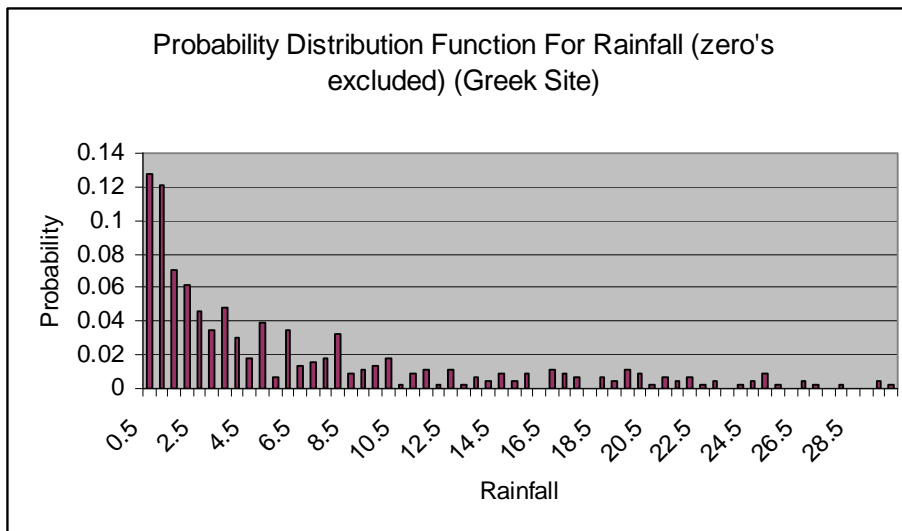


Figure 11 PDF for daily rainfall for the Argolid.

An understanding of these characteristics assists in the development of models to generate daily rainfall on the basis of monthly totals. The important characteristics of the rainfall (daily total, storm size and duration of dry periods) must be replicated by such as model in order to correctly simulate the hydrological characteristics of the climate

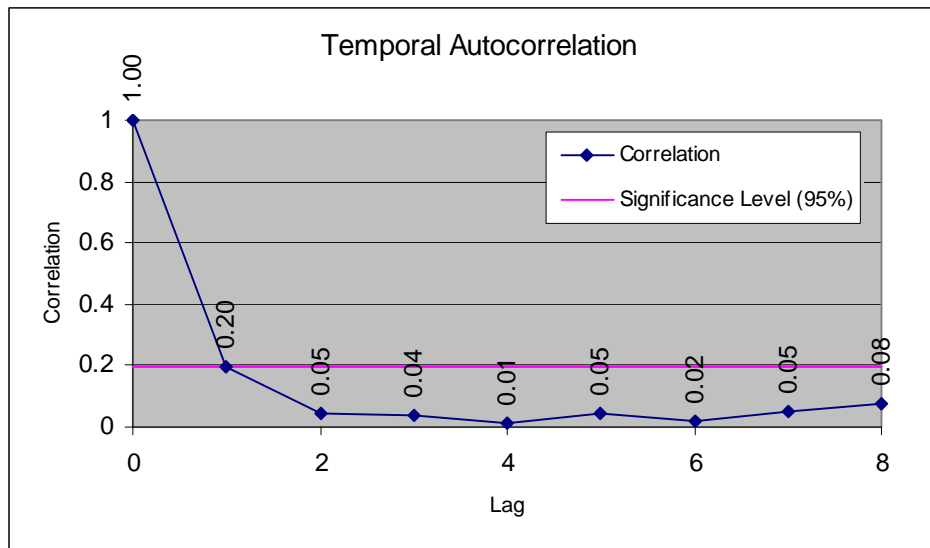


Figure 12 Temporal autocorrelation for daily rainfall in the Argolid.

There are a number of ways of generating daily rainfall series from monthly totals. Perhaps the simplest and most robust are the Monte Carlo, Markov chain methods and sequence based models. These will be discussed further here.

Monte Carlo Models

A Monte Carlo model is the simplest method of simulating rainfall with a known distribution. The model stochastically selects daily rainfall values from a measured probability distribution. Each day is taken to be independent of the previous. The model requires historic daily rainfall observations from which to calculate the probability distribution function. This record does not have to be complete, as long as the gaps not associated with the rainfall. The problem with this kind of model is that we already know that rainfall is highly temporally autocorrelated and a simple Monte Carlo does not replicate this important feature.

Markov Models

Markov chains have been used by many workers for the stochastic modelling of daily rainfall (e.g. Gabriel and Neumann 1962 cited Gregory *et al* 1993, Gregory *et al* 1993). Each day is described by its state, for example the state of the day could either be wet or dry. The change from one state to another is determined stochastically by transition probabilities. The series of states is called a Markov Chain. The two main properties of the chain are its number of states (n) and its order (k). The transition probabilities are determined by the state of the chain on previous days, for example, they determine the probability of rainfall occurring given that it rained on the previous day. The order of the chain is the number of previous days which are considered to determine the transition probability, if only the previous day is considered, then the chain is a first order chain. In order to calculate the transition probabilities, a continuous data series is required since sets of days are considered. Gaps in the series would greatly reduce the number of sets. When the chain is in a state where it rains, the amount of rainfall is determined by a Monte Carlo model.

Three Markov chain models have been developed. There are two first order models one with two states (wet and dry) and one with five states (dry, light rain, moderate, heavy and extreme¹), and a second order two-state model with the states being either wet or dry.

¹ Dry = 0-mm, Light rain = 0.5 – 2-mm; Moderate = 2.5 – 10-mm; Heavy = 10.5-40-mm; and extreme > 40-mm

Sequence Based Model

This model simulates the time series by creating runs of dry and wet days, this being the same approach employed in the LARS-WG model (Racsko *et al.* 1991). To generate the rainfall amount on wet days it uses a Monte Carlo model. Racsko *et al.* (1991) found that this approach overcame the ‘limited memory’ of models based on Markov chains.

Parameterisation of the models

To assess the sensitivity of the models to differing amounts of parameterisation data, the input parameters were calculated for two of the above models. The Monte Carlo model and the five state, first order Markov model were chosen since they represent the range of model complexity. A fifty-year time series of daily rainfall from central Spain (the longest record available at the time) was divided into periods of one, two, four, eight, sixteen, thirty-two and fifty years. A starting year was chosen at random (1966), the range of years was then extended both forwards and backwards from this year to give the necessary datasets. The analysis showed that a Monte Carlo model requires a minimum of between eight and sixteen years of data for an accurate parameterisation. The most important parameters for the five state Markov model are the transition probabilities. The most sensitive state to the amount of parameterisation data is the fifth state which simulates extreme raindays. For the central Spain record, days in this state constitute only 0.22% of the record.

The transition probabilities were calculated for the same sets of years as above and then the percentage deviations from the fifty-year values were produced. Using only one year of data, for rainfall values less than 40-mm (the lower four states) the largest error was 12.14% for the transition from state one (light rain) to state zero (no rain). This error falls to below 2.5% (2.05%) when thirty-two years of data have been used. For the fifth state, the percentage deviation only falls to 4.4% when thirty-two years have been used. Therefore, to calculate the transition probabilities for the first four states to within 97.5% of the fifty-year total and the fifth to within 95%, thirty-two years of data are required.

Assessment of Model Performance

By examining the statistical properties of the time-series generated by these models and comparing them with those of the measured series, the model’s performance can be assessed. The characteristics considered were the percentage of raindays, the average rainfall per day, the variance and skew of the time series and the temporal autocorrelation of daily rainfall. All of the models were parameterised using six years of daily rainfall from the Argolid.. The models were then run for 2,500 days (6.85 years) and the statistical characteristics of the time series examined, as summarised in Table 8.

Property	Measured	Monte Carlo	Sequence Based	Markov k1, n2	Markov k1, n5	Markov k2, n2
Percentage of Raindays	17.1%	11.8%	26.4%	37.9%	29.9%	32.4%
Average Daily Rainfall (mm)	1.29 (1.15)	0.708	0.309	0.35	2.665 (2.062)	0.353
Skew	7.462 (4.393)	5.905	9.244	9.128	3.847 (3.222)	10.154
Variance	25.362 (12.876)	9.435	1.832	5.638	50.554 (26.953)	2.175

Table 8 Statistical Characteristics of Model Output. K=order.

The model that came closest to simulating the statistical properties of the measured series was the Monte Carlo model. Overall the model gives less rainfall than the observed series, as can be seen in the percentage of raindays and the average daily rainfall. The variance is too low, although this may be improved upon by the use of a greater range of rainfall totals. The sequence-based model generates many more raindays than the measured series, each with only a small amount of rainfall, hence the low average daily rainfall, the high positive skew value and the very low variance value. All of the Markov model overestimates the number of raindays, suggesting that the transition probabilities from dry to wet days are lower than they should be. The two-state models both underestimate the average daily rainfall, again leading to high positive skew values. The five-state model generates an average daily rainfall that is twice the measured value. This model does create a high variance value which none of the other model do, it is however twice the measured value (generated and adjusted).

The rainfall generator applied.

The rainfall generator used for the MODULUS DSS is a Monte Carlo simulation. The model was applied to a long term central Spanish dataset and replicated the rainfall properties well (Table 9).

Test	Measured	Modelled
Average Daily Rainfall	1.735	1.679
Percentage raindays	0.194	0.156
Variance	29.485	24.498
Temporal Autocorrelation (lag of one day)	0.233	0.066

Table 9 Statistical properties of measured and modelled daily rainfall.

The model was then applied to a shorter term dataset for the Argolid and, as shown in Table 10, most characteristics of the measured dataset are generated. The model generates the same amount of rainfall but on fewer days. The skew shows that this has been done with fewer smaller storms. The temporal autocorrelation has been recreated due to the reason mentioned above.

Test	Measured	Modelled
Average Daily Rainfall	1.3	1.3
Percentage raindays	16.16 %	13.42 %
Variance	26.297	19.803
Skew	6.149	3.818
Temporal Autocorrelation (lag of one day)	0.123	0.2697

Table 10 Agreement between measured and modelled properties of daily rainfall for the Argolid dataset.

The process of rainfall generation is outlined in graphical form in the appendix.

Interception

The process of interception of rainfall by vegetation with subsequent changes to the hydrological pathway was not part of PATTERN because this process is of little significance at the hillslope scale. At the regional scale it is much more significant, since large volumes of water can be lost to evaporation where the canopy is wet. In addition a partially wet canopy impedes transpiration (and photosynthesis to some degree). Interception must therefore be incorporated into PATTERN^{LITE}. The simplest model possible has been developed. Interception is assumed to occur until the canopy storage capacity for water is filled. This capacity is the amount of water held on the canopy and lost only to evaporation. It is measured per unit leaf area and thus scaled according to vegetation cover and LAI in order to obtain canopy storage capacity.

$$C_c = SWR \times V_c \times LAI$$

Equation 17

Where

SWR = specific water retention (mm/m² leaf)

Canopy storage is incremented in each timestep according to the canopy storage available.

$$Rf < (C_c - C_s)$$

$$C_{s_t} = C_{s_{t-1}} + Rf$$

$$Rf^i = 0$$

Equation 18

$$Rf > (C_c - C_s)$$

$$C_{s_t} = C_{s_{t-1}} + (C_c - C_s)$$

$$Rf^i = Rf - (C_c - C_s)$$

Equation 19

where

Rf = rainfall (mm)

The canopy storage is depleted by evaporation only (as discussed on page 15). Canopy drainage is implicit in the fact that the measured SWR included water that can be removed by evaporation only.

Soil Erosion

The PATTERN model does not incorporate the process of soil erosion. Again, at the hillslope scale this is not a significant control or impact. At the regional scale the consequences of soil erosion can be much more significant. The process is, therefore, included here. A number of models of erosion are available from the simple empirical (Elwell and Stocking, 1976; Rogers and Schumm, 1985; Diaz et al., 1992) through to complex multifactorial models (Kirkby and Neale, 1985; Williams et al., 1989). The model applied here lies in between these two extremes. It is based on the model of Thornes (1990) and Thornes and Brandt (1993) and is a simple but physically based representation of the processes of wash erosion. The model calculates the erosion on the basis of slope, extracted from the DEM, overland flow calculated in the hydrology model and the vegetation cover. The model equation is :

$$E = kQ^m S^n e^{-0.07Vc}$$

Equation 20

Where

E = Erosion (mm/hour)

K = soil erodability (a function of texture and organic matter)

Q = overland flow (mm/hour)

m,n= empirical constants

Vc = vegetation cover.

Because wash erosion is determined primarily and non-linearly by overland flow, which is an infrequent and intense occurrence in Mediterranean environments, the erosion model has to be integrated at the bucket-tip timestep to avoid averaging errors.

Data Requirements for PATTERN^{LITE}

One of the key requirements of the MODULUS DSS is that the models require as little specialist data as possible. In order to achieve this the KCL group have combined the assimilation, harmonisation and rationalisation of existing datasets with innovative generation techniques for improving the quality of crude data or proxy variables. The data required for PATTERN^{LITE} is summarised in Table 11. The model obtains all other parameters required for the equation outlined in the previous sections by generation from this data or from lookup tables of data provided with the model.

PATTERN^{LITE} DATA

Meteorology

monthly or daily precipitation record (many stations, user defined period)

monthly or temperature record (many stations, user defined period)

1 year automatic weather station record in same climate zone (within 300km)

 tipping bucket rainfall

 hourly, or daily max and min air temperature

 solar and net radiation (if available)

Scenarios for climatic change for GCM grid cell which the region belongs to

 precipitation

 temperature

Landscape

Digital Elevation Model (100m resolution)

Digitized Geology Map (lookup of rock properties provided in the DSS)

Digitized Soil Map (if available, lookup of soil properties provided in the DSS)

Vegetation

CORINE land cover (100m resolution, lookup of vegetation properties provided in the DSS)

Land management information for particular cover types

 Ploughing

 Stone removal

 Sow date

 Harvest date

 Irrigation

 Terracing

Table 11 Data requirements for PATTERN^{LITE}

Spatialisation of data

Much of the data required by the various models is not available in a spatial form especially at the 100m scale. This section outlined some of the techniques performed to generate model parameters at the 100m scale from this kind of data. Spatialisation of the main model parameters is essential if (a) the model is to accurately re-produce the spatial variability of the environment and (b) the value of using a spatial model (as opposed to a lumped model) is to be realised.

The 100m grid and tiles

Though the model cellsize has been set at 100m as a compromise between data availability, accuracy, runtime and the level of data required by the end user, some processes have to be represented at a subgrid scale. In order to achieve this the tile model concept is used. The tile concept represents the growth or recession of a property in terms of its fractional surface area within the grid with no reference to the spatial pattern of the same property. For example vegetation cover and soil compete for space upon the tile as the vegetation cover grows. The fractional area occupied by each is used in the partitioning of transpiration and soil evaporation. The main cover types permitted for the subgrid tiles of MODULUS hydrology are (a) vegetation [leaves], (b) bare soil and (c) surface stones. Within the vegetation category the surface is tiled to represent the area of leaves covered by intercepted water.

The calculation of evaporation using this tile concept is outlined on page 15.

Temperature

Air temperature is one of the easiest variables to spatialise. It is basically a function of altitude with some correction for local topographic conditions and continentality. Monthly temperature data for 1971-1980 from six stations in the Argolid were used. The stations vary in altitude from 31 masl to 474 masl. The relationship between temperature and altitude is shown Figure 13.

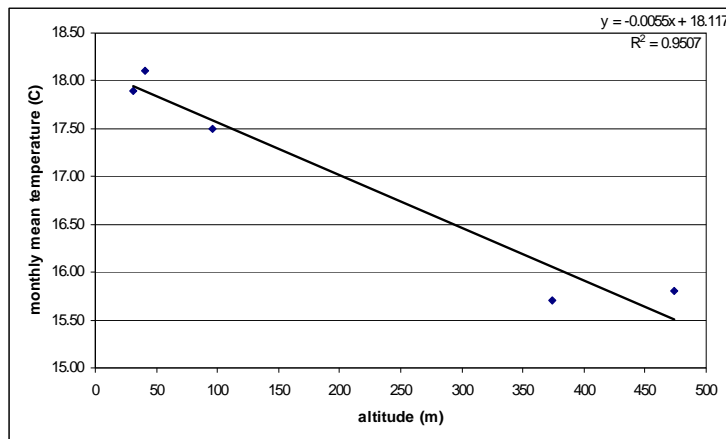


Figure 13 Relationship between temperature and altitude for the Argolid.

The gradient of this line (0.0055 °C/m) is very close to the theoretical adiabatic lapse rate of 0.006 °C/m (Holdridge, 1947) and the relationship is of sufficient quality in order to regionalise the temperature data. The theoretical value of 0.006°C per metre will be used because the value obtained here also incorporates the effects of local topographic factors. These effects are taken into account separately by correcting all of the station temperature data to sea level and observing the long term average differences between the stations. This gives us a series of correction factors which isolate the local effects measured at each station. These correction factors are applied across a thiesen polygon network. Skafidaki (649116, 4159107 UTM, 40.8 masl) has the most complete temperature record and is used as the base station for historic simulations and for calibration of GCM data. Data for all other pixels is regionalised by first applying the altitudinal correction shown in Figure 13 according to the DEM (Figure 14), and then applying the regional temperature correction (Table 12) based on the thiesen polygons (see Figure 17 and Figure 19). Irrespective of altitude there is a difference of over 1°C between stations as a result of other climatic factors. For the GCM data, altitudinal correction is applied according to the altitude value for the GCM grid cell used. The spatial differences in temperature for the Argolid are clearly very strong.

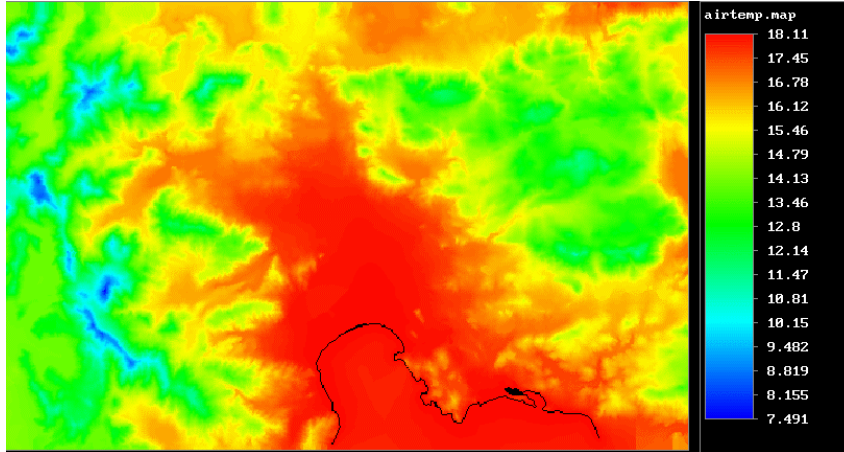


Figure 14 Spatial variability in air temperature for the Argolid based on altitudinal correction (average 1971-1980)

Station	Ag. Triata	Achladokabos	Fichtia	Merkouri	Nafplio	Skafidaki
Average temperature (1971-1980)	18.04	18.63	18.05	17.91	17.41	18.30
Correction factor	0.98	1.01	0.98	0.97	0.84	1

Table 12 Thiessen temperature correction factors for stations.

Temperature data is not yet available for Marina Baixa.

Rainfall

It is also important that rainfall is properly regionalised. Rainfall stations are as few as temperature stations yet the spatial variability of rainfall is also high. Regional hydrological models can be orders of magnitude in error if single station values are averaged over the whole area and account is not taken of rainfall variability over space. Rainfall data for eleven stations (1965-1994) in the Argolid were analysed. Figure 15 shows that there is a good relationship between rainfall and altitude with local residuals resulting from topographic (e.g rainshadow) or other effects. Since some of these deviations are significant the same approach as adopted for temperature will be used here. In other words, rainfall is distributed on the first hand through the altitudinal relationship with the DEM and then corrected by a correction factor that accounts for the local residual, according to a thiessen representation of rainfall zones. Altitudinally corrected rainfall for the Argolid is shown in Figure 16.

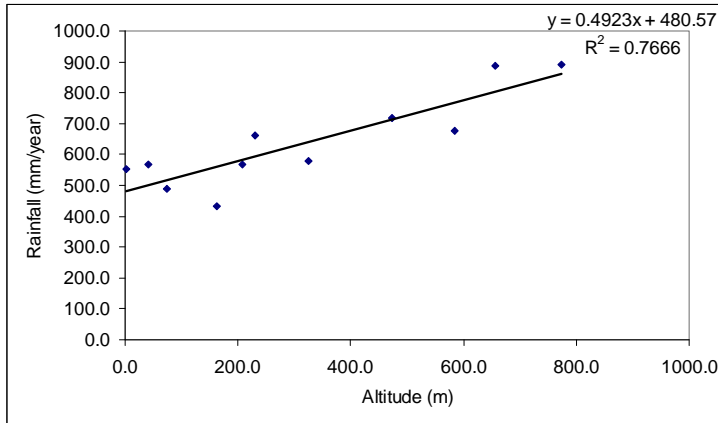


Figure 15 The relationship between rainfall and altitude for the Argolid.

The altitudinally corrected rainfall image is shown in Figure 16. Though large parts of the catchment show an annual total rainfall of less than 600mm, small parts of the catchment provide inputs of greater than 1200 mm/year. The correction factors applied to the Thiessen regions are shown in Table 13.

Station	Sterna	Kefalovriso	Arachneo	Ligourio	Karia	Skafidaki	Kiveri	Acladokabos	Neo Roino	Assini	Amigdalitsa
Average (1965-1994)	568.5	892.2	676.2	578.7	888.4	567.5	551.0	717.6	434.0	489.7	661.6
Regression - value	583.0	861.6	768.1	640.6	803.3	500.7	481.5	713.8	560.9	517.5	594.3
Thiessen correction factor	0.975	1.035	0.880	0.903	1.106	1.133	1.145	1.005	0.774	0.946	1.113

Table 13 Thiessen rainfall correction factors for the Argolid.

The Thiessen polygons for the Argolid are shown in Figure 17.

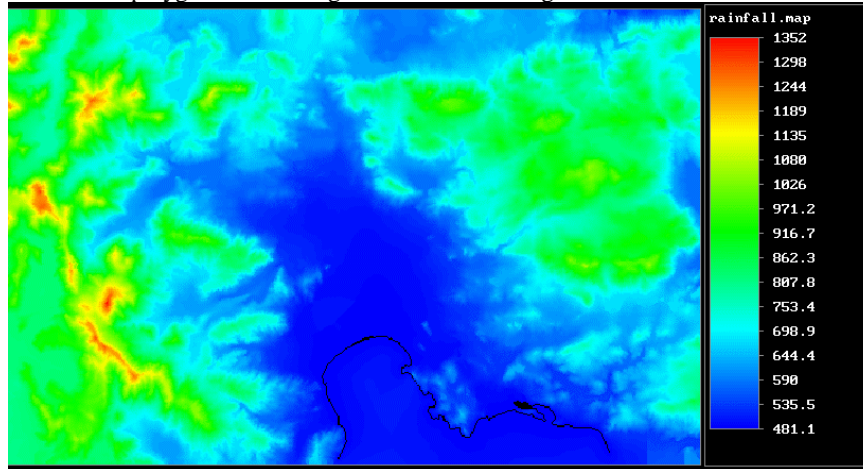


Figure 16 Spatial variability in precipitation (mm/year) for the Argolid based on altitudinal correction (average 1965-1994).

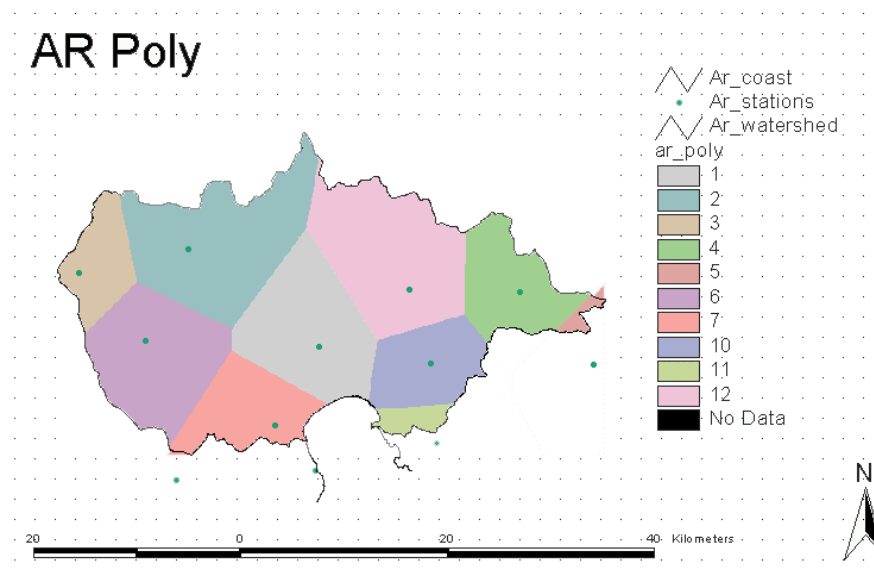


Figure 17 Rainfall Thiessen polygons for the Argolid.

For Marina Baixa the relationship between rainfall and altitude is much less clear. This may be in part due to the paucity of stations for which data is available but also reflects a different meso-climatic situation than is present in the Argolid, in particular, the dominance of convective rainfall. The relationship described in Figure 18 is not of significance and thus cannot be used for regionalisation. Regionalisation for Marina Baixa will be achieved on the basis of Thiessen correction

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alone. The Thiessen correction factors for Marina Baixa are shown in Table 14. Station 8034 (Sella, LATLON 38° 36' 30", 00° 16' 17.2', 419 masl) has the best historic record and is used as the base station for Thiessen correction for histroc and GCM rainfall data.

Station name	Relleu	Embalse de Amadorio	Sella Altea	Tarbena C H Jucar	Bolulla	Callosa de Ensarria
Station No.	8033a	8033e	8034 8038	8039a	8040	8041a
Correction factor	0.867	0.736	1 1.02	1.937	1.536	1.299

Table 14 Thiessen correction factors for Marina Baixa.

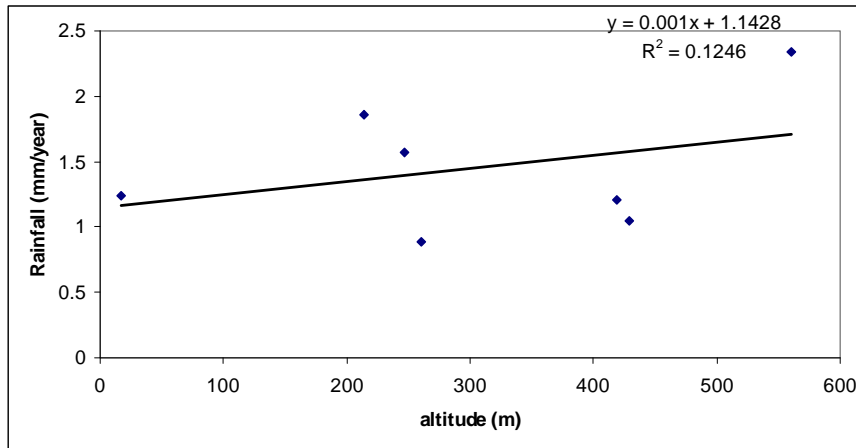


Figure 18 The relationship between rainfall and altitude for Marina Baixa.

The Thiessen polygons for Marina Baixa are shown in Figure 19.

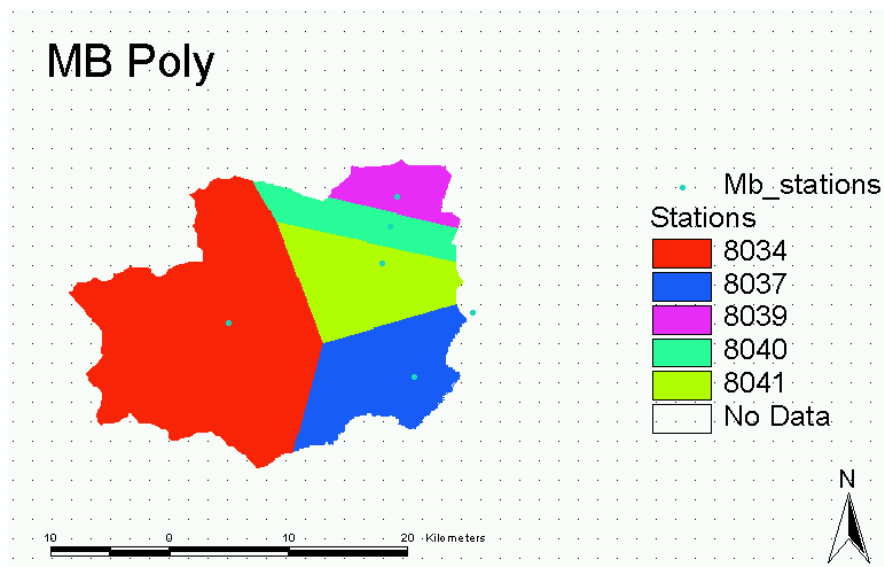


Figure 19 Thiessen polygons for Marina Baixa rainfall.

Modelling soil hydraulic properties from geological data

At a regional scale the kind of soil data available for PATTERN at the hillslope scale would clearly not be available. To overcome this deficiency the hydrological equations were simplified and methods

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were developed to generate hydraulic properties of soils from a knowledge of readily available parameters such as soil texture. Parameters such as bulk density and stone content are modelled on the basis of landscape properties derived from the digital elevation model. The key soil parameters required for accurate simulation of soil and surface hydrology and their method of production are summarised in Table 15

Soil physical and hydraulic properties :	
Ksat, bvalue	modelled on the basis of soil texture itself modelled on the basis of geology
Soil bulk density, stone content	modelled on the basis of landscape position
Soil depth	modelled as rooting depth for given cover types
Macropores	modelled according to stone content and bulk density

Table 15 The derivation of soil physical and hydraulic properties.

The pedotransfer functions of Campbell (1985) were used in PATTERN^{LITE} to model soil hydraulic conductivity and the nature of the soil moisture characteristic and hydraulic conductivity-soil moisture function on the basis of texture. This PTF has been widely applied and was used to parameterise PATTERN where measured data were not available. The functions are discussed in detail in Mulligan (1996) and the derivation of texture itself is discussed on page 29.

Soil bulk density

Soil bulk density is calculated as a surface bulk density (which can be made a function of land use) with the generic bulk density depth relationship applied except where stones are present. Bulk density impacts mainly on soil porosity.

Soil porosity

Soil porosity is calculated from soil bulk density throughout the soil profile using:

$$P = (1 - BD / sd)$$

Equation 21

P = porosity (m³/m³)

BD = final bulk density (kg/m³)

sd = stone density (kg/m³)

The total available porespace for infiltration and soil moisture is then:

$$CP = \sum_{i=1}^j Pmm$$

Equation 22

CP = cumulative porespace (mm)

Pmm = porespace (mm)

The depth of the wetting front at any time during the rainfall event can be calculated from soil moisture :

$$\theta = \sum_{i=1}^j P \cdot \Delta D$$

θ soil moisture (m³)

Equation 23

or from mm precipitation

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$$P_n = \sum_{i=1}^j P_{mm}$$

P_n precipitation

Equation 24

Soil stone fragment content

The landscape distribution of soil stone fragment content at the 100m scale will be modelled according to the outcome of the dominant processes of the horizontal re-distribution of the various sediment sizes (see van Wesemael et al, *in press*). It will also be affected by the geological structure. Rock fragment cover may also be simulated along the lines of Poesen et al. (1997), Poesen et al. (1998).

Soil thickness

Soil thickness is viewed as that part of the regolith which is in hydrological contact with the atmosphere, in other words the root zone. Soil depth is modelled as the minimum of some erosion and transport modelled regolith thickness (Boer et al., 1996) and the land cover dependent rooting depth. Water leaving the root zone is assumed to be recharge. So soil depth is modelled as:

$$\text{Min}(dL, dR)$$

Equation 25

where

$$dL = f(A/\tan(\beta))$$

Equation 26

where

dL = landscape controlled soil thickness (m) for a cell

A = upslope area draining to cell

β = slope of cell

dR = root zone depth for cover type occupying cell.

Soil texture

Soil texture will be modelled according to the textural composition of underlying geology with some diffusive mixing along the river networks and associated flood zones

Soil macropores

Macroporosity is important in the hydrology of semi arid environments since macropore flow is rapid and bypasses the wetting front pathway for infiltration. Macropores can sometimes connect surface waters directly with the base of the root zone, providing a rapid transport mechanism for recharge.

Land cover and land use

Land use will be provided to PATTERN^{LITE} by the Cranfield and RIKS models, though the initial condition will be provided by the CORINE data. The CORINE data is the best routinely available source for land use information in the EU. However the CORINE classification system is not the optimal classification for hydrological studies. The disadvantages of CORINE for hydrological modelling include:

- (a) Too many classes
- (b) Overlap between classes
- (c) Classes not defined in terms of functional characteristics
- (d) Some very broad classes in terms of functional attributes

For these reasons, a conversion algorithm has been developed to reclassify the CORINE data (or Cranfield/RIKS) output to hydrological useful classes. In terms of the regionalisation discussed on page 35 the fewer the number of classes, the more computationally efficient so class numbers are kept to a minimum. The classification adopted is a functional one whereby the functional attributes of a

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particular land use are emphasised. This means a great deal of aggregation but given the lack of land use specific data for particular crops and the functional nature of the hydrology and growth models, this is warranted. The PATTERN^{LITE} classification has 9 functional classes (1) urban and rock, (2) disturbed ground, (3) non irrigated grass, (4) irrigated grass, (5) tree, (6) dwarf shrub, (7) sparsely vegetated, (8) water and (9) unknown. The relationship between the PATTERN^{LITE} classification and the CORINE classification is shown in Table 16. Note that during this process of reclassification individual pixels recorded as unknown by CORINE are assigned the majority land cover of their neighbouring 2km radius.

PATTERN ^{LITE} Classification	PATTERN ^{LITE} name	CORINE Classification	CORINE name
1	urban/rock	1	Continuous urban fabric
1	urban/rock	2	Discontinuous urban fabric
1	urban/rock	3	Industrial or commercial units
1	urban/rock	4	Road and rail networks and associated land
1	urban/rock	5	Port Areas
1	urban/rock	6	Airports
1	urban/rock	31	Bare rocks
2	ground disturbed	7	Mineral extraction sites
2	ground disturbed	8	Dump sites
2	ground disturbed	9	Construction sites
2	ground disturbed	30	Beaches dunes sands
3	non irrigated grass functional type	12	Non-irrigated arable land
3	non irrigated grass functional type	18	Pastures
3	non irrigated grass functional type	19	Annual crops associated with permanent crops
3	non irrigated grass functional type	20	Complex cultivation patterns
3	non irrigated grass functional type	26	Natural grassland
4	irrigated grass functional type	10	Green urban areas
4	irrigated grass functional type	11	Sport and leisure facilities
4	irrigated grass functional type	13	Permanently irrigated land
4	irrigated grass functional type	14	Rice fields
5	tree functional type	15	Vineyards
5	tree functional type	16	Fruit trees and berry plantations
5	tree functional type	17	Olive groves
5	tree functional type	22	Agro-forestry areas
5	tree functional type	23	Broad-leaved forest
5	tree functional type	24	Coniferous forest
5	tree functional type	25	Mixed forest
5	tree functional type	28	Sclerophyllous vegetation
6	dwarf shrub functional type	21	Land principally occupied by agriculture with significant areas of natural vegetation
6	dwarf shrub functional type	27	Moors and heathland
6	dwarf shrub functional type	29	Transitional woodland-scrub
7	sparsely vegetated	32	Sparsely vegetated areas
7	sparsely vegetated	33	Burnt areas
8	Water	34	Glaciers and perpetual snow
8	Water	35	Inland marshes
8	Water	36	Peat bogs
8	Water	37	Salt marshes
8	Water	38	Salines
8	Water	39	Intertidal flats
8	Water	40	Water courses
8	Water	41	Water bodies

PATTERN ^{LITE} Classification	PATTERN ^{LITE} name	CORINE Classification	CORINE name
8	Water	42	Coastal lagoons
8	Water	43	Estuaries
8	Water	44	Sea and ocean
9	Unknown	0	Not part of map
9	Unknown	49	Missing data

Table 16 The PATTERN^{LITE} land use classification

All model parameters that are land use dependent will be supplied as lookup tables on the basis of these land use classes. The PATTERN^{LITE} land cover maps for the Argolid is shown in Figure 20.

Argolid Pattern Light Land Cover

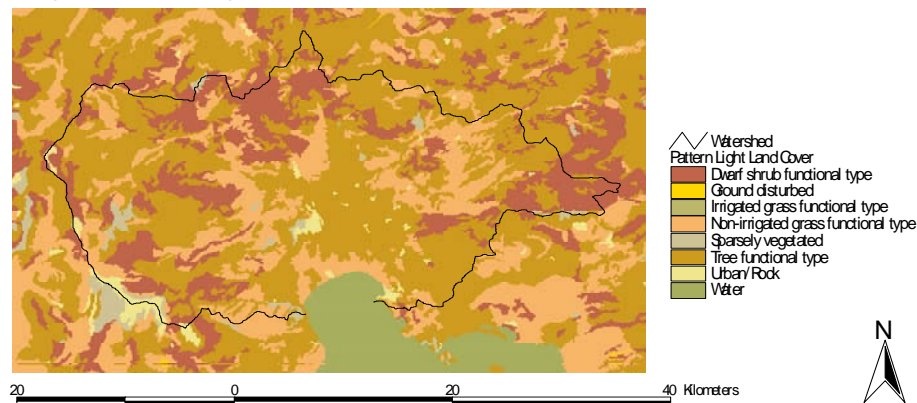


Figure 20 Argolid PATTERN^{LITE} land cover.

Spatialisation of the PATTERN model

Land use dependence

A number of the parameters of the Soil Erosion, crop growth and hydrology model have vegetation dependence. These parameters will be modified with the vegetation cover through an indexed look-up table.

Interface with the channel model

The responsibility of KCL for the hydrology stops at the base of the hillslopes, which is defined for simplicity as all stream orders >1. KCL will model hillslope hydrological fluxes for all stream orders of 1, that is 170427 of 239385 cells (71%) for Marina Baixa and 135112 of 204432 cells (66%) for the Argolid. This scheme can only function if the channel model accepts a direct input of rainfall for the atmosphere and loses water as transmission loss. If not then the model will be in error by losing the hydrology in whichever cells are termed channels. Another approach would be to use only the top two orders in the catchment as representative or large channels that would occupy the majority of the cell—all other orders would be dealt with by the hydrology model.

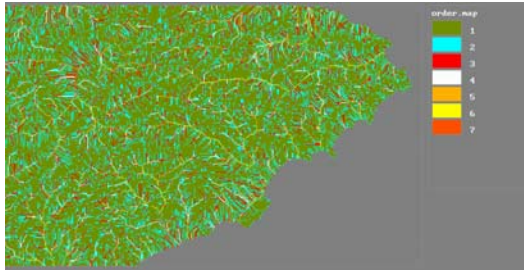


Figure 21 Orders for Marina Baixa. Currently PATTERN^{LITE} is integrated only in order 1.

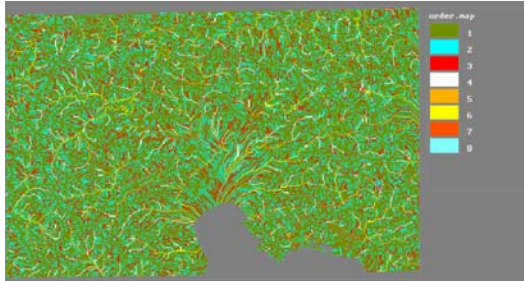


Figure 22 Orders for the Argolid. Currently PATTERN^{LITE} is integrated only in order 1.

Flow Routing and redeposition

Flow routing in the PATTERN model was achieved using a diffusive algorithm since this is computationally efficient over small areas and representative of hillslope microtopography. PATTERN^{LITE} uses a single unidirectional flow routing algorithm which routes overland flow from each cell to its downslope neighbour in a local drainage direction (LDD) map. The drainage direction is defined as the maximum drop in height between a cell and its eight immediate neighbours. The LDD map is preprocessed in a GIS. LDD for the Guadalest catchment in Marina Baixa is shown in Figure 23

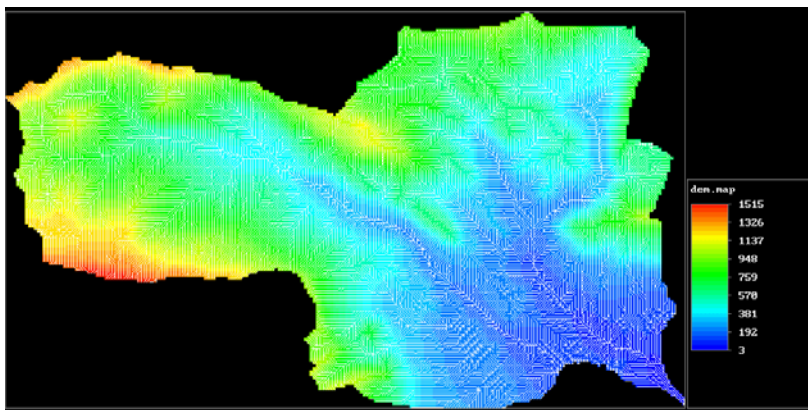


Figure 23 Local drainage direction draped over DEM for Guadalest catchment.

The critical issue of run-time

Perhaps the most critical issue for modelling complex hydrological processes over one quarter of a million cells in a 'responsive' manner is the issue of computational efficiency. The working rule for building models for decision support is that all excessive computational precision must be removed and

the computations should not be more precise than the data on which they are based. The computational precision should be determined only by the importance of the process and the quality of the data available. Efficiencies can be achieved in two main ways (a) intelligent timesteps and (b) intelligent spatial simulation.

Optimising time : Intelligent timesteps

Most hydrological models run on a fixed timestep. This has two disadvantages. First in hydrological systems two states can be identified : dry and raining. During these states the rapidity and nature of hydrological processes are quite different. With a fixed timestep they are treated in the same way numerically. Second a fixed timestep is very inefficient and it therefore limits the minimum timestep of the order of one hour or more. This is not sufficient to account for the rate of change of surface hydrology during a rainfall event.

Instead of integrating every hour of every day (8760 times a year), PATTERN^{LITE} follows the example of PATTERN and has a variable timestep which integrates in proportion to the rate of rainfall during rainfall events (giving maximum accuracy in the characterisation of overland flow generation). During dry periods (85-93% of days in Marina Baixa) the model is integrated twice daily at sunrise and sunset. The sunrise and sunset integrations are chosen as physically realistic integration periods since sunrise and sunset separate two different process domains for energy driven hydrological processes.

For an average rain-year in Marina Baixa this integration scheme reduces the number of timesteps required by 77% by providing the precision only when it is required. Variables can still be output as hourly totals if necessary. As well as the hydrological processes, soil erosion is calculated using these timesteps. Non hydrological processes like plant growth are not calculated at the rainfall timesteps, only at sunrise and sunset.

Optimising space : Regionalisation

For a model to be truly regional it has to cover areas of 50Km*50Km and greater. At the same time, for the model to accurately represent hydrological processes, within the constraints of widely available data the cell size has to be around 100m. This means repeating all calculations hundreds of thousands of times per time step i.e. for each cell. In many cases resolving an equation for each grid cell is inappropriate because the variability in properties from one cell to another is smaller than the accuracy required of the output. If we take the example of temperature calculation on the basis of altitude, for the Argolid:

$$T = -0.006 * \text{Altitude} + 18.117$$

If this equation were resolved using a lookup table of altitude data grouped into 10m classes (177 classes for the Argolid altitudinal range) instead of the 204 432 individual cells, the accuracy in temperature estimation would be +/-0.06°C with a reduction in the number of calculations of 204255 calculations! Given the accuracy with which temperature can reasonably be measured one could probably use just 18 classes which would give a computational accuracy of +/- 0.6°C. In other words, large parts of the landscape have very similar responses. If we define a margin of error for the calculations then we can regionalise the grid and dramatically reduce the repetition of calculations without losing information.

This regionalisation can be applied to many of the equations in the hydrological model. It is most efficient for equations with few variables but could also be used for multi-variate equations, though the number of classes required begins to multiply rapidly once combinations of variables have to be taken into account. For many variables the likely distribution of errors within the class chosen will be approximately equal so that they are in fact cancelled out and the class representation is therefore remarkably accurate. Figure 24 shows that this is certainly the case for evaporation (late morning, 1st June, Guadalest). Evaporation values were regionalised into 100 classes to replace the 20863 pixels of the Guadalest. The within class errors are distributed equally through the class and so the middle of the class is a good representation of the true evaporation.

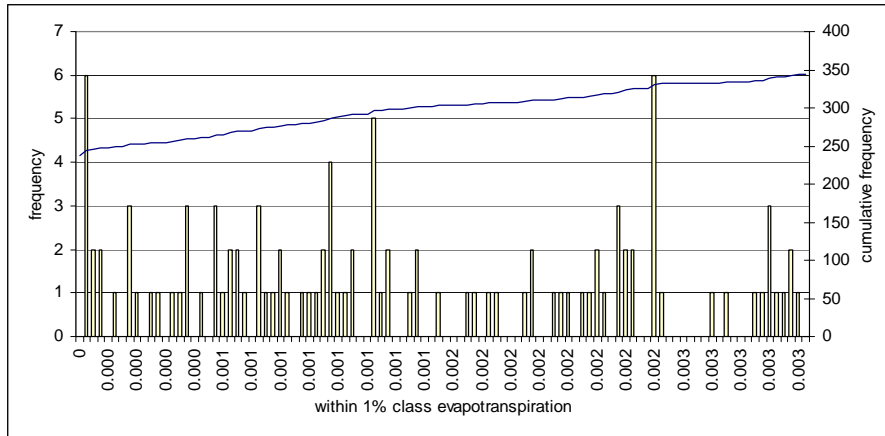


Figure 24 Within class errors for evapotranspiration.

Links with other models

The links between PATTERN^{LITE} and other models are as important as the models themselves. It is through these shared variables that the models communicate. The dataflows between PATTERN^{LITE} and other models are summarised in Table 17.

Required inputs from other models

monthly leaf area index (m²leaf/m² ground)
 monthly vegetation cover (fraction) for each 'functional type'
 monthly or constant rooting depth (m, lookup table according to veg. type)
 monthly vegetation functional types (from lookup table)

outputs to other models

hourly* interception loss (mm/hr)
 hourly* transpiration (mm/hr)
 hourly* soil evaporation (mm/hr)
 hourly* erosion (mm soil/hour)
 hourly* routed infiltration and overland flow (mm/hr)
 hourly* soil moisture (m³water/m³soil) recharge (mm/hr)

*can be aggregated to daily or monthly if preferred

Table 17 Dataflows between PATTERN and other models.

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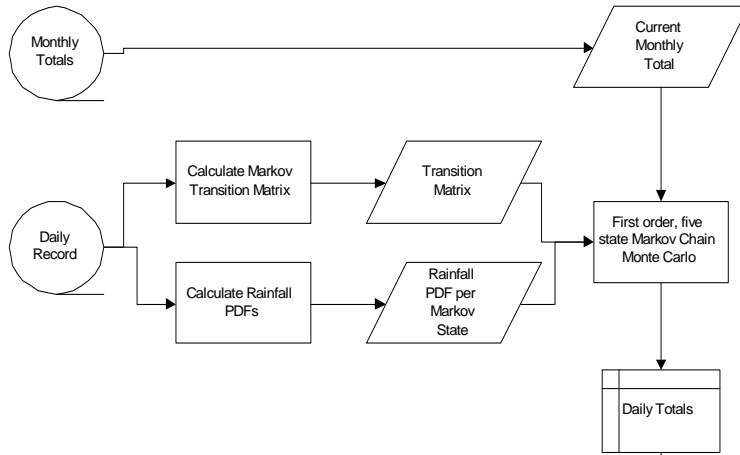
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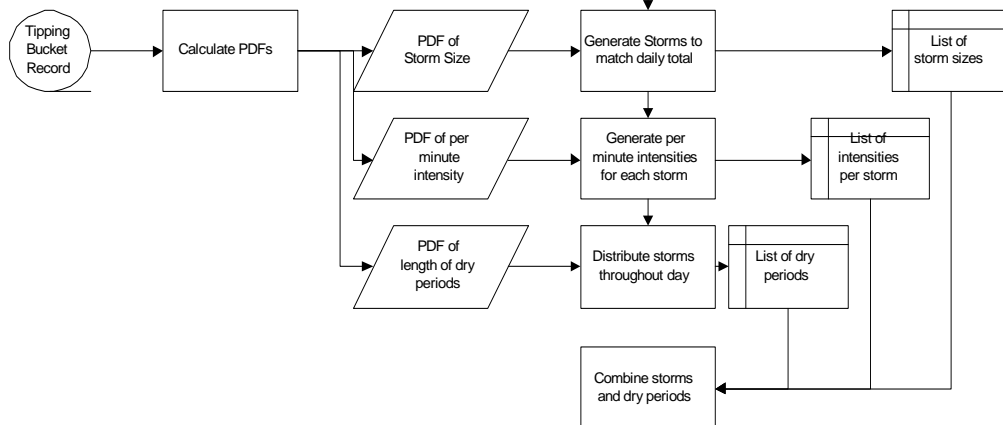
Appendix

Rainfall generation flow diagram (general)

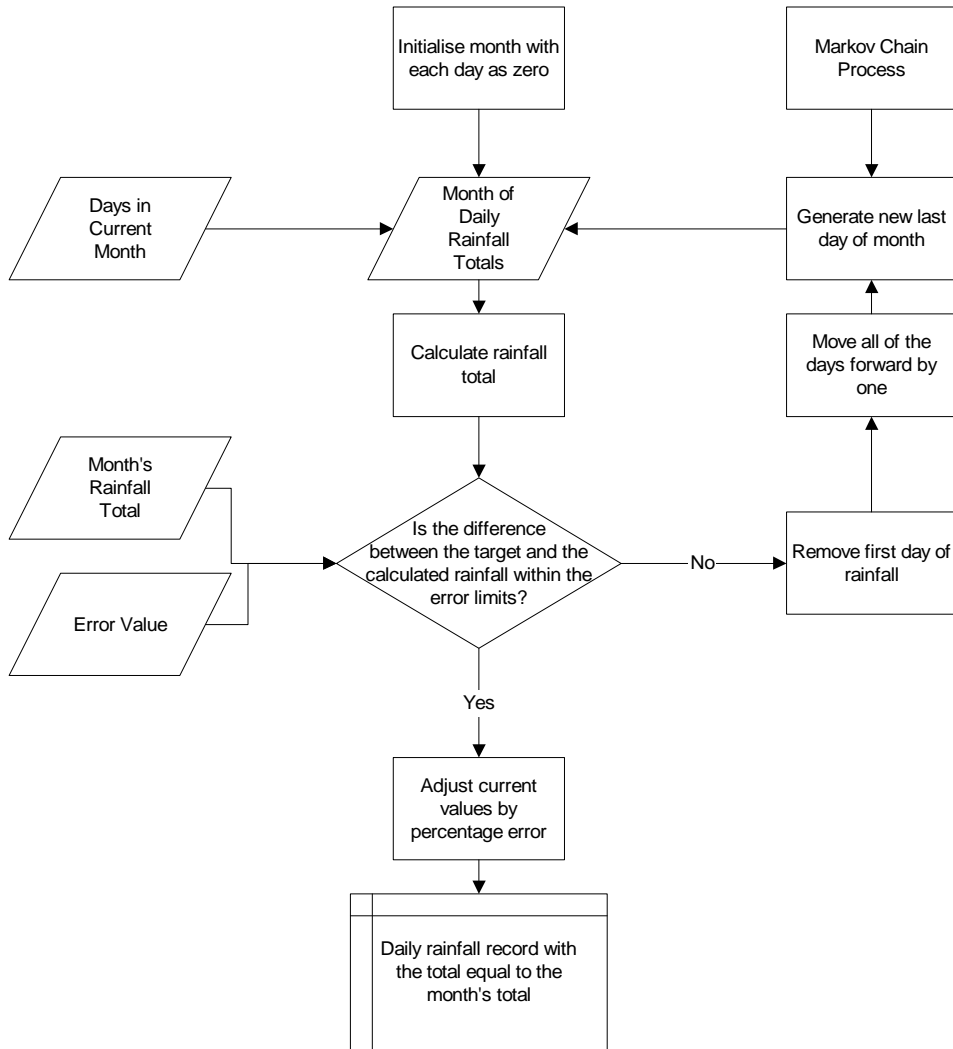
Monthly to Daily



Daily to Storm



Rainfall generation flow diagram (detailed)



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